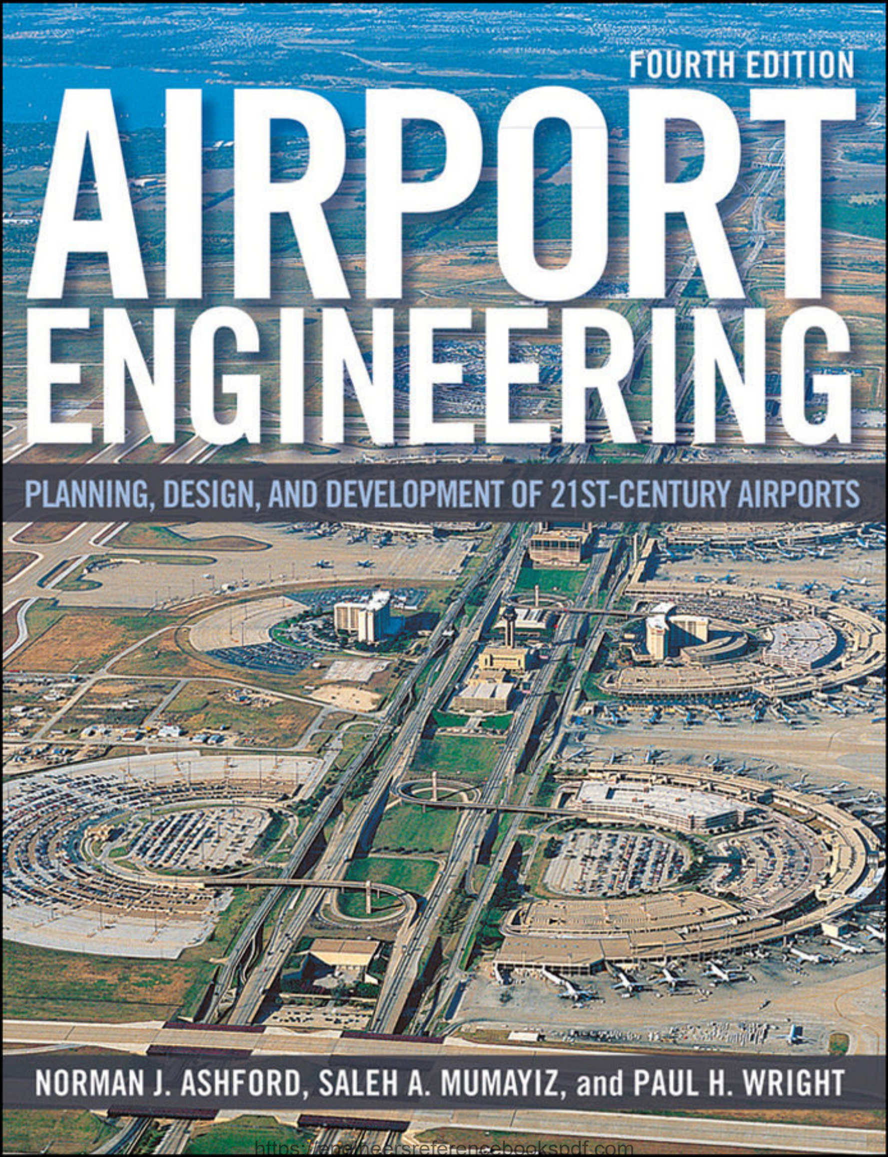

FOURTH EDITION

AIRPORT ENGINEERING

PLANNING, DESIGN, AND DEVELOPMENT OF 21ST-CENTURY AIRPORTS

NORMAN J. ASHFORD, SALEH A. MUMAYIZ, and PAUL H. WRIGHT

Airport Engineering

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Planning, Design, and Development of 21st Century Airports

Fourth Edition

Norman J. Ashford
Saleh Mumayiz
Paul H. Wright

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To Joan, Lubna, and Joyce

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Preface

This book has been rewritten in its fourth edition to continue to serve as a basic text for courses in airport planning and design. In the past it has been of value as reference to airport designers, planners, and administrators worldwide as well as to consultants in airport infrastructure development. The fourth edition is a complete update of the third edition, published in 1992, taking into account major revisions to Federal Aviation Adminstration (FAA), International Civil Aviation Organization (ICAO), and International Air Transport Association (IATA) standards and recommended practices. Furthermore, the revisions reflect the experiences of the authors in teaching, consulting, and research in this field. The authors have teaching experience in postgraduate and post-experience courses throughout the world and extensive consultancy experience, having in the last 20 years participated in the planning and design of many airports around the world, both large and small.

This fourth edition of *Airport Engineering* appears 18 years after its predecessor and in the interim very big and far-reaching changes have occurred in civil aviation. Security has been dramatically and irrecoverably tightened throughout the world, especially in the United States, since the 9/11 terrorist atrocities in the northeastern United States in 2001. Passenger facilitation has been revolutionized with the introduction of almost universal electronic ticketing and check-in procedures. The introduction of the A380 aircraft into service has heralded the arrival of what had, up to then, been termed the New Large Aircraft. The information technology (IT) revolution had profound influence on air travel and the air transport industry. The widespread usage of the Internet has also permitted the rapid and broad publication of standards and recommended practices by the FAA and other regulatory bodies. The nature of civil aviation itself has changed with the evolution and proliferation of the low-cost carriers and growth of this market. Moreover, air freight has grown considerably and now has a significant proportion of its traffic carried by the door-to-door service of the integrated carriers. The general availability of desktop computers and low-cost software allows designers and operators to use computerized techniques [e.g., modeling, simulation, and geographic information system (GIS)] more widely and effectively as a day-to-day tool of airport design and operation. In the area of the environmental impact of aviation, the aircraft of the twenty-first century are an order-of-magnitude quieter than their predecessors: The importance of noise impact has decreased as the industry faces increased scrutiny and regulation in areas of water and air pollution, carbon footprint, renewable energy, and sustainable development. In this edition, the authors have addressed these changes and have restructured the shape of the text to reflect conditions as they are a decade into the twenty-first century.

Chapters 6, 7, and 8 have seen major restructuring to cover airport–airspace interaction, airport capacity (both airside and landside), and airside geometric design, respectively. These three areas of airport planning and design have come to the forefront in a major and comprehensive way. In particular, airport capacity has become the basis of evaluating airport performance and as the primary determinant of airport improvement, expansion, and development. Chapters 10 and 12 incorporate the recently published procedures and practices relating to spreadsheet design using new Transportation Research Board (TRB-Airport Cooperative Research Program and FAA methods for passenger terminal planning and pavement design. New Chapters 15 and 16 have been included to cover matters relating to the increasingly important subjects of simulation and the developments of the airport city concepts. Chapter 17 has been totally revamped and updated to describe current thinking and regulations in the area of environmental impact. Elsewhere, all chapters have been updated to 2010 standards and practices to reflect industry structure, operational and market practices, and modern technology.

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Transportation Research Board, United States

1

The Structure and Organization of Air Transport

1.1 THE NEED FOR NATIONAL AND INTERNATIONAL ORGANIZATIONS (1)

For those who have matured in an age marked by the noise, bustle, and efficiency of jet aircraft travel, it is difficult to realize that it is just over 100 years since the first brief flight of the Wright brothers at Kitty Hawk, North Carolina, and Bleriot's later historic crossing of the English Channel. Before the early years of the last century, except for the infrequent use of nonpowered balloons, man had been restricted to the earth's surface. In 2010 civil aviation was a major international industry that carried approximately 3 billion passengers each year in aircraft which fly an aggregate of close to 4.5 trillion kilometers. Since aviation is largely international, problems are created that individual nations cannot solve unilaterally; consequently, from the earliest days of civil aviation, there has been an attempt to find international solutions through the creation of international bodies. Typically, civil aviation requires the building of airports to accepted international standards, the establishment of standard navigational aids, the setting up of a worldwide weather-reporting system, and the standardization of operational practices to minimize the possibility of error or misunderstanding.

National institutions can assist in the general aims of providing safe and reliable civil air transport. Their role is to furnish procedures for the inspection and licensing of aircraft and the training and licensing of pilots and to provide the necessary infrastructure—that is, navigation aids and airports. Although the establishment of an infrastructure for a country's civil air transport is a national concern that cannot realistically be assumed by an international body, it is clear that there is a need for the standardization of procedures, regulations, and equipment, as well as infrastructure, on a worldwide basis.

1.2 THE INTERNATIONAL CIVIL AVIATION ORGANIZATION

The first attempt to reach an international consensus was unsuccessful; in 1910, representatives of 19 European nations met to develop an international agreement. Another attempt was made to internationalize civil aviation standards after World War I, when the Versailles Peace Conference set up the International Conference for Air Navigation

(ICAN). Although this organization lasted from 1919 until World War II, its effectiveness was extremely limited because of the regionality of air transport even up to the early 1940s.

World War II provided a huge impetus to civil aviation. New types of fast monoplane aircraft had been developed, and the jet engine was in its infancy; navigational aids that had been developed for military purposes were easily adapted to civilian use, and many countries had built numerous military airports that were to be converted to civilian use after the war. A generation of peacetime development had been crammed into the period of the European war from 1939 to 1945. In early 1944, the United States sought out its allies and a number of neutral nations—55 in all—to discuss postwar civil aviation. The result of these exploratory discussions was the Chicago Convention on Civil Aviation in November 1944, attended by 52 countries. Its purposes are best described by the preamble to the convention (1):

> WHEREAS the future development of international civil aviation can greatly help to create and preserve friendship and understanding among the nations and peoples of the world, yet its abuse can become a threat to the general security; and
>
> WHEREAS it is desirable to avoid friction and to promote that cooperation between nations and peoples upon which the peace of the world depends;
>
> THEREFORE the undersigned governments, having agreed on certain principles and arrangements in order that international civil aviation may be developed in a safe and orderly manner and that international air transport services may be established on the basis of equality of opportunity and operated soundly and economically;
>
> HAVE accordingly concluded this Convention to that end.

The Chicago Convention established 96 articles which outlined the privileges of contracting states, provided for the establishment of international recommended practices, and recommended that air transport be facilitated by the reduction of formalities of customs and immigration. After ratification by the legislatures of 26 national states, the International Civil Aviation Organization (ICAO) came into existence on April 4, 1947. By 2008, the original 26 ratifying states had grown to 190 member states. The modus operandi of the ICAO is stated in Article 44 of the Convention:

> ICAO has a sovereign body, the Assembly, and a governing body, the Council. The Assembly meets at least once in three years and is convened by the Council. Each Contracting State is entitled to one vote and decisions of the Assembly are taken by a majority of the votes cast except when otherwise provided in the Convention. At this session the complete work of the Organization in the technical, economic, legal and technical assistance fields is reviewed in detail and guidance given to the other bodies of ICAO for their future work.

Although the sovereign body of the ICAO is the Assembly, in which each contracting state has one vote, the governing body of the organization is the 36-member Council, which emphasizes in its makeup the states of chief importance to air transport, with a provision for geographical balance. One of the principal functions and duties of the Council is to adopt international standards and recommended practices. Once adopted, these are incorporated as annexes to the Convention on International Civil Aviation (Table 1.1).

Table 1.1 Annexes to the ICAO Convention on International Civil Aviation

Annex[a]	Covers
1. Personnel Licensing	Licensing of flight crews, air traffic control officers, and aircraft maintenance personnel
2. Rules of the Air	Rules relating to the conduct of visual and instrument flights
3. Meteorological Service for International Air Navigation	Provision of meteorological services for international air navigation and reporting of meteorological observations from aircraft
4. Aeronautical Charts	Specifications for aeronautical charts for use in international aviation
5. Units of Measurement to Be Used in Air and Ground Operations	Dimensional systems to be used in air and ground operations
6. Operation of Aircraft	
Part I—International Commercial Air Transport	
Part II—International General Aviation	Specifications that will ensure in similar operations throughout the world a level of safety above a prescribed minimum
7. Aircraft Nationality and Registration Marks	Requirements for registration and identification of aircraft
8. Airworthiness of Aircraft	Certification and inspection of aircraft according to uniform procedures
9. Facilitation	Removal of obstacles and impediments to movement of passengers, freight, and mail across international boundaries
10. Aeronautical Telecommunications	Standardization of communications equipment and systems (Vol. 1) and of communications procedures (Vol. 2)
11. Air Traffic Services	Establishment and operation of air traffic control, flight information, and alerting services
12. Search and Rescue	Organization and operation of facilities and services necessary for search and rescue
13. Aircraft Accident Investigation	Uniformity in the notification, investigation, and reporting of aircraft accidents
14. Aerodromes	Specifications for the design and equipment of aerodromes
15. Aeronautical Information Services	Methods for the collection and dissemination of aeronautical information required for flight operations
16. Environmental Protection	Specifications for aircraft noise certification, noise monitoring, and noise exposure units for land use planning
17. Security	Specifications for safeguarding international civil aviation against acts of unlawful interference
18. Safe Carriage of Dangerous Goods by Air	The storage, handling, and carriage of dangerous and hazardous cargo

[a] All annexes, except 9, are the responsibility of the Air Navigation Commission. Annex 9 is the responsibility of the Air Transport Committee.

Source: Memorandum on ICAO, Montreal: International Civil Aviation Organization, July 1975 as updated.

1.3 NONGOVERNMENTAL ORGANIZATIONS

There are a number of industrial organizations active in the area of air transportation, both at the international and the national levels. The most important of the international organizations are as follows:

1. *International Air Transport Association* (*IATA*). An organization with more than 100 scheduled international carrier members. Its role is to foster the interests of civil aviation, provide a forum for industry views, and establish industry practices.
2. *Airports Council International* (*ACI*). This organization was founded in 1991 as *Airports Association Council International* (*AACI*) to serve as a forum and a focus for the views and interests of civil airport operators. The ACI came about from a merger of the mainly U.S. Airport Operators Council International (AOCI), a mainly North-American association, and the International Civil Airports Association (ICAA), which had been dominated by European operators.

In the United States, the more important domestic organizations with views and policies affecting the civil aviation industry are the Air Line Pilots Association, the Aircraft Owners and Pilots Association, the Air Transport Association of America, the National Association of State Aviation Officials, and the American Association of Airport Executives.

1.4 U.S. GOVERNMENTAL ORGANIZATIONS (2)

The administration, promotion, and regulation of aviation in the United States are carried out at the federal level by three administrative bodies:

1. The Federal Aviation Administration
2. The National Transportation Safety Board

After the calamitous terrorist incidents of September 2001, security aspects of the aviation were assumed by the newly created:

3. Department of Homeland Security, which set up the Transportation Security Administration within its structure

The Federal Aviation Administration (FAA)

The FAA has prime responsibility for civil aviation. Formerly called the Federal Aviation Agency, it was absorbed into the Department of Transportation under the terms of the reorganization contained in the Department of Transportation Act of 1967 (80 Stat. 932). It is charged with:

Regulating air commerce in ways that best promote its development and safety and fulfil the requirements of national defense

Controlling the use of the navigable airspace of the United States and regulating both civil and military operations in such airspace

Promoting, encouraging, and developing civil aeronautics

Consolidating research and development with respect to air navigation facilities

Installing and operating air navigation facilities

Developing and operating a common system of air traffic control and navigation for both civil and military aircraft

Developing and implementing programs and regulation to control aircraft noise, sonic boom, and other environmental effects of civil aviation

The administration discharges these responsibilities with programs in nine principal areas:

1. *Safety and Regulation.* Issuance and enforcement of regulations relating to the manufacture, operation, and maintenance of aircraft; rating and certification of airmen and certification of airports serving air carriers; flight inspection of air navigation facilities in the United States and, as required, abroad.
2. *Airspace and Air Traffic Management.* The operation of a network of air traffic control towers, air route traffic control centers, and flight service stations. The development and promulgation of air traffic rules and regulation and the allocation of the use of airspace. Provision for the security control of air traffic to meet national defense requirements.
3. *Air Navigation Facilities.* The location, construction or installation, maintenance, and operation of federal visual and electronic aids to air navigation.
4. *Research, Engineering, and Development.* Research, engineering, and development activities directed toward providing systems, procedures, facilities, and devices for safe and efficient air navigation and air traffic control for both civil aviation and air defense. Aeromedical research to promote health and safety in aviation. Support for the development and testing of new aircraft, engines, propellers, and other aircraft technology.
5. *Test and Evaluation.* The agency conducts tests and evaluations on items such as aviation systems and subsystems, equipment, devices, materials, concept, and procedures at any phase in the cycle of design and development.
6. *Airport Programs.* Maintenance of a national plan of airport requirements; administration of a grant program for development of public use airports to assure and improve safety and to meet current and future needs; evaluation of environmental impacts of airport development; administration of airport noise compatibility program; developing standards and technical guidance on airport planning, design, safety, and operations; provision of grants to assist public agencies in airport system and master planning, airport improvement and development.
7. *Registration and Recording.* Provision of a system for the registration of aircraft and recording of documents affecting title or interest in aircraft, aircraft engines, and spare parts.
8. *Civil Aviation Abroad.* Under the Federal Aviation Act of 1958 and the International Aviation Facilities Act (49 U.S.C. app 1151), the agency promotes aviation safety and civil aviation abroad by information exchange with foreign aviation authorities; certification of foreign repair stations, airmen, and mechanics; negotiating bilateral airworthiness agreements; technical assistance

and training; technical representation at international conferences and participation in ICAO and other international organizations.

9. *Other Programs.* Aviation insurance, aircraft loan guarantee programs, allotting priorities to civil aircraft and civil aviation operations, publication of current information on airways and airport service, issuing technical publications for the improvement of safety in flight, airport planning and design, and other aeronautical services.

The National Transportation Safety Board (NTSB)

The NTSB was established as an independent agency of the federal government in April 1975 under the terms of the Independent Safety Board Act of 1974 (88 Stat. 2156; 49 U.S.C. 1901). Its five members are appointed by the president. Its function is to ensure that transportation in the United States is conducted safely. The NTSB assumed responsibility for the investigation of aviation accidents, which previously had been carried out by the Civil Aeronautics Board, the economic regulatory organization which became defunct in the early 1980s as part of domestic deregulation of civil aviation. The Bureau of Accident Investigation, the section within the agency responsible for investigating aviation accidents, reports directly to the five-member board through the Office of the Managing Director.

Department of Homeland Security (Transportation Security Administration)

Part of the Department of Homeland Security is the Transportation Security Administration, which is responsible nationally for transportation security and in particular that of aviation. Federal staff is responsible for, among other matters, air passenger screening, baggage screening, air cargo inspection and screening, federal air marshals and federal flight deck officers, and canine explosive detection.

1.5 AVIATION PLANNING AND REGULATION AT STATE LEVEL

In the early days of civil aviation, the federal government saw no role for itself in the provision of airports. This was stated to be a local responsibility that should be financed principally by the municipalities or by private sources (3). The Air Commerce Act of 1926 gave the secretary of commerce authority "to designate and establish civil airways and, within the limits of available appropriations hereafter made by Congress, to establish, operate and maintain along such airways all necessary air navigation facilities except airports."

In that municipalities draw all their power from the authority delegated by the sovereign states, government at the state level necessarily became involved in aviation. Consequently, state aviation departments and bureaus and, in some cases, state aeronautical commissions were established. Most states have some form of user taxation on aviation, which is channeled back into airport development in the form of matching-fund grants.

The planning and financing of airports vary from state to state, and the practice of a particular state depends greatly on the organizational structure of the overall administration of transportation within the state. All states now have state Departments of Transportation (DOTs), which act as intermediaries in federal–local negotiations. A number of different organizational forms of state DOTs have evolved. In extreme forms, they vary from *functional* structures, in which individual departments are multimodal, to *modal* structures, which strongly reflect the single-mode agencies prior to the formation of state DOTs. Frequently, the structure is of a *hybrid* form that is somewhere between these two extremes. Figure 1.1 illustrates the forms of functional, modal, and hybrid state DOTs.

1.6 PATTERNS OF AIRPORT OWNERSHIP (4, 5)

In the early days of civil aviation in the United States, airports typically were owned by local authorities or private organizations. Massive increases in passenger volume, however, required building an extensive infrastructure in the passenger terminal area; at the same time, the increasing weight and sophistication in aircraft necessitated greater investment in extensive pavements for runways, taxiways, and aprons; equally necessary were navigational and landing aid systems. These requirements were generally beyond the capability of private finance, and the private airport operator tended to disappear, except at the smallest airports.

Until the late 1980s, public ownership of a nation's large airports was a worldwide model that was generally upheld as being the natural state of things. However, by the late 1980s, it became apparent that some airports had grown to be both large generators of revenues and profits and the centers of activities which required very large infusions of capital financing. In the wake of de jure deregulation of U.S. domestic civil aviation and progress toward de facto deregulation of European airlines, strong moves were made in a number of countries to "privatize" or denationalize the nation's airports. The United Kingdom took a lead in this direction with the Airports Act (1986), which required all its medium and large airports to become private companies by 1987, placing them in the private sector. In 1987, the BAA plc, which had formerly been the British Airports Authority, handling three-quarters of all British air passengers, became the first airport company to be quoted on the public stock exchange.

Since the late 1980s, except in the United States, the international tendency has been to move from public to private ownership, but the form of public or private ownership varies from country to country. The principal forms of ownership are the following:

1. Ownership by a governmental agency or department whereby airports are centrally owned and operated either by a division of the overall Ministry of Transport or by the more specialized Ministry of Civil Aviation
2. Quasi-governmental organizations—public corporations set up by government for the specific purpose of airport ownership and operation, where the governmental unit may be national or regional (including state or provincial governments)
3. Authorities for individual airports or for groups of airports authorized by a consortium of state, provincial, or local governmental units
4. Individual authorities that run one airport on behalf of one local authority
5. Departments of a local authority
6. Single private companies or private consortia owning one or more airports

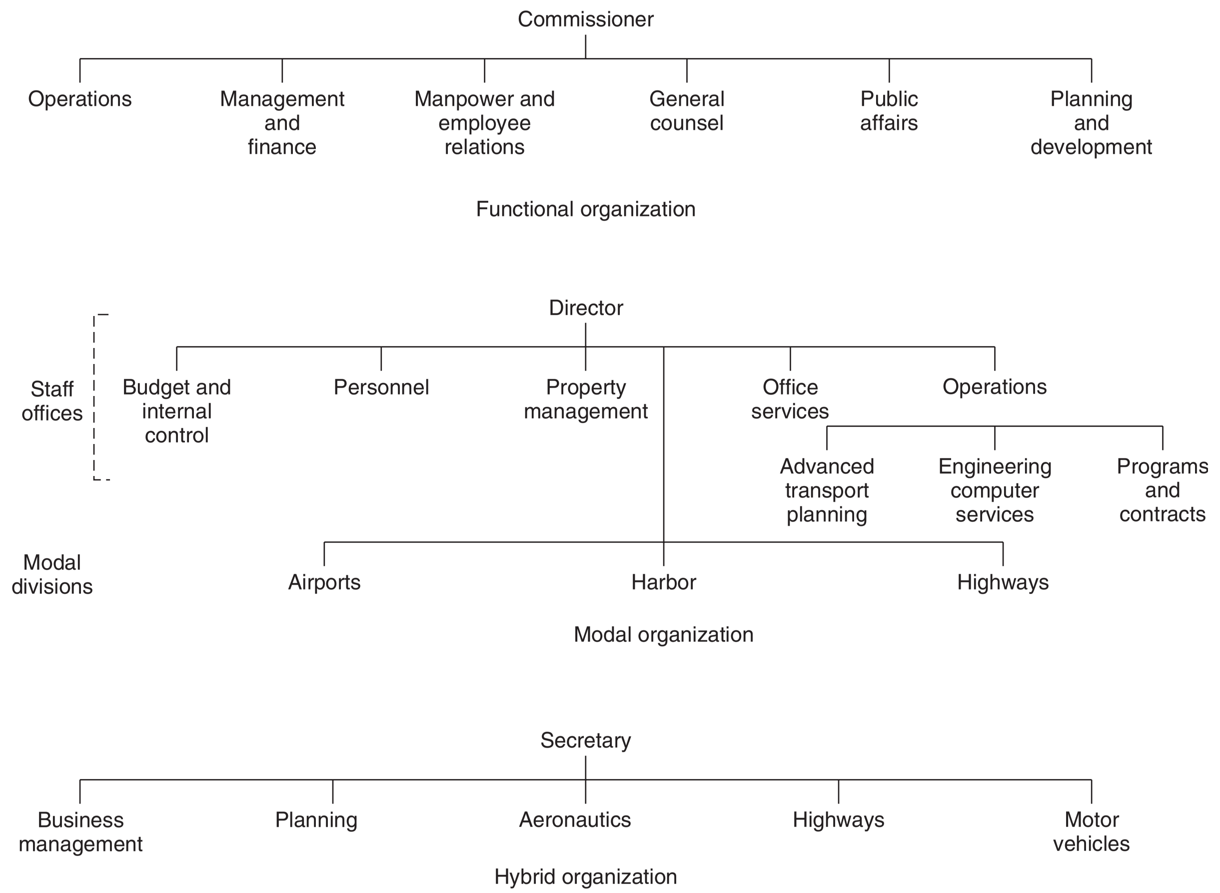

Figure 1.1 The aviation function within state DOTs.

An examination of international patterns of ownership indicates no special trends. In 2010, France, Italy, Germany, Holland, and the United States had the majority of their airports in public ownership, run by individual airport authorities. In a number of developing countries, as well as the United Kingdom, South Africa, Australia, Canada, Mexico, Chile, and Argentina, airports have been sold to private companies. In many cases, the largest airports in a country are owned and operated by private companies or consortia from foreign countries. In 2010 countries such as Holland, Ireland, Nigeria, and Brazil still owned and operated their airports through centralized organizations that are owned by or are part of the national government.

1.7 REVENUES AND EXPENDITURES AT U.S. AIRPORTS

Since the feasibility of developing and building an airport rests heavily on the anticipated revenue and expenditure, the financial aspects of airport planning must take into consideration both *revenues* and *expenses.* These two principal divisions may be further grouped into operating and nonoperating areas.

Revenues

Operating Revenues. The operating revenues at airports may be categorized into five major groupings (5).

1. *Landing Area.* Revenues are produced directly from the operation of aircraft in the form of landing fees and parking ramp fees.
2. *Terminal Area Concessions.* Nonairline uses in the terminal areas produce income from a varied range of activities, including *specialty areas* (e.g., duty-free stores, souvenir vendors, bookshops, newsstands, banks), *food and drink areas* (e.g., restaurants, cafeterias, bars), *leisure areas* (e.g., television, movie, and observation areas), *travel services* (e.g., lockers, wash-rooms, nurseries, insurance desks, car rentals, rest areas, telephones), *personal service areas* (e.g., barber shops, beauty salons, valet service), and *off-terminal facilities* (e.g., office rentals, advertising).
3. *Car Parking and Ground Transportation.* Especially at large airports, car parking is a very substantial contribution to airport revenues. In conjunction with ground transportation, this area of revenue generation is both large and profitable.
4. *Airline Leased Areas.* Within the terminal itself or in the general airport site, substantial revenues can be generated by leasing facilities to the airlines. Airlines normally rent offices, hangars, ticket and check-in counters, operations and maintenance areas, and cargo terminals. Ground rents are paid when the facility is provided by the airline.
5. *Other Leased Areas.* Many larger airports function as industrial and transport complexes incorporating a number of nonairline operations. These operations, which constitute another source of revenue, typically include industrial areas, fuel and servicing facilities, fixed-base operators, freight forwarders, and warehousing.

6. *Other Operating Revenue.* Sources of revenue in this category include equipment rental, resale of utilities, and, at some airports, services such as baggage handling.

Nonoperating Revenues. All income that accrues from sources that are not directly connected to airport functions is nonoperating revenue. Such income may derive, for example, from the rental of nonairport land or from interest on accumulated surpluses.

Expenditures

Operating Expenses. Numerous operating expenses are associated with the provision of airport services. These can be categorized into maintenance costs and operations costs:

1. *Maintenance Costs.* Expenditures are required for the upkeep of facilities; these are largely independent of traffic volume. Maintenance must be provided to the landing area (runways, taxiways, aprons, lighting equipment, etc.), the terminal area (buildings, utilities, baggage handling, access routes, grounds, etc.), and hangars, cargo terminals, and other airport facilities.
2. *Operations Costs.* This category, which includes administration and staffing, utilities, and to some extent security, reflects to a greater degree the amount of traffic. To some degree, these costs are escapable when demand is low.

Nonoperating Expenses. The inescapable costs that would have to be met even if the airport ceased operation are said to be nonoperating expenses. Typically, they include the interest payments on outstanding capital debt and amortization charges on such fixed assets as runways, aprons, buildings, and other infrastructure.

Table 1.2 shows the effect of the magnitude of passenger operations on the sources of income and expenditure for 43 airports in the United States. The data reveal a moderate tendency for nonoperating income and expenses to increase as airports

Table 1.2 Average Income and Expense Breakdown for U.S. Airports with Different Levels of Operational Activity

Income or expense	Average percentage breakdown of airport income and expenses by hub type		
	Large hubs (1% or more of U.S. enplanements)	Medium hubs (at least 0.25%, but less than 1% of U.S. enplanements)	Small hubs (at least 0.05%, but less than 0.25% of U.S. enplanements)
Income			
Operating income, %	48.4	42.3	46.4
Nonoperating income, %	51.6	57.7	53.6
Expenses			
Operating expenses, %	31.7	32.1	40.4
Nonoperating expenses, %	68.3	67.9	59.6

Sources: FAA Form 127 download and R. Golaszewski, GRA, Inc.

become larger. The overwhelming source of both revenue and expenditure remains in the operating category. The low level of nonoperating expense at U.S. airports reflects high levels of FAA funding for infrastructure. In fundamentally differently financed systems, nonoperating costs could rise substantially higher.

When the expense and revenue structure of non-U.S. airports is examined, it is found that the aeronautical income covers aeronautical expenditure only at the largest airports. At small airports, the aeronautical operations cause substantial losses. Non-aeronautical income which includes commercial income usually covers nonaeronautical expenditure at all but the smallest airports. At large airports, the intense commercialization of the passenger terminals generate large profits from nonaeronautical sources. These profits have proved to be highly incentive for commercial enterprises to buy into the airport industry. Investment in airports has come from banks, construction companies, and a variety of nonairport sources.

Structure of Revenues

Operating revenues vary considerably from airport to airport, in structure and in size. Their structure depends greatly on operating volume. (Since nonoperating revenues are, by their nature, not dependent on the operating characteristics of the airport, they tend to be peculiar to the individual airport.) As the number of airport operations increases across the range of airport sizes, the busier airports attract a higher proportion of commercial air carrier operations. The larger passenger capacity of commercial carrier aircraft ensures a disproportionate increase in passenger traffic, in comparison with the increase in aircraft movements. Consequently, air terminal income increases rapidly in importance in the overall revenue structure with growing operational activity.

Operational growth that accompanies increasing air carrier traffic requires substantial investment in terminal infrastructure to provide for the rapid increase in passenger movements. Table 1.3 indicates, for U.S. airports across a range of operational volumes, a historic estimate of the declining relative importance of the landing area as a source of revenue and the increasing dominance of terminal income. Table 1.4 shows the average figures for large, medium, and small U.S facilities.The financial stability of the operation of large airports is strongly related to the income generated by the terminal area. More than half of this income relates to surface access in the form of parking charges and leases to car rental firms, but more than one-quarter of terminal income is almost discretionary, coming from restaurants, bars, shopping concessions, and similar sources. Careful design can optimize this income relative to expenditure.

1.8 SOURCES OF CAPITAL FINANCING FOR U.S. AIRPORTS (5)

All airports are to some degree self-financing, and some large airports give a healthy return on invested capital. The initial capital requirement for the construction and development of airports is very large, and frequently the owning authority is unable to supply the necessary amount from its own resources. In the United States, ownership of airports rests almost entirely in the hands of local governmental units with slender capital resources. Airport development therefore proceeds on the basis of money aggregated from a variety of sources, such as general obligation bonds, self-liquidating general obligation bonds, revenue bonds, local taxes, and state and federal grants.

Table 1.3 U.S. Airport[a] Sources of Total Annual Revenues/Types of Costs

	Year 2008 or 2007 ($Millions)		
Revenues	Large hubs	Medium hubs	Small hubs
Landing fees	$2,088.2	$551.7	$147.1
Terminal rental	$2,620.5	$582.1	$216.5
Other aeronautical	$965.8	$296.0	$155.9
Total Aeronautical	**$5,674.6**	**$1,429.8**	**$519.4**
Rents, land, and other nonterminal	$249.0	$80.2	$83.0
Rents, terminal	$1,198.6	$205.3	$59.2
Car rental	$799.9	$369.6	$178.6
Parking	$1,763.8	$773.5	$302.0
Other nonaeronautical	$651.0	$76.0	$42.7
Total Nonaeronautical	**$4,662.4**	**$1,504.5**	**$665.5**
Bond proceeds and interest income	$7,497.4	$1,932.8	$473.5
Grants	$762.3	$431.8	$445.6
Passenger facility charges	$1,918.5	$501.3	$173.7
Other	$856.0	$1,139.6	$280.4
Total Nonoperating	**$11,034.2**	**$4,005.5**	**$1,373.2**
Total Revenue	**$21,371.1**	**$6,939.8**	**$2,558.1**
Expenses			
Personnel compensation	$2,414.1	$754.5	$382.8
Communications	$634.9	$170.6	$84.3
Supplies	$550.3	$87.3	$51.0
Services	$2,208.6	$704.9	$255.2
Insurance	$159.9	$44.6	$26.7
Other operating	$538.2	$132.1	$60.1
Total Operating Expense	**$6,506.0**	**$1,894.1**	**$860.1**
Interest	$2,235.7	$500.1	$137.4
Capital expenditures	$7,095.3	$2,256.1	$881.1
Other nonoperating expense	$174.3	$78.7	$24.2
Reporting year debt payments	$4,542.1	$1,174.7	$221.9
Total Nonoperating Expense	**$14,047.5**	**$4,009.6**	**$1,264.6**
Total Expenses	**$20,553.5**	**$5,903.6**	**$2,124.6**
	$817.7	**$1,036.1**	**$433.5**

[a]Number of reporting airports: large hub, 29; small hub, 36.
Excluded airports: large hub, FLL; small hub, TUS and SJU.
Note: DOT hub airport definitions:
The definitions and formulas used for designating primary airports by hub type and percentage of annual passenger boarding are: Large, 1% or more; Medium, at least 0.25% but less than 1%; Small, at least 0.05% but less than 0.25%; Nonhub, more than 10,000 but less than 0.05%.
Source: FAA Form 127 data download March 2009 and GRA Inc. USA.

General Obligation Bonds

General obligation bonds are issued by a governmental unit. They are secured by the full faith, credit, and taxing power of the issuing governmental agency. Although the level of anticipated revenues is considered in the initial determination of the level of investment, the bonds themselves are guaranteed from the general resources of the issuing body,

Table 1.4 U.S. Airport Annual Average Revenues and Costs

	Year 2008 or 2007 ($Millions)		
Revenues	Large hubs	Medium hubs	Small hubs
Landing fees	$72.0	$15.3	$2.2
Terminal rental	$90.4	$16.2	$3.3
Other aeronautical	$33.3	$8.2	$2.4
Total Aeronautical	**$195.7**	**$39.7**	**$7.9**
Rents, land and other nonterminal	$8.6	$2.2	$1.3
Rents, terminal	$41.3	$5.7	$0.9
Car rental	$27.6	$10.3	$2.7
Parking	$60.8	$21.5	$4.6
Other nonaeronautical	$22.4	$2.1	$0.6
Total Nonaeronautical	**$160.8**	**$41.8**	**$10.1**
Bond proceeds and interest income	$258.5	$53.7	$7.2
Grants	$26.3	$12.0	$6.8
Passenger facility charges	$66.2	$13.9	$2.6
Other	$29.5	$31.7	$4.2
Total Nonoperating	**$380.5**	**$111.3**	**$20.8**
Total Revenue	**$736.9**	**$192.8**	**$38.8**
Expenses			
Personnel compensation	$83.2	$21.0	$5.8
Communications	$21.9	$4.7	$1.3
Supplies	$19.0	$2.4	$0.8
Services	$76.2	$19.6	$3.9
Insurance	$5.5	$1.2	$0.4
Other operating	$18.6	$3.7	$0.9
Total Operating Expense	**$224.3**	**$52.6**	**$13.0**
Interest	$77.1	$13.9	$2.1
Capital expenditures	$244.7	$62.7	$13.3
Other nonoperating expense	$6.0	$2.2	$0.4
Reporting year debt payments	$156.6	$32.6	$3.4
Total Nonoperating Expense	**$484.4**	**$111.4**	**$19.2**
Total Expenses	**$708.7**	**$164.0**	**$32.2**
Cash Surplus (Deficit)	**$28.2**	**$28.8**	**$6.6**
Numbers of Airports	**29**	**36**	**66**

Source: FAA Form 127 data download March 2009 and GRA Inc. USA.

not from the revenues themselves. With this degree of investment security, general obligation bonds can be sold at a relatively low interest rate, requiring a lower level of expenditure on debt servicing. Since local authorities are constitutionally limited in the total debt that can be secured by general obligation, the use of this type of bond reduces the available debt level. Because of the high demand on local authorities for capital investment, usually for facilities that produce no revenue, most government agencies consider it unwise to use general obligation bonds for such income-generating projects as airports.

Self-Liquidating General Obligation Bonds

Self-liquidating general obligation bonds have been recognized by the courts of some states. These instruments are secured in exactly the same way as ordinary general obligation bonds; however, since it is recognized that the bonds are financing a revenue-producing project, the issue is not considered to contribute to the overall debt limitation set by the state. This type of financing is particularly desirable in that it bears low interest rates without limiting other general obligation debt.

Revenue Bonds

Revenue bonds can be issued where the entire debt service is paid from project revenues. Although subject to the general debt limitation, these bonds bear substantially higher interest rates than general obligation bonds, the interest rate often being dependent on the anticipated level of coverage of revenues to debt service. Before issuing revenue bonds, it is normal practice to prepare a traffic-and-earnings report that includes the forecasting of revenues and expenses during the life of the bond issue. Revenue bonds are sold on the open market, but they suffer from the disadvantage that banks are forbidden to deal in revenue bond issues. Banks, on the other hand, are responsible for a large share of the underwriting of general obligation issues.

Some authorities have negotiated airport–airline agreements to provide a greater degree of security to revenue bond issues in order to assure a lower interest rate. Under these agreements, the airline guarantees to meet all airport obligations with respect to the issue. Usually, however, this sort of agreement requires that capital decisions be made by the airline—a restriction that few airports are prepared to accept.

In the past, almost all airports were financed by general obligation bonds, but the rapidly increasing sophistication of the required facilities has necessitated an increasing trend toward the use of revenue bonds, with an increasing level of commitment by the airlines in guaranteeing the revenues for debt service. As airports have become larger revenue generators and have been seen as capable of generating substantial operating surpluses if commercial development is encouraged, previously unconventional means of financing have become more important. These include:

Nonprofit Corporation Bonds. These bonds are issued by specially created nonprofit corporations and are backed by special-use taxes. The improvements financed in this way usually revert to the airport or municipality on bond retirement.

Industrial Development Authority Bonds. These bonds are issued and underwritten by a separate corporate entity located on the airport on leased land. Bonds of this nature permit nonaeronautical development without the involvement of the airport.

Third-Party Private Finance. This is now more frequently attracted into the airport, which is seen to be a high potential investment site because of the sustained growth of aviation.

For further discussion of this type of finance, reference should be made to Section 5.13 and texts on airport financing (5).

Local Government Taxes

In the early days of aviation, most airports were supported by general local government taxes. As facilities grew, the fiscal requirements rapidly outpaced the local governments' abilities to provide capital from their own annual revenues. As a source of capital, this form of finance is now generally unimportant for all but the smallest facilities.

State Finance

The individual states contribute substantially to the financing of airports. Most states require federal funding to be channeled to local government through state agencies. It is normal in these circumstances for the state to share in the nonfederal contribution of matching finance for federal funds. Where no federal funds are involved, state funds may be matched to local funds. Much of state funding comes from taxes on aviation fuel, which are largely reused for airport development.

Federal Grants

The federal government has provided substantial support for the development of inputs through a series of peacetime programs in the 1930s; the Federal Airport Act of 1946 as amended in 1955, 1959, 1961, 1964, and 1966; and, currently, the Airport and Airways Development Act of 1970, as amended in 1976, as the Airport Development Acceleration Act of 1973, the Airport and Airway Improvement Act of 1982, the Airport and Airways Safety and Expansion Act of 1987, and the Aviation Safety and Capacity Expansion Act of 1990. Federal financing is discussed more extensively in the following section.

1.9 FEDERAL FINANCING

Up to 1933, the financing of airports in the United States was carried out almost entirely by local governments and by private investors. The first significant infusion of federal monies into the development of airports came in 1933, at the height of the Depression. In that year, through the work relief program of the Civil Works Administration, approximately $15.2 million was spent on airports. After a short period of support by the succeeding work relief program of the Federal Emergency Relief Administration in 1934, the Works Progress Administration (WPA) assumed responsibility for the administration of federal aid to airports and spent approximately $320 million between 1935 and 1941. The WPA programs required a degree of matching local support, and it was at this time that the practice of sharing airport development costs among federal, state, and local governments became established.

In 1938, the Civil Aeronautics Administration (CAA) was created to formulate policies to promote the overall development of the aviation industry; this body, with several reorganizations and retitlings later, is now the FAA.

Toward the end of World War II, Congress was aware that postwar civil aviation was likely to achieve a remarkable growth rate. The CAA was authorized by House Resolution 598 (78th Congress) to carry out a survey of airport needs during the postwar period. This survey, and the clear need for federal funds, led to the Federal Airport Act of 1946. This legislation authorized the spending of approximately $500 million in federal aid to airports over seven years. In 1950, the original 7-year period was extended to 12 years, reflecting the realization that federal appropriations were falling significantly below the levels of authorization.

Further major amendments were made in 1955, 1959, 1961, 1964, and 1968. During that period, the authorizations grew from $40 million in 1956 to $75 million for the period 1968–1970. By the late 1960s, however, it was clear that the scale of capital investment required to provide airports and airways to meet the sustained growth in aviation that could be expected in the 1970s and 1980s called for a restructuring of airport financing beyond what could reasonably be achieved by further amendment of the Federal Airport Act.

The Airport and Airways Development Act of 1970 further developed the use of the Airport and Airway Trust Fund (previously established in 1954), with authorizations amounting to $2.5 billion for airports over a period of 10 years and a further $2.5 billion for airways and air traffic control systems. Financing was handled by a series of user taxes. The act substantially increased the amount of federal funds available for airport development. Each year, funds were to be made available for air carrier and reliever airports; one-third of this fund was earmarked for air carrier airports based on the number of enplaning passengers, one-third was for air carrier and general aviation reliever airports on the basis of state population and state area, and one-third was to be disbursed at the discretion of the Secretary of Transportation. Grant agreements were to extend over three years, rather than the one-year basis of funding authorized by the Federal Airport Act.

For a project to be eligible to receive funds under the Airport Development Aid Program (ADAP), the airport had to be publicly owned and in the National Airport System Plan. The 1970 act retained the federal share of eligible project costs at 50%, a holdover from the Federal Airport Act; this federal share was subsequently modified by amendments in 1973 and 1976.

Under the terms of the development act, airport facilities associated with safety and necessary operation were eligible for federal grants. Over the 10-year period of the act, planning funds were also made available to a limit of $15 million for airport system planning on a regional basis and the master planning of individual airports. Federal planning funds were available on a 75% cost-sharing basis, with a limit of $1.5 million to any one state.

The Airport Development Acceleration Act of 1973 made some substantial changes to the operation of the trust fund. Federal funds for airport development were increased, with the federal proportion going from 50 to 75% for airports with passenger enplanements less than 1% of total national passenger enplanements; the federal share of airport certification and security requirements costs was set at 82%. This act also specifically prohibited the collection of state airport "head taxes."

Further significant amendments to the 1970 act were made in 1976 (Public Law 94-353) with respect to the federal share of project costs and the use of funds for non-revenue-producing areas of the passenger terminal. These amendments increased the level of annual authorization for airport development. For airports enplaning less than 1% of national enplaning passengers, the federal share of allowable project costs was increased to 90% in 1976–1978 and 80% in 1979–1980; for the busier airports, the federal share was increased to 75%. This act also permitted the use of federal funds for passenger transfer vehicles on both the air side and the land side.

More changes to airport financing were made by the Airport and Airway Improvement Act of 1982, which replaced ADAP with the Airport Improvement Program (AIP), which was to fund the new National Plan of Integrated Airport Systems (NPIAS). The same act authorized funds for facilities and equipment associated with air traffic control and navigation over the same period and further monies for airspace system operation and maintenance. Fifty percent of the total authorization was designated for primary airports (see Section 1.10), with the apportionment formula remaining the same as that for air carrier airports under the former program, with increases from 10% in 1984 to 30% in 1987. State apportionments amount to 12% of total apportionment. In the contiguous United States, 99% of the states' apportionments is for nonprimary airports. Other fund limitations legislated were that at least 10% of total apportionment was for reliever airports, at least 8% for noise compatibility, and at least 5.5% for commercial service airports that are not primary airports and for public noncommercial service airports that had scheduled service in 1981. At least 1% of total funds was designated for planning, with 13.5% remaining to be used at the discretion of the secretary. The 1982 Act was amended by the Airport Safety and Capacity Expansion Act of 1987 (Public Law 100-223), which increased program authorizations.

The Airport Safety and Capacity Expansion Act of 1990 permitted airports to levy the previously prohibited passenger facility charges (PFC), with some restrictive clauses. These limited the number of charges which could be applied during the course of a trip and reduced improvement program apportionments to medium and large hubs which imposed the charges. The act also established federal shares of project cost at the levels shown in Table 1.5.

Included were the purchase of land for physical facilities and the purchase of long-term easements to protect navigable airspace in the clear zones; construction and reconstruction of runways, taxiways, and aprons; resurfacing of runways, taxiways, and aprons for structural but not maintenance purposes; airfield lighting; buildings associated with safety, such as the airport fire and emergency buildings; and roads, streets, and rapid-transit facilities; airfield signage; airfield drainage; planning studies; environmental studies; safety area improvements; airport layout plans; roads on airport property; and reduction of hazards.

Wendell Ford Aviation Investment Act for the 21st Century of 2000

Also known as the Air 21 Act, this legislation contained provisions for safety and whistleblower protection but importantly sought to unlock the Airport and Airways Trust Fund to allow higher passenger facility fees and exempted the Trust Fund from discretionary spending caps and congressional budget controls. The provisions were

Table 1.5 Federal Share (Percentage of Project Costs)

	Type of airport	
Type of project	Large and medium primary airport	All other
Individual airport planning	75	95
Airport development	75	95
Noise compatibility programs	80	95

designed to help small airports hold on to low-volume services and to aid high-volume facilities to solve their capacity problems. For the period 2000–2004, the act authorized $47.6 billion for FAA operations, facilities, and equipment and a further $19.2 billion for the Airport Improvement Program.

Aviation and Transportation Security Act of 2001

Rushed through Congress in the wake of the terrorist attacks of September 2001, this act dealt mainly with aspects of security. These included the transfer of authority for civil aviation security to the Transportation Security Administration, with the federalization of airport search and screening of passengers and baggage, the expansion of the number of sky marshals, and other measures. Importantly, this legislation provided for the new security program to be paid for by passengers by a $2.50 segment fee, capped at $10.00 per ticket.

Vision 100 Century of Aviation Act

This act extended federal funding to aviation beyond 2003, when the Air 21 Act provisions expired. The period of late 2001 and 2002 had proven difficult for the airlines and airports in the wake of the severe drop in traffic due to the aftereffects of the attacks of September 2001. AIP authorizations were increased from $3.4 billion in 2004 to $3.7 billion in 2007. The act permitted extended use of PFC and AIP funds to make funding easier for airport/airside improvements and existing debt servicing.

FAA Reauthorization Act of 2010

Among its provisions, the act reauthorized appropriations to the FAA for airport planning, development and noise compatibility planning, air navigation facilities and equipment and FAA operations, research, engineering, and development. Furthermore, the act broadened the usage of the passenger facility charges, including their application to intermodal ground access pilot projects. It extended the expenditure authority of the Airport and Airway Trust Fund through fiscal year 2012.

1.10 THE U.S. NATIONAL PLAN OF INTEGRATED AIRPORT SYSTEMS: A CLASSIFICATION OF AIRPORTS (6)

For the purposes of federal administration, airports in the United States are classified within a framework identified by function, industry role, and hub type (in terms of percent of annual passenger boarding), that essentially constitutes the U.S. airport system plan. This plan, officially termed the national plan for integrated airports system (NPIAS), is described in detail in Chapter 4 (see Figure 4.8). In the United States, there are nearly 20,000 airports of which approximately 5200 are open to public use. All airports which are considered to contribute significantly to the national air transportation system and which are open to the public are included in the NPIAS. However, as of 2008, over 1800 public use airports are not included in the NPIAS framework, because they do not meet the criteria for inclusion, are located on inadequate sites, or cannot be expanded and improved to provide a safe and efficient public airport.

Table 1.6 Definitions of U.S. Airport Categories

Airport	Classifications	Hub type percentage of annual passenger boardings	Common name
Commercial service: Publicly owned airports that have at least 2500 passengers boardings each calendar year and receive scheduled passenger service	Primary: Have more than 10,000 passengers boarding each year	Large, 1% or more	Large hub
		Medium, at least 0.25% but less than 1%	Medium hub
		Small, at least 0.05% but less than 0.25%	Small hub
		Nonhub, more than 10,000 but less than 0.05%[a]	Nonhub primary
	Nonprimary	Nonhub, at least 2500 and no more than 10,000	Nonprimary commercial service
Nonprimary (except commercial service)			Reliever
			General aviation
Other than passenger classification			Cargo service

[a] Nonhub airports—locations having less than 0.05% of total U.S. passengers, including any nonprimary commercial airports, are statutorily defined as nonhub airports. For some classification purposes, primary locations are separated within this hub type, although more than 100 nonhub airports are currently classified as nonprimary commercial service airports.

The four main categories of airports in NPIAS—large, medium and small hubs, plus nonhub airports—with their various subcategories, comprising the NPIAS airport classification system are as indicated in Table 1.6.

General aviation airports are further classified according to usage into *basic utility* airports and *general utility* airports.

A basic utility (BU) general aviation airport accommodates most single-engine and many of the smaller twin-engine aircraft—about 95% of the general aviation fleet.

Basic Utility Stage I. This type of facility accommodates approximately 75% of single-engine and small twin-engine airplanes under 12,500 pounds. It is primarily intended for low-activity locations that serve personal and business flights.

Basic Utility Stage II. This type of airport accommodates the same fleet of aircraft suited to Basic Utility Stage I airports plus a broader array of small business and air-taxi type twin-engine airplanes. It is primarily intended to serve medium-sized communities, with a diversity of usage and a potential for increased aviation activities.

Basic utility airports are designed to serve airplanes with wingspans of less than 49 ft. Precision approach operations are not anticipated for either of the Basic Utility airport classes.

A general utility (GU) airport accommodates virtually all general aviation aircraft with maximum takeoff weights of 12,500 pounds or less.

General Utility Stage I. General utility airports are primarily intended to serve the fringe of metropolitan areas or large, remote communities. General Utility Stage I airports are designed to accommodate all aircraft of less than 12,500 pounds. These airports are usually designed for aircraft with wingspans of less than 49 ft and are not intended to accommodate precision approach operations.

General Utility Stage II. This class of airports accommodates airplanes with approach speeds up to 120 knots. These airports are designed to serve airplanes with wingspans of up to 79 ft. They usually have the capabilities for precision approach operations.

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2

Forecasting Air Transport Demand

2.1 INTRODUCTION

Projecting air travel for an airport, city, or region is a critical and fundamental step in the airport planning process. Yet it is more of an art than science, or perhaps an inexact science. This important step of the planning process could be subjective and varies with the views a forecaster may hold, individual experience, methodology adopted, and the forecaster's background.

Forecasting is essentially attempting to replicate a future situation based on historical data, developing patterns and scenarios of future demand for air travel. In essence, it considers industry and market forces of today and yesterday to build a case for the future. History of the market, society, and air transport industry would provide the basic ingredients of the forecasting process. The expert forecaster could arrive at certain conclusions on market and industry relationships that would determine the size, pattern, and characteristics of air travel demand at an airport or region.

Internationally, the International Civil Aviation Organization (ICAO) has been compiling statistics on air travel since the start of commercial air travel (1). Figures 2.1 and 2.2 depict the pattern of world international air travel since the inception of commercial air travel between the great wars. They represent three basic descriptors of demand since air travel data started to be globally recorded:

- Passengers
- Aircraft movements
- Passenger-distance traveled, or more precisely "revenue" passengers traveled, in terms of revenue passenger-kilometers

It is important to note that the world airline charts in Figures 2.1 and 2.2 present several levels of aggregation: regions of the world, countries in regions, parts of countries, and airports. They also represent different sectors of the air transport industry: scheduled and charter airlines, domestic and international sectors, and even general aviation (GA) and air taxi.

The forecast of demand at a given airport would go deeper than passengers or aircraft or air cargo in any given year. To really be useful for planning and development purposes, the annual forecast must only be the first step from which a whole array of forecasts are derived. To design facilities, forecasts of hourly passenger flows are required. To operate different facilities of the airport, weekly and daily patterns are

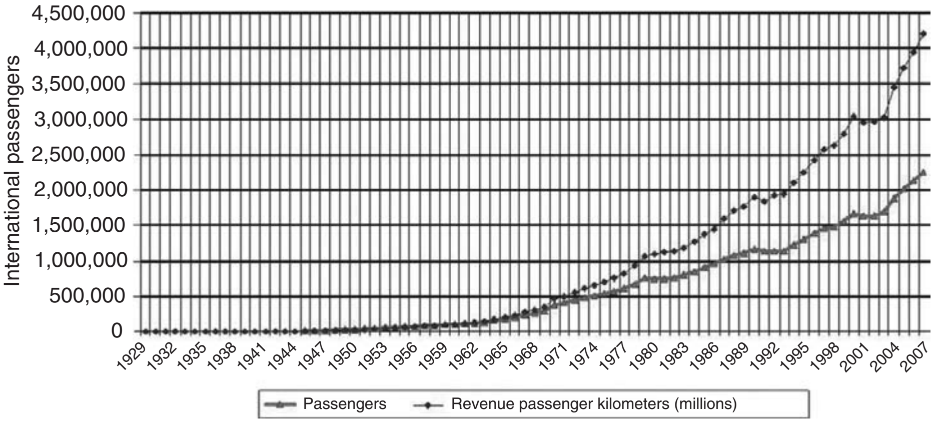

Figure 2.1 World's passengers (1).

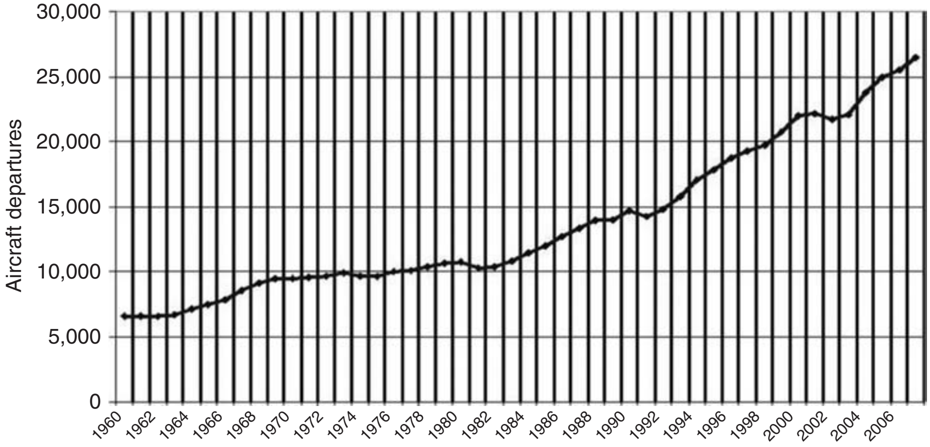

Figure 2.2 Aircraft departures (1).

also needed. Moreover, while the forecasts of aircraft on the airside and passengers on the landside are the basis for their respective facilities design, some estimate of ground vehicles on the airport access is important to design the airport access and parking infrastructure. All these separate facilities ultimately would rely on the basic air transport demand forecasts.

The quality and accuracy of a forecast are reflective of the tools, data, and methodology adopted in the forecasting process. The logic of assumptions, analytical models used, and accuracy and validity of data all contribute to the quality and accuracy of the forecasts.

Rationale for Air Travel Forecast

People normally travel to fulfill business obligations, for leisure, for other personal reasons, or for some combination thereof. Air travel is not significantly different from other modes of intercity travel, but it is inherently unique in many other ways. One principal difference between air and ground inter-city travel modes relates to the traveler's perception of time involved in travel and restrictions on the traveler's desire to select a route, a carrier, a transport mode to reach final destination, in addition to safety, cost, convenience, and accessibility to the traveler (2).

As the world air travel industry has matured after undergoing phases of growth, regulation, deregulation, consolidation, globalization, and liberalization, the industry has matured and stabilized in terms of basic structure, operating characteristics, underlying economic forces driving the market, and interrelationships with the socioeconomic environment within which it exists and functions. Air travel industry has long become the backbone and vital link of interstate culture and commerce regionally, nationally, and internationally. Air travel demand relates primarily to certain basic economic, demographic, behavioral, and market factors that simply provide people and business with the means to travel and connect. It is simply the outcome of supply of people with motivation to travel, who have resources of time and money, utilizing a transport infrastructure that fulfills their requirements to travel at the time, location, and cost they desire. During each phase of the industry, the rationale and methodology to forecast demand for air travel would be unique and distinct.

Factors Contributing to Air Transport Demand

Demand for air travel is invariably affected by a variety of causal variables. These variables should be unambiguous and measurable and the available data should reasonably conform to mathematical formulation and statistical analysis (3). These causal variables are intrinsic to models that provide future estimates of demand. They reflect the different sectors of air transport demand represented in the respective demand models. Causal variables typically used for demand forecasts, their influence on demand, and corresponding model type are indicated in Table 2.1.

Air passenger demand is correlated to a region's population and the motivation of individuals to travel (i.e., their propensity to travel) as well as socioeconomic activities and measures that support travel and the availability of related services and infrastructure. The underlying assumption in all forecasts is the strong correlation between demand and trip-generating factors that are derived from historical data, and this correlation is applicable for the forecasting horizon. Expected future demand environments expressed as forecasts of such factors as airfare levels, airline service, gross national product, and so on, are all inputs to the forecasting process. An underlying assumption in all forecasts is that forecast models hold in the future as long as assumptions related to all factors hold in the future as they do at past and present. Typically, econometric forecast models are developed based on time-series historic database or industry cross-sectional data. Availability and accuracy of the data used are critical to this process both for airlines and for airports.

In conducting forecasts of airport demand, the following factors are considered (2):

1. Availability of capacity; airports and airspace
2. General economic situation; locally, nationally, and internationally
3. Socioeconomic and demographic variables of the airport region
4. Economic factors directly related to airlines operating at the airport

Table 2.1 Demand Variables and Application (3)

Type of influence	Variable	Application
Size and spending ability of market	Population or number of households	Passenger forecasts
	Gross domestic or national product for a country or region	All types of forecasts
	Personal disposable income	Nonbusiness passenger
	Exports	Outbound international freight
	Imports	Inbound international freight
Ethnic (or linguistic) ties between areas	Proportion of population of one area born in other area	Passenger forecasts for route or group of routes
Price of air service	Published tariffs	Route forecasts
	Revenue yield	All types of forecasts
Quality of air service	Departure frequency	Scheduled forecasts
	Number of stops or connections on a route	Scheduled route forecasts
	Travel time	Route forecasts
Access to air transport services	Number of destinations served	Regional forecasts
	Proportion of market within a certain distance or travel time from airport	Airport or route forecasts
Price and quality of competing service	Tariff of a competing air service	Route forecasts
	Departure frequency on competing air service	Route forecasts
	Fare on competing surface transport service	Route forecasts
	Travel time on competing surface transport	Route forecasts

5. Competition between airlines serving the airport as well as competition between the air and other modes of transport
6. Environmental and political constraints on the air transport system and airline industry
7. Technological advancement in aeronautics, telecommunication, air navigation, and other related fields
8. Overall safety, security, and convenience of air travel

The forecaster must pay good attention to the manner in which airport forecasts are presented. Sound presentation of forecast is vital to acceptance of the forecasts and success of the project. Deriving the forecast model, including performing the required statistical tests, may not be enough for acceptance.

The airport planner must also cover the following aspects (3):

- Statement of purpose for the airport project and the forecast
- Relation of the forecast being presented to the entire airport forecasting process, and not just an isolated step
- Description of the air travel environment and the unique airport situation
- Forecast methodology, including approach, use of assumptions, model mechanics, and reasons to adopt the particular approach

- Assumptions related to factors affecting demand and justifications for the assumptions
- Historical records and databases for the causal variables making the model, quality of these data, and data sources and definitions
- Discussion of the accuracy of the forecast indicating the range of uncertainty and model boundaries

From a quantitative perspective, the demand forecast is not a final objective on its own, but only a part of a larger goal and greater purpose (4). The forecast primary use is to guide the airport planner to develop a strategy for tackling several important interrelated tasks. These tasks include developing new or expanded facilities, determination of financial feasibility, mitigation of environmental impacts, and conducting a complete master plan for the airport development.

Typically, demand forecast is central to the formal airport master plan, which constitutes demand/capacity analysis, sizing facility requirements, airport development conceptual plans, and economic-financial feasibility.

In general, demand forecasting is the backbone to the plan of future development of the airport.

2.2 COMPONENTS OF AIR TRANSPORT DEMAND

The above factors—with respect to geographic scale; local, national, and international; sector of industry; and different components of air transport—will all act to varying degrees of impact and contribute to estimating the air transport demand at airports.

On the *local and regional levels*, the socioeconomic/demographic variables and the shifts and directions the economy takes would play the major role in defining the number of passengers within the region or airport.

On the *national level*, the state of the national economy and the state of the airline industry are the major factors that would dictate aviation demand. Other factors include geographic and demographic distribution of demand, technological advancement in the industry, and perhaps politically sensitive environmental issues.

Internationally, bilateral agreements, state of global and regional economies, political considerations vis-à-vis hostilities, regional turmoil and internal security, airline globalization, cultural and social ties between nations, and advances in aeronautics, telecommunication, navigation, and surveillance technologies all may contribute to the size and kind of international air travel.

In terms of components of air travel, the airports and airlines distinguish between the originating (origin–destination, or OD) passengers and the connecting passengers. The split of passenger demand between these two basic components of demand may impact how the airlines operate, but most importantly how the individual airport facilities are used.

OD passenger demand is the passenger trips originating or terminating at an airport. It represents the passenger demand directly associated with the airport/region local socioeconomic and "propensity to travel" characteristics.

Since deregulation of the airline industry in the late 1970s, airlines have resorted to "hubbing" as a strategy to gain market share and operate more profitably. *Connecting passenger demand* refers to passengers on flights to/from the passengers' origins and destinations who have to go through a third airport depending on the airline flown—the airline hub. Establishing a clear understanding of airline hub planning considerations and quantifying the connecting element of passenger demand have always been problematic and difficult to project. For one thing, establishing hubs has always been a closely guarded decision by airlines. It is a decision predominantly based on the airline's business model and marketing strategy. But in broad terms, the conditions that favor an airport to be established as a hub by an airline may include geography and orientation of the hubbing market, airport infrastructure capacity, strong OD base vis-à-vis extent of hubbing, aircraft fleet of the airline, competition with other airline and hubs in close proximity, the airline adding opportunities to improve its profitability and market dominance, and potential for establishing an international hub.

An important aspect of airline hubbing is the issue of partnering of commercial air carriers and regional/commuter airlines with well-integrated route networking to ensure good penetration to communities and effective market coverage. In the past a variety of strategies were used by airlines to gain more route structure integration to gain market control and enter new markets. Strategies such as code sharing, computer reservation systems, and acquisition of regional airlines helped provide better connections and service frequencies to passengers and higher load factors and hence yields to the airlines.

While not air travel related, airport demand forecast may be influenced by intermodal interactions with other transport modes that may be competitive with or supplementary to air travel. Therefore, in conducting air travel demand forecast for a particular airport, this aspect has to be carefully considered. Implementation of competing (or supplementing) ground transport modes will largely depend on such considerations as the geographic region's ground transport network, technological advancement in ground modes, financial and economic feasibility of all travel modes, future availability of options and their costs of energy, convenience and acceptability by the traveling public, and the environmental and social impacts of the modes.

2.3 CONVENTIONAL AIRPORT FORECAST METHODS

The conventional forecast methods outside the comprehensive frameworks described above are discussed below. While these simple methods have been applied with reasonable success on all levels, they are not as comprehensive or sophisticated, and their overall long-term expected accuracy is much less. It is also important to note that the possibility of using any of them may be limited by lack of data, resources, or time. Invariably, a more reliable forecast may include more than one approach and consolidating results into a unified forecast (3).

Expert Judgment

Total lack of data on the airport and airline industry would prevent making any reasonable estimate of future demand. Under certain conditions, a crude but effective method of forecasting is the judgment estimate by an expert close to the problem and environment who would be able to integrate and balance the factors involved in the specific situation. However, the chances of success diminish as the complexity of the particular situation increases, number of factors increase, and the need for long-term forecasts becomes necessary.

Survey of Expectation

This method is one step above the previous one—essentially providing an aggregate judgment of several experts in the airport and air transport industries who are in a position to cast their expert opinions and judgment to estimate future trends. By assembling an expert panel with broad range of interests and specialties, the forecaster would hope for a balanced view and a reasonable estimate.

A refined and improved version of this approach is the *Delphi technique*. It is essentially the informed consolidation of the responses of all the experts through an iterative procedure. The experts cast their opinion regarding the forecasts. This is administered with a questionnaire in which they are requested to indicate a most probable course of development in the activity being forecast (4). The initial returns and feedback on the opinions of the entire panel are consolidated in the first iteration of the procedure as a composite return by the entire panel. This composite figure is returned to the panel in the second iteration questionnaire, giving them the opportunity to revise their original assessment in light of the prevailing opinions among the entire panel. In this procedure, the range of expert responses after each iteration tends to narrow and consensus is ultimately reached. This technique is a practical means of bringing experts from a wide range of specialties and based on the information each provides moves toward consensus with aggregate composite values. In general, however, this method is more appropriate and suitable to aggregate forecasts at the national level than to disaggregate forecasts at the airport or regional levels.

Indeed, a version of this method is used in the United States to provide industry consensus on short-term industry trends to feed into the FAA National Forecast System (described elsewhere in this chapter). The biennial FAA Transportation Research Board (TRB) Forecast Workshop series was initiated in 1979, first including only U.S. participants, then branching out to international participants. Participants are experts drawn from government, industry, academic, and private consulting firms representing different sectors of the travel industry in the United States and the developed world. These experts are invited to an expert workshop hosted by the TRB (5) to discuss the state of the economy and factors impacting the air transport industry in the short term.

In an interactive workshop environment the experts discuss the issues at hand and cast their opinions on the future prospects for the different sectors of air travel, market directions and possible development in the economy, global energy cost, business environment, fare structures, competitive conditions, operations, and technology. Specific topics typically include domestic and international macroeconomic outlook, structure and operating patterns of major and regional U.S. air carriers, expected developments in international aviation and aircraft and engine manufacturers, impacts of the price of oil and jet fuel on the industry, trends in business aviation, and trends and patterns of air cargo operations. Consensus is reached on the level of economic growth, air traffic growth rates in the different sectors of the market, as well as geographic regions. The conclusions on economic growth, airfares, potential impact of fuel price, and other factors would be input in the FAA forecast system.

Ratios of National Forecasts

This technique is widely used in the United States, which benefits from the vast amount of demand forecast data generated by the FAA national demand forecast system. It is a simplistic approach typically used at the local level. It basically assumes that, for a city or region in the United States, the percentage of the annual national passenger volumes remains relatively stable over time in the short and medium terms. Airport passenger forecasts are obtained by a step-down percentage of the national forecasts.

The major drawbacks of this technique include:

1. The percentage of national figures does not necessarily remain stable; rapidly growing areas attract more demand than mostly slow-growing areas where the primary-sector economic base is static and growth is insignificant. Conversely, excessively large error will occur at an airport that starts operating as an airline hub.
2. Airport market areas in certain parts of the world may overlap within their regions. A certain level of competition comes into the picture that requires careful consideration and may render this technique less useful.
3. As discussed later, certain errors are typical in the national demand forecasts, primarily due to large variations with certain variables of the FAA national forecasting system such as load factor and average aircraft size.

Obviously, this method could not be used outside the United States without major assumptions made. The air transport industry in different parts of the world is structurally different than in the United States. Certain elements of the air transport industry have a different business model and are more influenced by fares.

In the United States, this method constitutes an essential part of the regional-level component of the Comprehensive Airport Demand Forecast Framework described elsewhere in this chapter. There are three variations for this technique:

Method A

1. Determine the percentage of national enplaned passengers that the airport has attracted in the past.
2. Adjust this percentage to reflect anticipated abnormal growth trends.
3. Obtain data for national passenger traffic for the design year.
4. Calculate step-down design figures as the product of the percentage of step 2 and the national figure from step 3.

Method B

1. Obtain the number of passengers per 1000 population that the airport has experienced in the past.
2. Compare the figure computed in step 1 with the number of passengers nationally per 1000 population
3. Compute the ratio of local to national rates, that is,

$$\frac{\text{Passengers/1000 population for airport}}{\text{Passengers/1000 population for nation}}$$

4. Obtain the national forecast of air passenger traffic per 1000 population for the design year
5. From steps 3 and 4 calculate the local passenger traffic per 1000 population.

Method C A slightly more detailed variation of this technique includes the airport, the state, and the nation:

$$E_i = M_{i/j} \; . \; M_{i/s} \; . \; M_{s/\mathrm{US}} \; . \; M_{\mathrm{US}} \; . \; E_{\mathrm{US}} \tag{2.1}$$

where

E_i = domestic passenger enplanement
$M_{i/j}$ = domestic passenger enplanement in location i
$M_{i/s}$ = percent market share for airport i of total scheduled domestic total passenger enplanement in rejoin j
$M_{s/\mathrm{US}}$ = percent market share for region j of total state market s
M_{US} = percent market share of state s of total U.S. market
E_{US} = total scheduled domestic passenger enplanement in the United States

A synthesis of airport forecasting practices (6) identified four major categories of forecasting methods:

- Trend projection, where a time series is used to establish a demand trend and extrapolate it into the future
- Market share analysis—based on market research and industry surveys, the local airport activity is calculated as a share of some larger aggregate forecast (e.g., local to national and local to regional)
- Econometric modeling, where aviation activities are tied to other economic measures
- Simulation—a technique that is separate and independent from demand forecasting used to provide high-fidelity operational snapshot estimates of traffic flows across a network through the airport

These techniques are described below.

Trend Projection

Trend projection of demand relies on the quality of the historical data (time series) and the stability of growth over time. In the short term this technique is reasonably reliable, especially when extrapolation takes into account adjusting growth rates to compensate for short-term disturbances and fluctuations in traffic levels. In deriving medium- to long-term forecasts by extrapolating current traffic trends, the primary assumption here is that underlying factors which determined the historical development of demand will continue to hold and operate in the future as in the past. Therefore, this method of forecasting is only appropriate when there is strong stability in the past trend of demand development and the level of confidence in this major assumption is high (2).

The simplest procedure for identifying the particular trend curve in a time series of historical data is to actually plot it. As each point in the time series is plotted (traffic as the y and time as the x of each point), a smooth curve of the trend appears. A trend may be stable in terms of demand values or in terms of percentage of demand. For the former growth would be linear, and for the latter growth would be exponential. In other words, the trend of the historical demand may be linear or exponential in formulation; it also could be a number of mathematical formulations, or curves. After the time-series trend is identified, the forecast demand would simply be extrapolating the fitted trend into the future.

The different types of trend curves can be better represented by their mathematical formulation on the computer. Figure 2.3 depicts the typical trend curves in linear and exponential formats. The respective mathematical formulation for each is stated below where Y is traffic, T is time (years), and a, b, c are coefficients that define the specific curve:

Linear: $Y = a + bT$

Exponential: $Y = a(1 + b)^T$

Parabolic: $Y = a + bT + cT^2$

Gompertz: $Y = [(ab)^{-c}]^T$

But which of the above formulations would represent the "best fit" for the historical data that would later be used to project into future?

Market Share Analysis

This method uses market analysis and industry surveys to conduct empirical analysis of the air transport market and examine how air transport traffic varies between the different sectors of the market sectors, the public, and the airline industry (3). This technique may be used in two distinctly different markets: in the developing world and in large metropolitan areas in the United States. For the former the majority of consumers of air transport services belong to a limited number of well-defined sectors of society. The latter refers to well-developed, complex, and mature markets. Domestic air travel forecasts in major U.S. metropolitan areas have been generated using this method.

Based on the national travel market surveys conducted in major U.S. cities by market research companies, data are compiled on the air travel propensities of various socioeconomic groups. The population data (on national, regional, or local levels) are divided into a number of data cells that characterize a specific socioeconomic profile of the population by occupation, income, and education, among other factors. Each cell is identified by a specified trip rate per head of population associated with the particular profile. Relationships are then established, through sophisticated statistical and mathematical techniques, between trip rates for each cell and trends associated with trip frequencies of all the travelers. Forecasts of air travel are then derived by applying these "cell rates" to the corresponding forecast population from demographic databases (e.g., census). This approach is used typically to analyze the business air travel markets and air travel of population throughout wide metropolitan areas and for forecast of air freight based on type of trade, commodity and its value per unit weight, and shipping mode.

In this technique, rates per group calculated in a given year may be used in future years directly or after adjusting the rate for changes with time of the behavioral aspects and trends of air travel.

Econometric Models

Econometric demand forecasting incorporates various causal economic, social, and operational variables in determining, on the basis of historical data, a quantitative

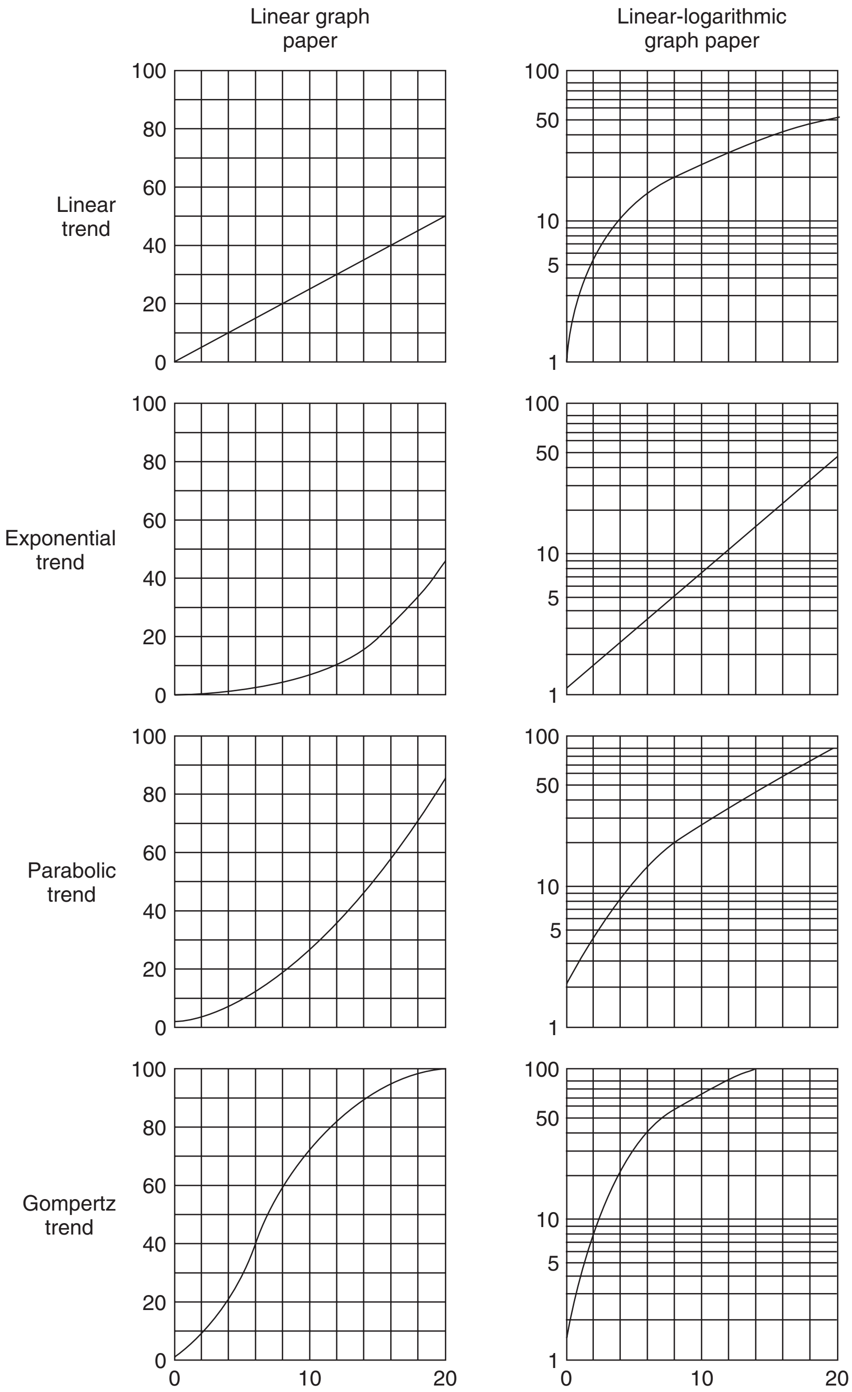

Figure 2.3 Typical trend curves (3).

relationship between air travel and the variables influencing the level of traffic. These models have been widely used over the years to predict urban passenger demand. When applied to air transport, an econometric model is established (and statistically tested to validate the model) between rate of passenger air trips and a number of predictive causal variables. Model development is usually carried out by evaluating air trip generation rates from survey data and records against socioeconomic data of the area and the physical characteristics of the overall OD air–ground transport system. The evaluation uses a variety of multivariate statistical techniques such as correlation analysis, factor analysis, and linear and nonlinear regression analysis to define suitable predictive variables selected as the independent variables of the model.

Future demand levels are developed based on the assumption that the relationship developed through econometric analysis is applicable in the future and valid in the future as it was in the past. However, it is possible to adjust the econometric models if the causal variables change in the intervening years after the models are developed. The causal variables of econometric models are monitored and any changes observed could be verified and necessary adjustments are made on the model parameters. This would ensure the continuing adequacy and verification of continuing applicability of the econometric model.

An econometric forecast of air travel typically involves several steps that include:

- Selecting the relevant and appropriate causal factors to be taken into account in the model
- Collecting data and verifying its accuracy
- Specifying the postulation of the functional relationship existing between air traffic demand and the relevant causal variables
- Conducting statistical analysis and testing of the proposed model and if statistical tests are successful
- Observing the future development of the variables to ensure future applicability before applying the model to forecast future air traffic

Econometric models are constructed to describe the relationship, which uses regression analysis techniques extensively (7). The typical multiple-linear regression model has the form

$$T = a_0 + a_1 x_1 + a_2 x_2 + \cdots + a_n x_n \tag{2.2}$$

where

T = number of air trips
$x_1, \ldots, x_n$ = independent predictive variables
$a_1, \ldots, a_n$ = regression coefficients

In developing the econometric models it is important to ensure that not only does a statistical correlation exist for the relationship, but also there is a logical or implied causal relationship between the predicted and predictive variables. Moreover, it is also an important statistical requirement that predictive variables are independent of each other.

Independent predictive variables commonly used to predict air trips to an airport include population, income, type of employment, and accessibility of the catchment's population to the airport. For national aggregate levels of demand, gross domestic product would be the better variable to use.

A typical regression-based econometric model to predict total air passengers at airports includes:

1. A regional airport in Virginia (8):

$$\ln E_i / P_i = 10.8 - 0.172F + 1.41 \ln Y_i \tag{2.3}$$

where

E_i = predicted passenger enplanements
P_i = population of catchment area
F = U.S. average airfare per mile
Y_i = per-capita income of catchment area

2. International and domestic passenger forecasts in Boston (9):

International passengers:

$$\text{BOSNYPC} = -33.31 + 431.3 \log(\text{RINCPC}) - 239.9 \log(\text{RARDT}) \tag{2.4}$$

Domestic passengers:

$$\log(\text{PDCEP}) = 0.5597 + 1.4757 \log(\text{RINCPC}) - 0.700 \log(\text{RARDT}) \tag{2.5}$$

where

BOSNYPC = Boston-based international air passengers per capita
RINCPC = Boston regional income per capita, in real terms
RAARIT = real average yield per international passenger-mile
PDCEP = Boston-based domestic passengers per capita
RARDT = real average yield per domestic passenger-mile

2.4 INTEGRATED DEMAND FORECAST FRAMEWORK

In order to have accurate forecasts for the airport in the future (whether existing or new airport) a comprehensive forecast framework that integrates three distinct levels of forecasting is warranted. This comprehensive framework integrates the following forecasting approaches:

- Top-down approach that essentially relates the airports with the larger airport system of the region, country, and region.
- Bottom-up approach that considers individual trip-making rates and personal decisions describing the propensity of the people the airport will be serving
- Economic, air travel market, and air transport industry principles that would determine certain demand forecast parameters of the airport in the future
- Ground transport variables (primarily trip travel time and modal convenience) that will influence the passenger's selection of ground transport mode and, in multiairport regions, even the selection of preferred airport

The top-down approach considers the incidence of demand, not the causation. It is based mostly on experience gained in the past with certain demand relationships assuming a rationale that the future will not be that different from the past. On the other hand, the bottom-up approach essentially establishes relationships correlating demand directly to the underlying variables that cause occurrence of demand. Valid in the past and in the future, these relationships (or models) address the "real" factors that will contribute most to the incidence of demand.

Such an airport demand forecast framework covering the above principles would be robust, reasonably accurate, and well balanced in predicting future airport demand levels. This framework was adopted in a major airport development study (10) and was thoroughly critiqued and verified. This forecasting framework outlines three demand levels: national, regional, and the airport.

The methodology the study used adopts the three levels described with the hybrid top-down/bottom-up approaches—the national level for the former and the regional level for the latter. The three demand levels of the methodology—national, regional and airport—are described below.

National Demand Level

In the United States, national demand forecast relies entirely on the FAA Aviation Demand Forecast system conducted and published annually (11). The FAA's Office of Aviation Policy and Planning routinely provides invaluable resources to undertake aviation demand forecasts in the United States on an annual basis and is responsible to administer this system supported by huge databases compiled through the implementation of the U.S. air transport regulation.

FAA U.S. National Forecasting System. This important national resource—a unique system developed by the United States for developing the national air transport demand forecasting—is not commonly available worldwide. It is integrated, interactive, continuous, and annually updated (12). It provides comprehensive long-range forecasts of the entire national air transport system at various levels of disaggregation (13). Its composition combines economic and time-series models with aviation industry forecasts, taking into consideration effects of airline industry trends (e.g., deregulation, consolidation, liberalization, globalization), and interactively adjusts model results for industry input and forecasters' expertise (14). The FAA forecast results are analyzed and adjusted periodically based on most recent developments in aviation and air travel trends, including factors expected to experience market and industry changes and growth rate variations.

In parallel and for different purpose, the FAA also conducts 'terminal area forecasts" for major U.S. airport hubs, the FAA jargon for major commercial airports colocated in a single metropolitan area. These forecasts could not be considered for comprehensive airport development planning, as their focus is primarily to estimate aircraft operation projections for terminal area air traffic control activities.

The structure of the entire methodology is a sequence of regression step-down models developed on the national level. The variables these models use are major factors that essentially define the aviation demand forecasts of the United States in any given year. They are in sequence of the methodology: yield, revenue passenger miles per kilometers, passenger enplanements, aircraft operations, and average aircraft fleet composition.

Data required for this system include:

1. Historic time series of airline operating statistics (mainly, passenger enplanements, aircraft operations, aircraft size, and load factor) from the U.S. DOT database of airline reporting system (15), which compiles and manages U.S. air carriers filing as per various parts of U.S. Code of Federal Regulation (CFR 14) (16). Elements of this system used in the FAA forecast process include various schedules of Form 41 for certified air carriers, part 298-C for regional-commuter airlines, and the T-100 system for large certified air carriers and foreign air carriers. Samples of the data generated by this system for different sectors on a monthly, quarterly, and annual basis are shown in Tables 2.2, 2.3, and 2.4.
2. National economic variables, mainly gross national product (GNP), and their forecasts, as published by the U.S. Office of Management and Budget (OMB) and leading economic forecasting consultants.

Table 2.2 Scheduled System (Domestic and International) U.S Airlines (18)

	Monthly			Year to date		
	May 2008	May 2009	Change, %	2008	2009	Change, %
Passengers (in millions)	65.9	59.7	−9.3	311.4	281.9	−9.5
Flights (in thousands)	889.5	812.7	−8.6	4,330.8	3,927.0	−9.3
Revenue passenger miles (in billions)	71.7	65.0	−9.4	337.1	304.6	−9.6
Available seat-miles (in billions)	88.6	81.6	−7.9	430.0	394.1	−8.3
Load factor[a]	80.9	79.7	−1.2	78.4	77.3	−1.1
Flight stage length[b]	718.7	716.0	−0.4	719.8	718.5	−0.2
Passenger trip length[c]	1,088.4	1,088.3	0.0	1,082.5	1,080.7	−0.2

[a]Change in load factor points.
[b]The average nonstop distance flown per departure in miles.
[c]The average distance flown per passenger in miles.
Note: Percent changes based on numbers prior to rounding.
Source: Bureau of Transportation Statistics, T-100 Market and Segment.

Table 2.3 Domestic Scheduled Airline Travel on U.S. Airlines (18)

	Monthly			Previous calendar years		
	May 2008	May 2009	Change, %	2008	2009	Change, %
Passengers (in millions)	57.9	52.9	−8.6	273.0	247.2	−9.4
Flights (in thousands)	816.0	747.0	−8.5	3,967.3	3,589.1	−9.5
Revenue passenger miles (in billions)	50.2	46.0	−8.4	238.0	214.8	−9.7
Available seat-miles (in billions)	61.7	56.5	−8.4	302.8	273.0	−9.8
Load factor[a]	81.4	81.4	0.0	78.6	78.7	0.1
Flight stage length[b]	622.4	616.1	−1.0	627.1	619.3	−1.3
Passenger trip length[c]	866.6	868.5	0.2	871.9	869.2	−0.3

[a]Change in load factor points.
[b]The average nonstop distance flown per departure in miles.
[c]The average distance flown per passenger in miles.
Note: Percent changes based on numbers prior to rounding.
Source: Bureau of Transportation Statistics, T-100 Domestic Market and Segment.

Table 2.4 International Scheduled Airline Travel on U.S. Airlines (18)

	Monthly			Previous calendar years		
	May 2008	May 2009	Change, %	2007	2008	Change, %
Passengers (in millions)	8.0	6.8	−14.8	38.5	34.7	−9.8
Flights (in thousands)	73.5	65.7	−10.5	363.6	337.9	−7.1
Revenue passenger miles (in billions)	21.5	19.0	−11.6	99.1	89.8	−9.4
Available seat-miles (in billions)	26.9	25.1	−6.8	127.2	121.1	−4.8
Load factor[a]	79.9	75.7	−4.2	77.9	74.1	−3.8
Flight stage length[b]	1,788.4	1,851.9	3.6	1,731.6	1,772.3	2.4
Passenger trip length[c]	2,699.4	2,800.5	3.7	2,577.0	2,588.4	0.4

[a]Change in load factor points.
[b]The average nonstop distance flown per departure in miles.
[c]The average distance flown per passenger in miles.
Note: Percent changes based on numbers prior to rounding.
Source: Bureau of Transportation Statistics, T-100 International Market and Segment.

3. Fuel price predictions based on U.S. Department of Energy and other international energy sources.
4. Airline industry operational data, including operating costs and fleet expansion plans.

The steps of the U.S. national air carrier forecasting process defining those factors are:

1. *Yield*. Expressed as revenue per passenger mile per kilometer; the independent variables of its regression model are airline aircraft utilization, airline operating and labor costs, and aircraft fuel cost. The regression model formulation is

$$Y = a_0 + \mathrm{JF}a_1 + Wa_2 + \mathrm{ATM}a_3 \tag{2.6}$$

where

JF = jet fuel price
W = airline industry wages
ATM = air transport movement per aircraft

2. *Revenue Passenger Miles*. It is the basic expression for air transport demand, and "real yield" and GNP are the independent variable. For GNP, the FAA uses the OMB economic forecasts and the consensus growth rates of economic forecasts prepared by private economic forecasting consultants. The formulation of the regression model for domestic certified air carriers, regional-commuter airlines, and U.S. air carriers on international flights, forecast separately, is

$$\mathrm{RPM} = b_0 + \mathrm{GNP}b_1 + Yb_2 \tag{2.7}$$

where

GNP = real gross national product
Y = real yield

3. *Airline Operations Variables*. The FAA uses the data of the DOT- Bureau of Transportation Statistics (BTS) and previously Research and Special Programs Administration (RSPA), augmented with subjective trend analysis and industry feedback to generate forecasts on the following based on historic trends, and market and technology changes:
   (a) Average system load factor
   (b) Average system aircraft size (seat per aircraft)
   (c) Average system passenger trip length
4. *Passenger Enplanements*. Domestic passenger enplanements are forecast separate from international. The average passenger trip length is estimated based on the BTS/RSPA airline filing database, for domestic and regional-commuters, separately. The U.S. domestic passenger enplanements for certified domestic air carriers and regional commuters are then calculated as

$$\text{Passenger enplanements} = \frac{\text{RPM}}{\text{average trip length}} \tag{2.8}$$

5. *Aircraft Operations*. Aircraft movements are forecast by dividing the passenger enplanements by the average load factor and average aircraft size; both are output of the BTS/RSPA airline filing.
6. *Aircraft Future Fleets*. Airline future fleet expansion plans are verified against the long-range forecasts conducted by major aircraft manufacturers, primarily Boeing and Airbus (17). These “industry outlook” forecasts provide not only projections of new aircraft entering the industry on the long term but also high-level aggregate passenger and aircraft movement forecasts globally.

Figure 2.4 depicts the FAA forecasting system relationships graphically.

FAA Forecast System Accuracy. The FAA reports about the accuracy of its own U.S. aviation demand forecasts and the degree of forecast variance (19): “Forecasts, by their nature, have a degree of uncertainty incorporated in them. They involve not only statistical analyses and various scientific methods, but also judgment, and reliance on industry knowledge and the forecaster’s experience to incorporate industry trends not yet reflected in recent results.” The U.S. Aerospace Demand Forecast, published by the FAA annually and used by various entities in the United States to generate their individual forecasts, is no exception. Given the dynamic nature of the air transport markets and the volatile nature of the U.S. airline industry, it would be inevitable that forecasts would exhibit forecast statistical variance from one year to the other.

Therefore, FAA forecasters have tried to build forecast models that give a consistent and predictable pattern of results. Analysts relying on the forecasts produced by the models would then be able to adjust for the predictable variance from actual results.

Since the FAA forecast system constitutes the first step of the study forecast methodology, it becomes crucial to verify that accuracy of the FAA forecasts is reasonable and within the standard margin of error. The entire forecasts would then rely on the level of accuracy of the FAA forecast. Several important airport forecasting studies in the United States had to rely on the assumption that the FAA forecast system

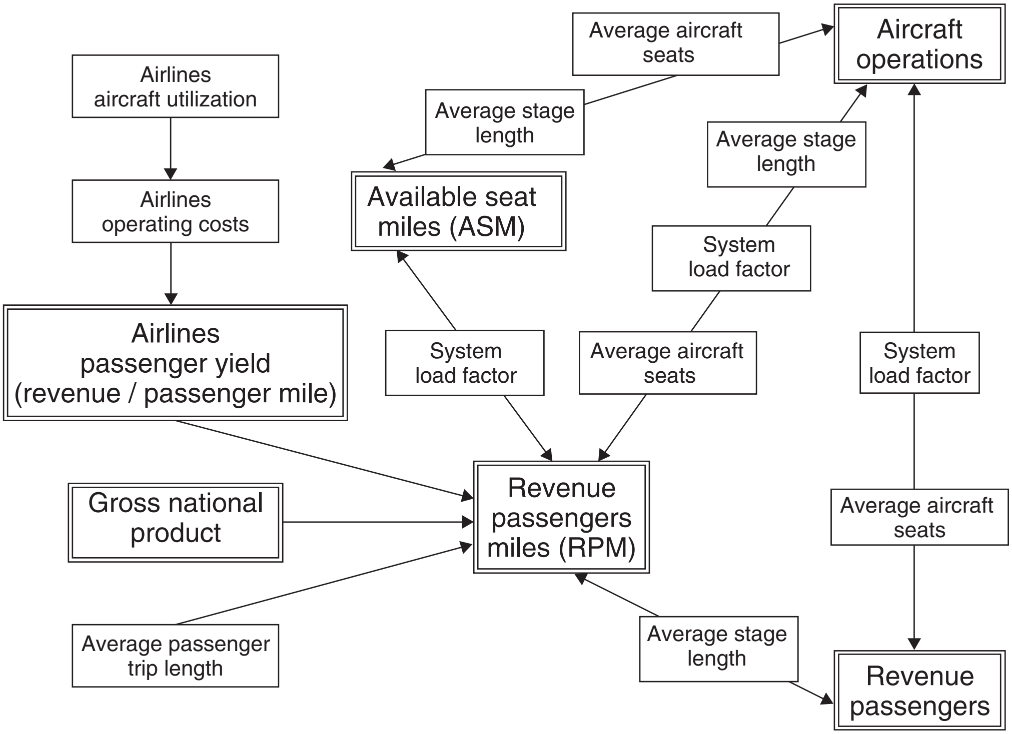

Figure 2.4 Aviation demand forecast process and relationships.

generates reasonable and statistically acceptable forecasts in the future. In conducting the aviation demand forecast of the Chicago South Suburban Airport study, the burden was on the consultant to prove that the FAA forecasts have the desirable level of accuracy to base the entire airport forecast reliably on it (20).

While the FAA forecasts typically generate debate and discussion on content and approach when they are published annually, they rarely undergo a diligent and systematic validation. Given its critical importance, the study consultant team conducted a validation exercise whereby the actual demand reported in a given year is compared to the published FAA demand forecast for the particular year, as conducted in the previous years (5). The consultant team reviewed the FAA forecasts of enplanements developed over 20 years prior. As depicted in Figure 2.5, the analysis showed that the variance of the forecast (when it was done) and the eventual demand (when it occurred) were indeed within the allowable statistical standards.

Subsequently, the FAA took it on its own to conduct an analysis of the variance from historical results for five key forecasting metrics during the fiscal year (FY) 2003–FY 2008 forecast period. Although this brief period has experienced industry upheaval, the FAA's forecast methodology remained consistent during this time. For these reasons, inclusion of prior periods in an analysis of forecast variance might lead to inconclusive, or inaccurate, implications about the accuracy of the FAA's current forecast methodology.

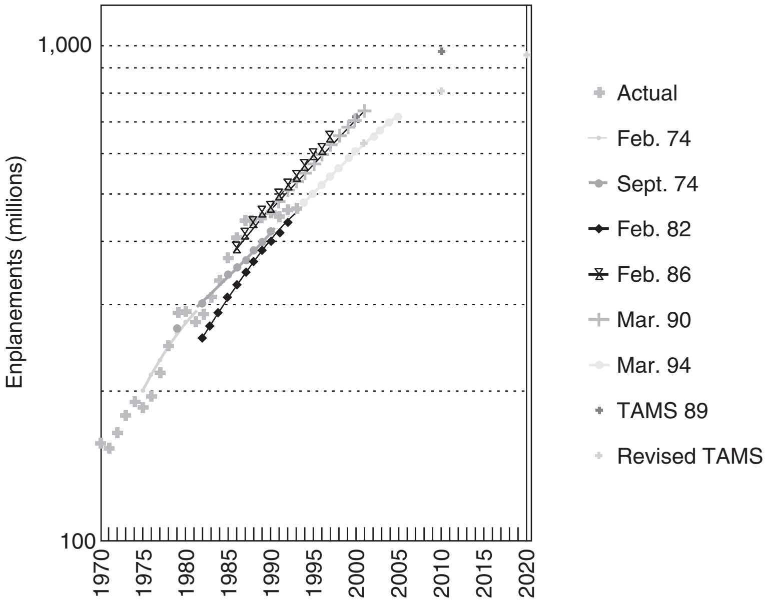

Figure 2.5 Analysis of FAA forecast accuracy (20).

Table 2.5 FAA Forecast Accuracy Evaluation (18)

Forecast variable	Mean absolute percent error (combined FY 2003–FY 2008) (Forecast variance from actual) forecast performed years prior to actual				
	1 Year	2 Years	3 Years	4 Years	5 Years
ASMs	0.7%	4.1%	7.2%	9.9%	10.9%
RPMs	1.5%	2.9%	4.1%	4.7%	5.4%
Pax enplanement	1.1%	1.7%	3.7%	4.6%	5.9%
Mainline Pax yield	2.8%	7.2%	8.6%	7.4%	5.9%
IFR aircraft handled	2.0%	4.1%	5.8%	6.1%	6.4%

This FAA accuracy analysis is shown in Table 2.5, which contains the mean absolute percent errors for the projected values versus the eventual results for U.S. carrier domestic operations. Each metric has five values showing the relative forecast variance by the number of years before the preparation of the forecast took place. For example, the three-year column for ASM shows that the mean absolute percent error was 6.5% for ASM forecasts prepared three years in advance. For the period under examination, preparation of the forecasts for FY 2005, FY 2006, FY 2007, and FY 2008 occurred in FY 2003, FY 2004, FY 2005, and FY 2006, respectively. Presenting forecast variances from actual data in such a manner simplifies a review of longer term trends. This allows for examining changes in the relative variances by time horizon, signaling when dramatic shifts in accuracy occur.

Examination of the forecast variances indicates:

1. All the metrics examined show declining variances as the forecast time horizon decreases, although the variances in yield increase somewhat between years 3 and 5. The largest variances were found in the forecasts of ASMs and yield, the two variables most directly affected by carrier business decisions. However, both variables show largest declines in variance between years 3 and 1.
2. The FAA's forecast model produces relatively small variances for both of the passenger traffic metrics, enplanements and RPMs, with none of the forecast variances exceeding 6% for any forecast time horizon examined.
3. The relative divergence in forecast variances between RPMs and ASMs suggests errors in forecasting load factor.

Examination of the forecast variances over time suggests two primary implications. Added focus on "load factor" might improve the model, as this variable is currently calculated by dividing the forecast RPMs by forecast ASMs. Since there are variations for both RPM forecast and ASM forecast, an even larger variance is expected in the forecast of load factor, which is the critical factor in converting passenger demand into aviation activity. But as the difference between the RPM and ASM forecast variance narrows, the near-term load factor forecasts become more reliable. Consequently, the large variances in load factor forecasts will lead to large variances in the long-term forecasts of aviation activity. Aircraft load factor is the most volatile variable of the FAA forecasting system.

Moreover, as carriers adapt to changing market situations, the ASMs become increasingly difficult to forecast beyond a relatively short time horizon. One reading on this fact is that the relatively large variances in the ASM forecasts suggest that carriers have reacted by permanently removing capacity. The FAA's longer term forecasts rely on anticipated aircraft deliveries and retirements as well as historic relationships between economic activity and capacity deployed. Given the volatile nature of many of the factors influencing longer term ASM forecasts, a simpler approach that could be adopted is dividing the RPMs by load factor, which may improve the long-run accuracy of the ASM.

Regional Demand Level

A step down from the national to the regional level may be required in certain cases, but not always. Establishing a correlation between national and regional demand forecast essentially determines the airport region's share of the entire national demand. This is particularly necessary when the region's share is not stable, for example, if it is undergoing significant growth more than other regions that will result in higher share in the future than presently. Base-year share of regional passenger demand to national is determined based on expected level and nature of the economic growth, particularly those aspects related to aviation and air travel (2).

The outcome of this level establishes a threshold to benchmark the aggregate regional demand derived through the bottom-up part of the framework. But it is only an approximation of the aggregate demand and does not consider inelasticity of:

(a) OD passenger demand in the region that is strongly correlated with its socioeconomic variables

(b) Airport demand constraints due to airport capacity shortages that restrict demand simply because it could not be physically accommodated
(c) If and when the airport becomes an airline hub, airport demand forecast is treated differently to include connecting passengers

Therefore, the forecasting methods described previously are quite simplistic to forecast regional air travel demand, and they could be considered only as thresholds or benchmarks. They mostly assume the future to simply be a continuation of past trends; hence, they represent a macroscopic model of regional air travel. In general terms, exponential growth is assumed at the advent of air transport activity (a new airport or a new air service) for a certain period of time beyond which rate of growth will stabilize and plateau due to various reasons. This behavior or demand pattern clearly describes the logistic curve formulation. However, it would be very difficult for forecasters to estimate the inflection points of this model without analyzing the building blocks of the regional or metropolitan air travel market. This bottom-up analysis of the market and demand would overcome the gross errors of the top-down approach.

While this approach attempts to relate air traffic at an airport with changes in a variety of causal and closely associated market and socioeconomic factors, it neglects to consider system-based variables (e.g., accessibility and frequency of service, level of service, and convenience and comfort). Therefore, changes in all these variables would ultimately guide the forecaster to predict the demand level and pattern in the future. The predictive power of this approach is more realistic and is far more accurate in its outcome. The framework for adopting this to forecast regional airport demand is very similar to that used very successfully in conventional transportation planning analysis to estimate vehicular trips in an urban context. It follows this modeling schema, with its primary functional models of:

Generation → distribution → modal choice → assignment

Generation models estimate the number of trips originating or terminating in a specific area based on the socioeconomic characteristics of the area vis-à-vis the entire region and the nature of the transport system.

Distribution models essentially mate specific pairs of origins and destinations to estimate trip interchanges between them using equilibrium models with time or distance as the parametric impedance to travel.

Modal choice models allocate trips made and distributed among the specific modes available to individuals. These models are normally a function of the structure and nature of the transport system as well as socioeconomic and demographic profiles of the trip market.

Assignment models relate particular trips with route and airport selected by the individual traveler to make the trip.

It is in the last two functions (modal split and trip assignment) that the relationship between the principles of air trip and ground trip models gets blurred and similarity breaks down. The airport demand modeling schema would then be transformed to:

Air trip generation → air trip distribution → airport choice

This modeling schema is implicit within the integrated forecast framework. Their models are described in the respective level of the framework.

But first it is important to rationalize the model's building blocks of this framework. Air travel can be recognized as the product of four basic factors that must be accounted for in the representation of the variables of the models to predict airport demand over time.

These basic factors are a supply of people, a motivation to travel, resources available for expenditure on travel in terms of time and money, and a transport infrastructure capable of supporting travel demand.

In considering these factors in the context of the framework over the horizon of the forecast, it is necessary to consider the nature of these underlying demand factors in the forecasting process, which should include the following:

1. Observation of past trends
2. Identification of exogenous variables that act as surrogates for the basic factors causing changes in level of air transport demand
3. Conduct of base socioeconomic, population, and demographic surveys to collect data that would describe the population's socioeconomic profiles, the nature of the airport area and region, and certain technological characteristics of the air transport system
4. Establish relationships of the predictive variables and changes in level and pattern of air transport demand
5. Establish relationships to predict the anticipated level of the exogenous variables in the forecast horizon, as per future planning increments to predict future air trip demand levels

It is important that the forecasting framework represent all factors likely to influence the independent variable in the models (i.e., air travel demand). Neglecting or omitting some of the causal variables may undermine the accuracy and predicting power of the model and affect the entire forecast. The list of variables previously used may include (21):

1. Demographic variables, including size and density of population centers
2. Proximity to other large population centers
3. Economic characteristics of the city
4. Government activity, including promotional and regulatory policies, subsidy of competing modes, environmental sustainability and energy conservation, and balance of payment policies
5. Airfare levels within the industry and the respective competitive influence on fares
6. Technological development and market competitiveness of other transport modes
7. Development in aircraft technology and air traffic systems
8. Adequacy of public transport infrastructure provision of the air mode and the competing modes
9. Urban and regional characteristics and related development trends
10. Various other imponderables, such as sociocultural changes in leisure and work patterns, changes in communication technology, and modernization in lifestyle patterns

2.5 MULTIAIRPORT REGION FORECAST FRAMEWORK

The discussion above is applied further to develop a demand forecast framework for regions with more than one commercial air carrier airport. In these regions, passengers would have the option to use any of these airports based on certain selection criteria. In this environment, supply for air travel to the region (i.e., the airports and their airlines) would accommodate the demand collectively based on the selection criteria of airports, where the passenger would select the airport of choice.

This relationship of regional supply and demand and the rationale involved make the airport forecasting process a complex one. The complexity of this framework is related to the variables required to address the distribution of regional passenger demand to the existing airports in the region or to include a new airport to the supply side of the equation. The number of variables required for developing the regional demand generation and distribution models would be high, and the associated data used to develop and calibrate the models would typically be quite large. These models, which cover the generation, distribution, and allocation of passenger trips in the region studied, would allocate passenger demand to the region's airports using actual and measurable travel demand and airport selection variables.

The variables and data for regional demand generation and distribution include (22):

1. Local population and employment geographic distributions based on standard local government-metropolitan geographic identification. Typically, this is based on an "analysis zone" identified by the urban planning council of the region.
2. Social and economic characteristics by analysis zone.
3. Travel time and route assignment between the population, commercial, and employment zones to the airports of the region. Typically, travel-related data are synthesized through use of urban transportation network models developed by the regional planning authority
4. Other travel-related data, including travel costs by mode.
5. Airline service measures for each airport, including the frequency, aircraft type, and fares by market and airline sector [i.e., major vs. low-cost carriers (LCCs)].
6. Other airport-related service quality and commercial attributes that may influence passenger selection of airports.

Given the model complexity and extensive data required, the effort, cost, and time required for such an undertaking are invariably substantial and require the collaboration of many organizations, authorities, and industry stakeholders. Such modeling frameworks have been developed in large metropolitan areas as part of their regional airport development plans, including Airport Authority of New York and New Jersey airports (22), Southern California Association of Governments (22), San Francisco Bay Area (23), Washington-Baltimore metropolitan area (24), and the Chicago Airport study (2).

The above methodology's rationale and components of the multiairport regional demand model are described in the following example—Chicago Third (Supplemental) Airport study:

Framework Application

This integrated three-level demand forecasting framework adopts a top-down, bottom-up methodology on three levels (national, regional, and airport) to furnish regional- and

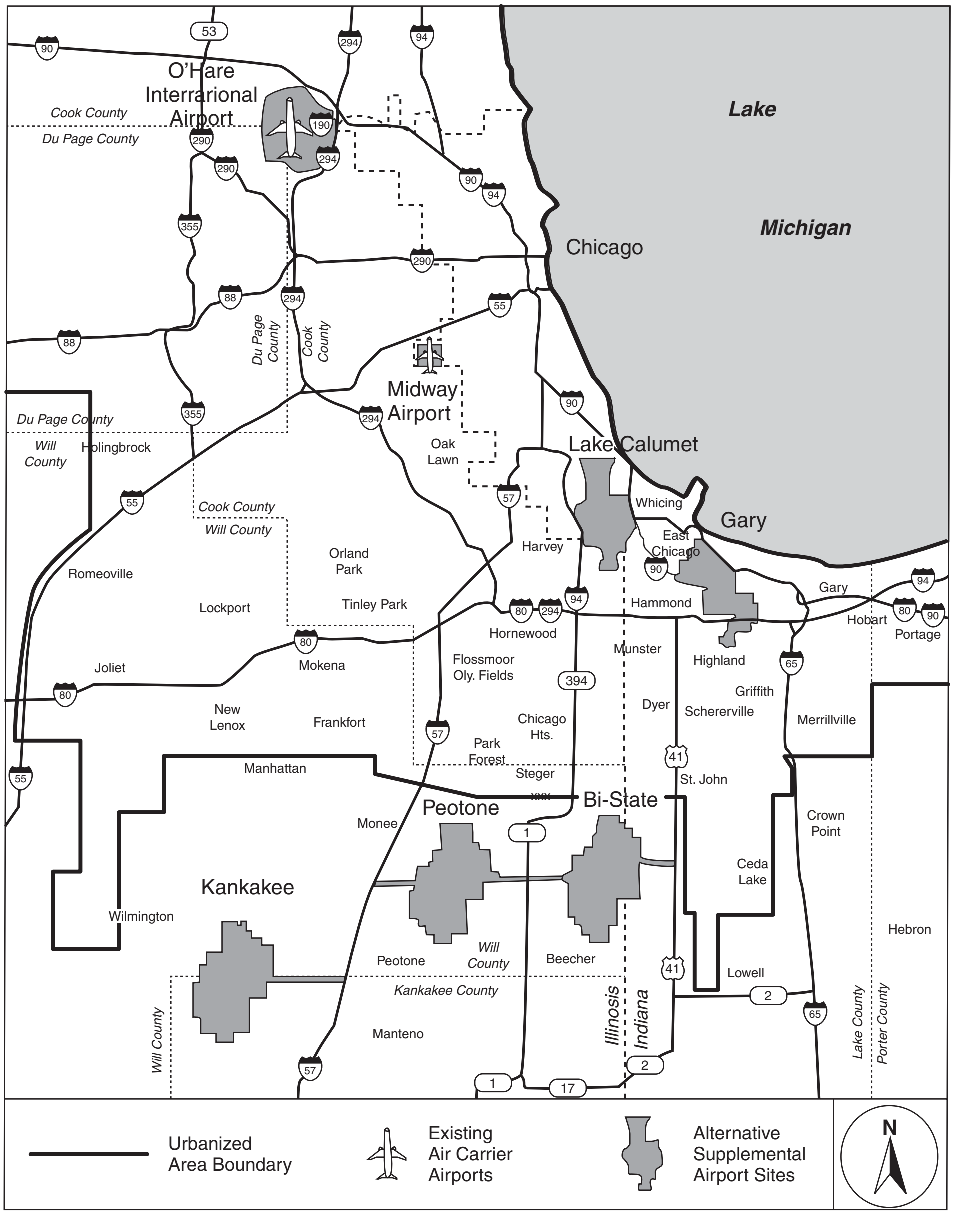

Figure 2.6 Chicago region, showing the two existing airports and five supplemental airport sites (25).

airport-level aviation demand forecasts for air carrier airports in the region. It was applied to the Chicago Supplemental Airport study that addressed concerns of long-term capacity shortages in this region. Figure 2.6 depicts the Chicago region, the two existing airports, and the five sites for a new supplemental airport evaluated in this study.

Level 1: National to Regional. The process starts with a step-down derivation of the regional air travel demand forecast based on the widely accepted FAA national demand forecast system (described previously). Regional demand control totals are derived as the Chicago region's share of the national forecasts. These shares are influenced by past trends and analysis of market movements in present trends reshaping the air transport industry locally, nationally, and internationally. Based on a region-specific airport selection model, the regional totals would then be allocated to each of the region's existing air carrier airports and new supplemental airports.

An extensive review is conducted for previous studies addressing air transport forecasts; relevant regional and local socioeconomic, demographic, national-regional economic studies; and market analysis of variables influencing aviation demand in the medium and long term. For the Chicago region, two were particularly important: The Illinois-Indiana Regional Supplemental Airport study was conducted (25) to respond to the findings of a previous study (26), which concluded that the Chicago region (covering nine counties; seven in Northeastern Illinois and two in Northwestern Indiana) will run short of airport capacity and will require a new "supplemental" airport to fulfill the long-term (2020) aviation demand with sufficient capacity. Both studies were part of a broader effort over several stages to set a long-term strategy for the Chicago region's requirements of airport infrastructure development. Figure 2.7 presents the entire Chicago region airport development planning process and its components and plan phasing. The Chicago Airports Capacity Study concluded that a new supplemental regional Chicago airport is both needed and feasible (25). An "expert consensus" preliminary passenger forecast was reached among industry stakeholders and study sponsors for a total of 65 million enplaned passengers that would need to be accommodated at the region air carrier airports by the year 2020.

In the dynamic market and industry environment of Chicago at that time, it would have been particularly difficult to predict airport demand accurately. The following measures were adopted in the Chicago Supplemental Airport study to arrive at a more accurate forecast (27):

- Both pre- and post-deregulation periods of the air transport industry were covered,
- The FAA national forecasts were accepted as given and used in level 1 of the methodology after careful analysis of its accuracy,
- Allocation of the Chicago region's share of the national FAA forecasts was given reasonable consideration and consensus was maintained,
- Individual components of the forecasts (i.e., domestic OD and connecting, national and international, and air carriers and regional commuters) were thoroughly reviewed, debated, and analyzed,
- All forecast components were tempered with expert judgment, collective experience, and intuition of expert professionals and leaders of the industry and further offered for discussion and refinement by the public.

While the Chicago Airports Capacity study provided an industry consensus forecast, the independent forecast conducted in the Chicago Supplemental Airport study determined that this forecast may have been underestimating some of the region's

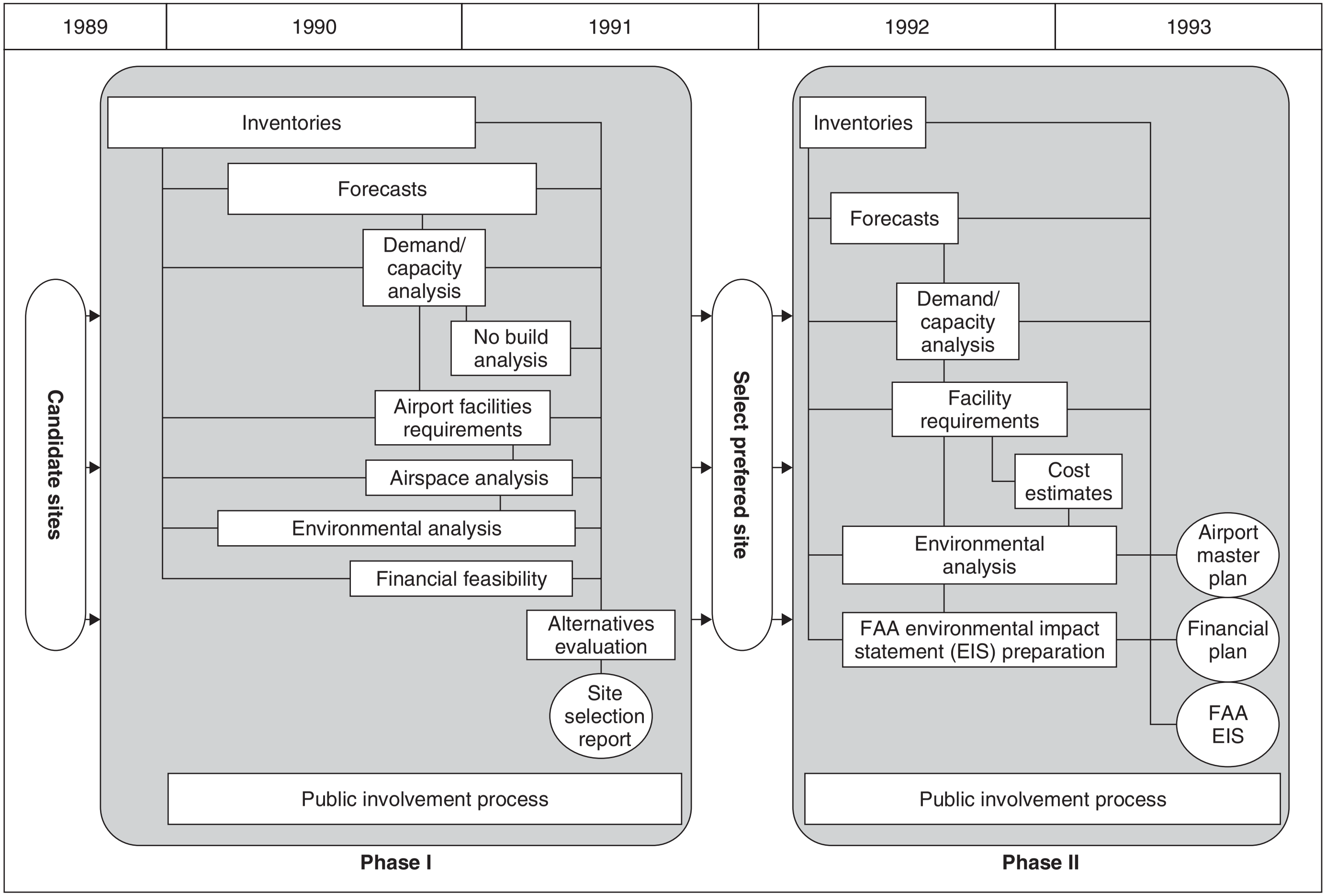

Figure 2.7 Chicago region airport development planning process (25).

air travel market and industry dynamics and should therefore be revisited and a more comprehensive approach to demand forecast applied. This approach was more robust based on sound industry, market, and region socioeconomics that consider a "discernable historic relationship between Chicago and the US" (27). In this study, the Chicago region is expanded into 15 counties covering 6 more counties in southeastern Wisconsin to account for demand interactions of the northern part of the study area with Chicago O'Hare and Milwaukee airports. To cover the wider regional demand to air service from the Chicago airports, the study included "external zones" beyond the study area that extends south and north to other counties in Illinois, Indiana, and Wisconsin and east to southwestern Michigan counties and shown in Figure 2.8 (external counties are the wider named grid, and the study area in the smaller grid).

Level 1 forecasting was carried out following the FAA forecasting system methodology as follows:

- Domestic air carrier yields and GNP were used to forecast the RPM of the region's air carriers.
- The FAA estimates for average passenger trip length for Chicago air carriers and regional commuters were estimated to derive the Chicago region's domestic enplaned passengers throughout the study horizon (2000, 2010, and 2020). This component was also used to project an average aircraft size to reflect that for Chicago air carriers' fleets. The base flight schedule developed is used to project flight schedule per aircraft type in the future.
- International enplaned passengers are developed in a similar process based on ICAO, IATA, and the aerospace industry "outlook" forecasts. The international passenger forecasts developed are compared against the FAA international passenger forecasts.

For the different forecast components, the study conducted variable sensitivity and elasticity analyses for factors determined to influence the resulting future forecasts.

The regional aviation demand forecast was analyzed and estimated for air carriers (OD and connecting; domestic and international), commuters, air taxi, and general aviation (GA) of the primary airports in the expanded Chicago region (O'Hare International, Midway, and Milwaukee airports) during the industry turbulent years of 1970–1988, which included airline deregulation in 1978 and recession cycles. The socioeconomic characteristics (population, households, employment, and per-capita income) for the 14-county study area "analysis zones" (a total of 260) were obtained from various studies and surveys conducted by the regional planning authorities of the three states, U.S. agencies, and economic forecast consultants.

This process is iterative and is conducted in three parts:

(a) *Air trip generation* based on base-year demographics and socioeconomic factors and for the future years based on the forecasts of the factors dictating the trip generation rates for the 14-county study area
(b) *Distribution of air passenger trips to capacity unconstrained airports* of the region, both at base year for existing airports and future years if a new one is developed

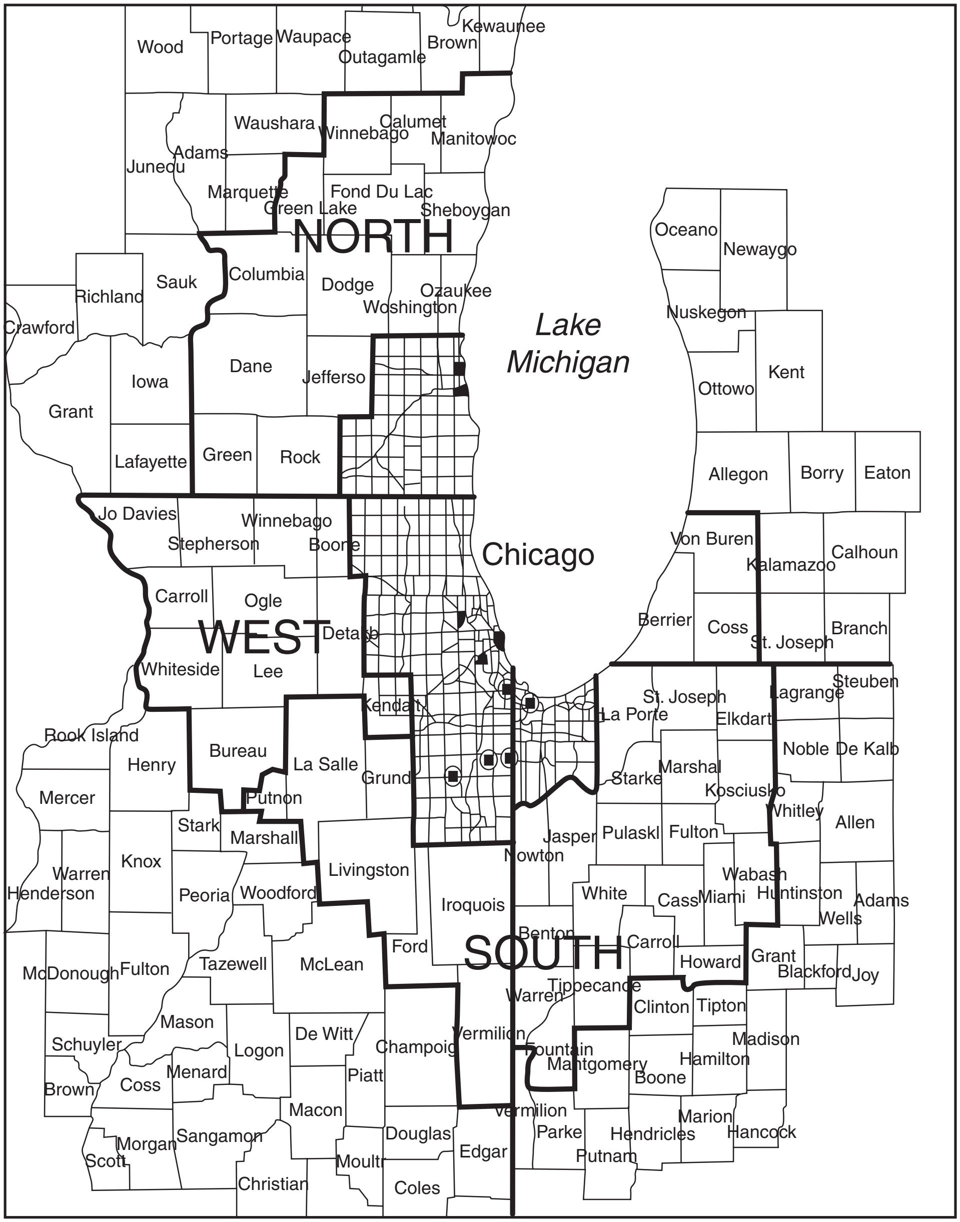

Figure 2.8 Chicago region airport development planning process (27).

(c) *Assignment of passenger trips under capacity-constrained airports*, where trips are allocated to airports considering their infrastructure capacity condition in the airport choice criteria

The region's socioeconomic databases compiled by regional planning and municipal agencies in the three-state study area and supplemented by federal sources are verified and analyzed to set the base regional socioeconomics for the study (28). Trends and forecasts of population, households, and per-capita income for the region were verified based on the aggregate structure of the economy, industry output and employment, labor force projections, specific relevant emerging issues, and indicators of regional dynamics (29). Based on extensive analyses of each of these variables, a socioeconomic profile of the 14-county, 3-state 214-analysis-zone study area was determined for the base year 1989 as follows:

- Population: 9.75 million
- Households: 3.6 million
- Per-capita Income: $15,750

Economic analysis determined that regional growth for the interim period 1990–2010 was expected to reach 7.3% for population and 17.6% for households. It was determined that projected estimates for growth of per-capita income in the study area analysis zones would yield inaccurate results and therefore were not included for the long-term forecasts. Employment levels by type were used instead.

Evaluation of the socioeconomic parameters influencing the domestic passenger forecasts indicated that economic and demographic activities in the Chicago region (as a major U.S. business, industry, and transport hub) are closely correlated to availability and adequacy of transportation services in general and, for Chicago, air transportation in particular. Forecasting one without forecasting the other would be problematic, and therefore an interactive approach to demand forecasting would need to be devised. Initially, the region's demographic and economic forecasts (as share of the total U.S. forecasts) are used to determine the share of U.S. aviation activities attracted to the study area (provided aviation infrastructure is available and service is unconstrained). The regional demographic and economic forecasts are then revised to examine the aggregate economic impacts on the region and each of its airports, including the new airport site. Based on these assumptions and rationale, the Chicago region's share of the national domestic OD and connecting passengers forecast is determined. The region's base-year total enplaned passengers' share of the United States was determined to be 7.45%: 11.5% for connecting and 5.3% of OD enplaned passengers. A similar rationale with different database and information is used to determine international OD and connecting passenger forecast.

To address subtle regional socioeconomic trends and market dynamics in the forecasting process, the Chicago Supplemental Airport study reviewed airport and regional aviation forecasts previously conducted; various socio-economic, regional, economic and demographic forecasts; industry market research; and other forecasting concepts set by consensus among experts in the field.

The study considered several forecasting techniques in response to industry and stakeholder reviews, queries, and desire. Regional OD forecasts allocated to analysis zones were estimated from base and forecast socioeconomic and demographic variables. Total "control" OD passenger demand forecast for the region is first determined. The analysis determined that certain techniques provided better results than others. In particular, total regional passenger enplanement was found to have strong correlation with total regional employment (30). A similar strong correlation between regional and national (U.S.) OD passenger enplanement was determined, which confirms the reliability of the share analysis approach. By contrast, regression analysis of the national to Chicago regional OD share forecast provided unsatisfactory results.

The OD passenger enplanement forecast process also included estimated “induced demand” generated by building a new airport. Since the new airport location has not been determined at this stage of the framework, an iterative process is used to estimate OD demand generated in analysis zones closer to the airport and influenced by airport activities.

The other element of OD demand, regional connecting passengers, is tackled separately based on analysis of airline hubbing activities in the region’s air carrier airports used as hubs (for Chicago, it is O’Hare International, the largest airport by volume during that time). This analysis covered such techniques as airline hubbing models, statistical analysis of hub centrality measurement, and the location of airline hubs vis-à-vis air travel markets and supplemented previous analysis (31). The outcome of this analysis indicated that total passenger enplanement forecasts in the region were split almost in half between OD and connecting passengers in the air carrier airports of the region—mainly Chicago O’Hare, the largest U.S. airline hub.

Level 2: Regional to Airports. The trip generation forecast approach involves a step-down allocation of recommended regional OD passenger enplanements to each analysis zone based on the future distribution of the major generators of air passenger trips (32). Passenger surveys conducted in the region airports in the base year (1989) indicated that 68% of all OD passenger trips originated at the residence, 14% at employment places, and 18% at hotels and convention centers. Future land use trip generation was adjusted considering Chicago’s future convention center and hotel expansion, yielding 65% from residence, 15% from business and employment, and 20% from hotel/convention centers.

The base-year trip generation is based on the OD passenger trips allocated to the analysis zone derived from its socioeconomic trip generator factors: households, jobs, and hotel rooms. The future trip generation per analysis zone is estimated from the future trip generator factors per zone for the three forecast horizons up to 2020. The forecasts of future socioeconomic factors are conducted by the respective agencies in the three states. These future forecasts are then distributed to the existing and future airports. At this stage five alternative sites were considered for the new supplemental airport based on the findings of the Chicago Airport Capacity Study: Bi-State, Peotone, Kankakee, Lake Calumet, and Gary; see Figure 2.6.

The allocation of the region’s passenger demand to existing and proposed alternative airport sites is the critical part of the airport demand forecasting framework. Future airport operations, airline schedules, employment forecasts, airport facility sizing and design, and even location of new airports are all dependent on these allocations (32). A comprehensive analysis must therefore be undertaken to ensure results are reasonable and accurate. In particular, there may be need to have several allocation iterations conducted, first in an unconstrained environment, then to capacity-constrained allocation.

The distribution of regional demand to the alternative airports is a three-step iterative process: First, a comprehensive *air trip generation* for the base-year demographics and socioeconomics for the 14-county study area is conducted, as discussed below.

Second, the air passenger *trips are distributed to capacity unconstrained airports* of the region. Third, *passenger trips are allocated to airports* (existing and proposed) according to the airport selection criteria subjected to the individual airports infrastructure real (constrained) capacities.

In general, the appropriate forecasting technique selected for a particular study depends on the history, industry environment, and role of the airport. Airports serving large urban areas are large enough to warrant sufficient competition. Activity in these airports are demand driven and in certain situations capacity unconstrained—airlines will provide enough capacity to accommodate the demand at that airport (33). For the Chicago region study, a bottom-up iterative methodology that uses modeling and simulation techniques is adopted. It starts with estimating trip generation per zone of the entire region. Trips of each zone are distributed to the region's airports using a predetermined airport selection criteria based on data from travel surveys and socioeconomic variables that would indicate the propensity of the population to make air trips under the stated air travel distribution parameters. The iterative process starts with the capacity-unconstrained condition, and then the airport selection model would reassign residual trips over the stated airport capacity to the other airports until equilibrium is maintained—the capacity-constrained demand. This trip generation–distribution–assignment process would estimate the aggregate passenger demand going to each of the region's airports. This aggregate demand, which is essentially the OD element of demand (both international and domestic), is in turn used to estimate other components, namely, the connecting and airport-induced elements of the demand.

Since trip allocation to airports is actually dictated by the individual passenger selection of airport, mode, and other factors, the behavioral characteristics of airline passengers become paramount. As air travel became more competitive, airlines and airports may have jointly influenced the passenger decision-making process, as it involved variables other than distance. De Neufville (34) was one of the first to identify airport choice patterns and the factors influencing passenger selection of airports. Kanafani (35) studied competition between airports and air travel markets using such supply variables as frequency of service, distance, access travel time, air fare, and other levels of service attributes, and aggregate models were developed. Passengers' choice of airport in a metropolitan area or region with more than one air carrier airport therefore becomes critical to locating and sizing new airports and would be central to the airport passenger demand framework.

Airport choice became very important in airport demand forecasting studies, and many have successfully developed and calibrated airport choice models worldwide using more robust and refined models. These have actually been used to predict the level of future airport activities under different market environments, provision of service, and effects of competition on existing airports as well as bringing a new airport into the competition.

The model most widely used in airport choice studies is the multinomial logit (MNL) model. Originally, it was developed by urban transportation planners to evaluate the public transport options available. It was later used by airport planners and has proved its robustness and success to develop the airport selection criteria in multiairport regions. Successful applications of the MNL model in airport selection were reported by Skinner (24) in the Washington Metro area, Harvey (23) in the San Francisco Bay area, Ashford (36, 37), in Central England, and Mumayiz (2) in the Chicago region.

In this section, the Chicago MNL application for airport choice model is described, including model formulation, information required, surveys conducted, databases used, and the model calibration process.

Mathematical Formulation of Airport Selection Criteria. To fully understand passenger behavior and related decision-making attributes, specific information is sought and different surveys are conducted. Equally important, base *composite trip generation tables* to summarize travel characteristics of the residents and visitors of the region would need to be developed.

A mathematical allocation model could then be developed that, when properly validated and calibrated, would systematically distribute the region disaggregate passenger demand generated on the analysis zone level and allocate it to airports. The airport selection model is the driver of the allocation mechanism, based on the assumptions considered in the analytical thought process for passengers to choose from options available.

The formulation of the MNL model is

$$P_{gk} = e^{V}_{gk} / \Sigma e^{V} gk(e, \ldots, r = 1) \qquad (2.9)$$

where:

P_{gk} = share of trips originating in alternative g using option k, or the probability that alternative g will be chosen by individual k

V_{gk} = utility function of the attributes for the options considered, such that

$$a_1 X_1 + a_2 X_2 + \cdots + a_n X_n$$

where

$X_1, X_2, \ldots, X_n$ = explanatory attributes (variables) of the utility function

$a_1, a_2, \ldots, a_n$ = parameters for coefficients (weights) of each attribute in the function

In choosing the variables or attributes of the utility function, two factors need to be considered: availability of accurate base data and ease of adequately predicting future values. The most influential variables dominating the passenger's decision-making process are cost of making the trip to the airport (in terms of access time and/or cost), convenient level of air service at the airports (in terms of flight frequency and/or destinations), and corresponding airfares.

While most of MNL applications cited used the three attributes, the model for this particular (Chicago) application used only travel time and airline service. The reason is it would be particularly difficult, if not impossible, to predict airfares in a deregulated and global environment 20 and 30 years into the future.

It was further surmised that the overall airline fare structure to common destinations from the region's airports would not vary significantly to merit including this attribute in the utility function. This particular attribute of airport choice would be of more importance where competition is limited between airports, and potential markets are of lesser magnitude.

The MNL model was calibrated as reported above using the following attributes:

Application	Utility function variables	Parameter/Coefficient			
(1) Central England (36, 37)					
	- Access time to airport	$(-0.136)^a$	$(-0.138)^b$	$(-0.178)^c$	$(-0.233)^d$
	- Flight frequency	$(1.66)^a$	$(1.07)^b$	$(2.07)^c$	$(2.69)^d$
	- Air fare	–	$(-1.2)^b$	–	$(-0.75)^d$
(2) San Francisco (23)					
	- Travel time to airport	$(-0.10)^e$	$(-0.138)^f$		
	- Flight frequency per week	$(0.003)^e$	$(0.002)^f$		
	- Air fare	$(-0.04)^e$	$(0.08)^f$		
(3) Washington-Baltimore (24)					
	- Travel time to airport	$(-0.059)^g$	$(-0.076)^h$	$(-0.073)^i$	
	- Nonstop flights per weekday	$(0.200)^g$	$(0.200)^h$	$(0.090)^i$	
Chicago Metro (32)					
	- Travel time to airport	(−0.06)			
	- Airline service as weekly flights	(0.0003)			

Notes:
(1) Linear utility functions calibrated for: (*a*) Business, (*b*) Leisure, (*c*) Tours, (*d*) Domestic.
(2) Nonlinear utility functions calibrated for: (*e*) Business, (*f*) Nonbusiness.
(3) Linear utility functions calibrated for: (*g*) Business-Peak, (*h*) Business-Off Peak, (*i*) Nonbusiness.

Information and Data Collection

The feasibility of using the MNL model for airport selection depends on the availability of data on the attributes and variables of the utility function. Information needed to calibrate and use the disaggregate MNL model is typically extensive and includes:

- *Travel Times*. As one of two variables of the utility function, travel time between analysis zone centroids and airports is required for the three horizons and on the disaggregated zonal level. These data were made available by the Chicago Area Transportation Study (CATS), a participant on the study team. CATS provided the base year and projected auto travel time on the regional highway network between zone centroids and each of the airport options under congested conditions, as generated by the CATS transportation network simulation model—one of the first and most extensive of its kind developed in the world.
- *Airline Service*. The other utility function attribute, airline service at the airport, refers to airport nonstop domestic departing flights per week. It is determined in two ways: from the Official Airline Guide (OAG) for the period when airport surveys were conducted and from the airport airline weekly activity records excluding non-air carrier/commuter and international flights.

- *Airport Surveys*. Surveys conducted by the airport authorities of the three existing airports in the region were conducted during the base year. These surveys provide a database for trips made by individual passengers responding to a survey questionnaire at the airport. These data provide a reference of the passenger's origin analysis zone, basic personal information reflecting some socioeconomic and demographic information, access mode, and route selected to the airport. These surveys also provide additional data on the independent variable (originating trips) for the trip distribution and allocation process.
- *Home Interview Surveys.* In addition to airport surveys, the regional planning authorities in Illinois and Indiana conducted home interviewing surveys as part of their work that provided additional samples to supplement airport surveys. These surveys would cover analysis zones that may not have provided passengers to respond to airport surveys. These surveys would provide more passenger and analysis zone reference information to refine the data for trip distribution and allocation. Special techniques were employed to merge and normalize the two types of surveys into one database.

Calibration of MNL Utility Function

Calibrating the MNL model depends on the quality and detail of data obtained from the travel surveys. This would determine the possibility of a discrete and disaggregate form of the model. Otherwise, an aggregate model would have to be developed using passenger trip data grouped into analysis zones.

The MNL calibration process is carried out in three steps:

Step 1. *Defining the Utility Function*. Given the importance and centrality of the utility function in the distribution of trips to airports, the Chicago application used two methods to calibrate the MNL airport choice model. The first followed the Harvey approach, which applied the MicroLOGIT (38) program to calibrate the utility function. The regression model developed estimates percent of passengers selecting any one airport on the basis of differences in travel time and airline service, the independent variables. A dataset is first created from the entire database (251 observations) that includes the differentials of the independent variables' probability (percent share) for passengers selecting between the three airports. Utilizing logarithmic relationships, the dataset is then regressed to define the following model:

$$\ln(P_1/P_{2,3}) = b_1(\mathrm{TT}_1 - \mathrm{TT}_{2,3}) + b_2(\mathrm{AS}_1 - \mathrm{AS}_{2,3}) \tag{2.10}$$

where

P_1 = percent of passengers in analysis zone using airports 1, 2, and 3
$\mathrm{TT}_{1,2,3}$ = travel times from analysis zone to airports 1, 2, and 3
$\mathrm{AS}_{1,2,3}$ = airline service (weekly departing flights) from airports 1, 2, and 3
$b_{1,2}$ = coefficients of respective utility variables (b_1 for travel time and b_2 for airline service)

The calibrated model for a dataset of 251 observations had a reasonably good correlation of $r^2 = 0.74$ and t-value $= 0.8$. The utility function is

$$\ln(P_1/P_{2,3}) = 1.2 - 0.06(\mathrm{TT}_1 - \mathrm{TT}_{2,3}) + 0.0003(\mathrm{AS}_1 - \mathrm{AS}_{2,3}) \quad (2.11)$$

The second independent calibration was conducted by CATS using the disaggregated maximum-likelihood approach and the UNILOGIT software (32, 38) and calibration procedure of the UTPS (urban transportation planning system). The calibration results were virtually identical to the first method.

Step 2. *Analysis of Airport Choice Probability*. The MNL model is used to analyze the percent shares of passenger trips from analysis zones to each airport. The data generated from the MNL model are compared to the actual shares (probability) of passenger trips going to each airport. The purpose of this step is to ascertain that predicted probabilities in the base year fall within reasonable statistical limits of variation as a condition to using the model to predict the probability of airport selection in future years. Any inconsistencies, variations, and influence of other factors are investigated, analyzed, and adjusted accordingly to ensure that the model is equally applicable and valid to predict airport selection probabilities in the future and for new airports in the region.

Step 3. *Airport Choice Model Validation*. The probabilities (shares) of passengers originating from each analysis zone using the three existing airports are determined. The model is validated by comparing the calculated predicted analysis zone OD passenger enplanements and percent shares (probability) of selecting an airport with the actual base-year recorded airport trips and respective airport choice as reported in the airport and home interview surveys. Statistical analysis is conducted to measure the variability of the predicted versus actual data, which indicated excellent correlation between predicted and actual data.

It is important to note that this part of the process generates a capacity-unconstrained scenario for distributing passenger OD trips to airports. It does not consider airport infrastructure capacity—both airside and landside to handle passengers. Therefore, to achieve reasonable balance between passenger selection of airports and the "residual trips" at the alternative airports, an iterative balancing process would be required to determine acceptable capacity-constrained demand at the airport. An iterative process is conducted in two steps: distributing air passenger trips to capacity-unconstrained airports and then assigning passenger trips to airports under capacity-constrained conditions.

Regional Aircraft Movement Forecast

An estimate of aircraft movement forecasts in the region on the aggregate level is derived from the regional passenger enplanements forecasts. Air carrier aircraft movements are typically predicted on the aggregate regional level using the refined analysis of air passenger forecasts developed through the modeling approaches discussed previously.

Any analysis of air transport demand must take into account relationships between air passengers and aircraft movements. To convert annual air passenger demand to aircraft movements, two major factors are considered: aircraft size and associated fleet mix and the system aircraft load factor. Average system aircraft size, aircraft fleet mix in target years are estimated based on industry projections, aircraft technology trends and load factors. Both factors are particularly difficult to forecast with accuracy due to short-term changes in the airline industry, market dynamics, and future aircraft fleet composition under changing aircraft and aeronautical technologies. Load factors in target years are normally determined on the regional level using trend analysis, time-series correlation, or simply expert judgment with feedback from air transport market analysts and airline experts.

Load factor is the ratio of passenger.miles carried to the aircraft seat.miles operated in the system (i.e., passenger.kilometers/aircraft seat.kilometers). Airlines naturally wish to maintain high load factors, which provides higher yields and hence increases airlines' profits in operating aircraft. Since the average load factor covers peak as well as off-peak operation, excessively high system load factors over long periods indicate passenger demand may not have been captured at peak periods, and this may be less profitable to the airline than accepting less load factor but using larger equipment. Therefore, there is a delicate trade-off between average load factors and system equipment capacity. Airlines manage this trade-off by accepting a lower average system load factor and lowering the acceptable net airline yield per passenger kilometer through offering low fares but with seat availability restrictions. Due to principles of airline operation at airports and aircraft operational and scheduling requirements, load factors cannot reach beyond 85% on a systemwide basis. For planning purposes and as average system load factors are subject to systemwide variations and strong variation in seasonal and daily peaking patterns, a ceiling of about 80% load factor is applied for analysis.

The planner must also observe both past and new emerging trends and confer with airlines and industry analysts on future aircraft fleet mix. Obviously, the type and size of aircraft the industry would put in its systems would undoubtedly impact the aircraft movement forecasts. An example of this is the proliferation of regional jets (RJs) by airlines in the 1990s as a means of maximizing yield on thin routes or as feeders to airline hubs. This trend took airport planners by surprise as the number of operations at certain airports grew much higher than passenger traffic, which altered the expected average system load factor for these airports by changing the fleet mix at these airports. The lesson learned is that judging what aircraft type would be available and the timing of their introduction is extremely important and perhaps the most difficult element in forecasting aircraft movement demand.

Level 3: Airports. Air passenger demand at airports is related to the region's passenger air trip generation, their distribution from their origin to the region airports, and the airports the passenger prefers to use. Prior to allocating demand to each of the region's airports, it would be necessary to estimate the capacity of individual airports. Typically, airport capacity may be reached with excessive demand, when the airport would be severely s are constrained.

The balance between demand and capacity will probably be influenced by fare levels. At highly competitive "spoke" airport markets, fares tend to be low. Fares tend to be higher at airline hubs dominated by a single airline and at smaller, less competitive airports. Demand-driven markets lend themselves to certain forecasting techniques. Regression analysis is the most commonly used technique, where passenger origination (the dependent variable) is correlated as a function of one or more independent variables representing the regional economy such as employment, income, or gross domestic product (GDP), a price variable such as average fare level or yield (airline revenue per passenger mile), and sometimes an air service variable.

Airport forecasting models thus require a large amount of historical data in a consistent format. More importantly, a forecasting model based on regression analysis requires that the future relationship between passenger origination and the independent variables remain similar to what they were for the historical period for which the regression data were collected. If there is a change in this relationship, whether it results from a new airport site, a change in regulations, or a fundamental change in the structure of the economy, this relationship will no longer hold true. Accurate projections of the independent variables are as critical to the forecast, particularly socioeconomic projections from local/national planning agencies, and the FAA yield projections used to estimate future levels of the price variable. To address the uncertainty inherent in the forecast, demand and market scenarios are used in a “what if” format. This approach is more realistic, practical, and superior to the typical high-, medium-, and low-range forecasts.

The methodology for estimating passenger traffic on the airport level is governed by the following rationale: At airline hub airports, connecting traffic is typically estimated as a percentage of originating (OD) traffic. Total passenger enplanements (i.e., the sum of originating and connecting passengers) are divided by the airline system load factor as an estimate of “seat departures.” In the United States, load factor projections are usually obtained from the FAA National Aviation Forecasting system. Seat departures divided by average seats per aircraft adjusted by airlines are obtained. As detailed system-level information becomes available on the hub bank structure at the OD airports and on the fleet acquisition plans of the airlines, flight frequency with airline fleet mix/aircraft type per market at that airport provides a more accurate forecast.

Peak-Design Concepts

The annual passenger and aircraft movement forecasts are required as a measure of the size of the airport in terms of its air passenger demand, and this is used primarily for financial-based planning. For the purpose of airport facility planning and design, however, annual levels do not lend themselves to short-term (hourly, daily) traffic variations that are typically used to plan and design airport facilities. It is the short-term demand variation and peaking characteristics that are the primary factors for facility planning and design—the peak hour and typical business day. These demand measures are used on the airport landside for passengers and autos and for aircraft on the airside.

One of the first peak-design concepts used is the typical peak-hour passenger developed by the FAA (39) described in Chapter 10. It provides empirical criteria to convert annual passenger demand to *typical peak-hour passenger* (*TPHP*) demand based on the size and peaking pattern of the airport. Certain ratios of peak passenger demand to annual passenger demand are provided to estimate the peak-hour passenger traffic at the airport. This concept generally replicates an average-day, peak-month peaking and assumes estimated 85th percentile use of ultimate capacity. A similar approach is adopted to convert annual aircraft operation forecast to peak aircraft operation by applying the average load factor and aircraft size to the TPHP estimated. Another concept, devised by the British Airports Authority, is the 30th highest hour or standard busy rate (SBR)—passenger traffic flow which is exceeded by only 29 other hours of operation during the year (40).

The relationships between peak-hour flows and annual passenger volumes are normally given in conjunction with other estimates used for peak-period planning. Figures 2.9 and 2.10 show these relationships as graphs recommended for preplanning purposes, which relate peak-hour passenger flows and peak-hour aircraft operations to annual passenger enplanement throughput. The BAA concept of the 30th highest hour is more widely used worldwide than the TPHP. Figure 2.11 depicts the log-log relationship between the SBR and the total annual passenger flows observed over an eight-year period for a range of British airports plotted against the TPHP relationship (dashed line) to demonstrate the similarity of both concepts (40). The reader is referred to Chapter 10 for a comparative discussion on the TPHP relationship.

The IATA devised a similar approach to estimate the peak passenger demand for planning and design purposes based on airline operations methodology. The IATA's *airport busy-day* concept is defined as the second busiest day in an average week during the peak month (41). For the peak month at the airport an average weekly pattern of passenger traffic is calculated for that month, and peaks associated with special events are excluded and handled separately. The busy-day analysis assesses relevant factors far deeper than the FAA TPHP method.

The source of data to generate the "base" busy day is the airport tower flight log, the operations equivalent of the flight schedule, and includes airline flight number, aircraft type, aircraft registration, seating capacity, flight origin/destination, arrival/departure

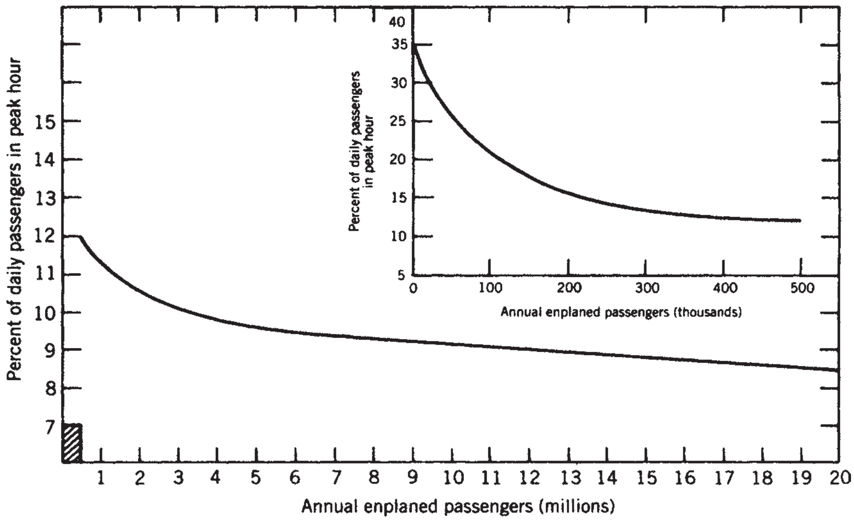

Figure 2.9 Percent of daily passengers in peak hours versus annual enplaned passengers. (*Source*: FAA.)

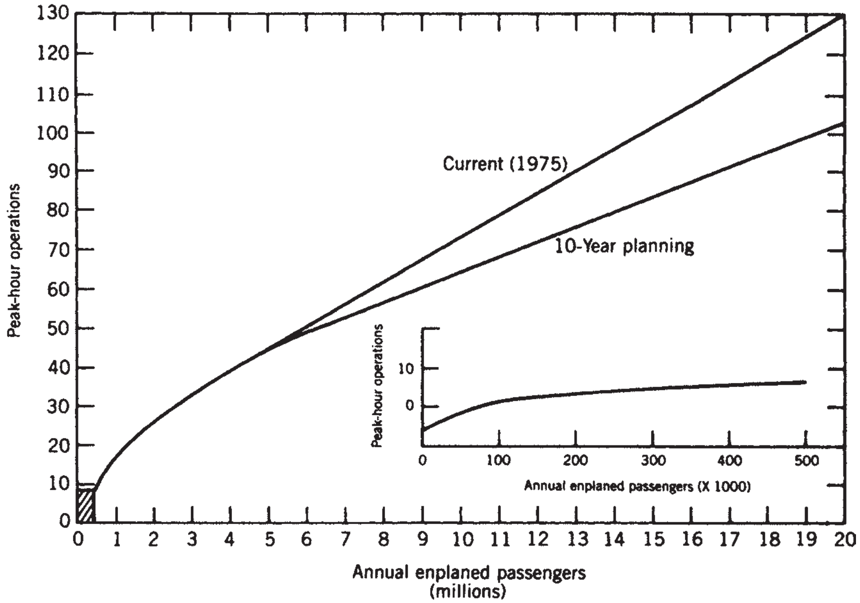

Figure 2.10 Estimated peak-hour aircraft operations versus annual enplaned passengers. (*Source*: FAA.).

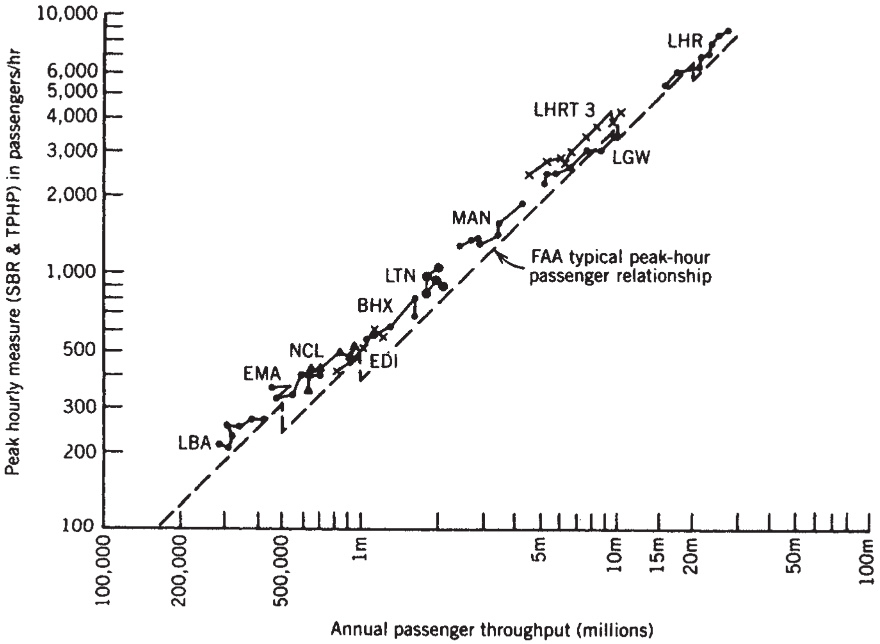

Figure 2.11 Relationship between the BAA SBR and the FAA TPHP and annual passenger throughput. (*Source*: FAA and BAA.).

time, terminal, and enplaning and deplaning passengers. In order to identify the peak hour, a computer model is developed to incorporate the database and display flow of traffic. Using a bottom-up approach, the computer model is used to forecast the airport aircraft movements, passenger flows, and aircraft gate requirements in future years. The IATA methodology projects passenger traffic for a typical busy day by determining historical (base) ratios of busy-day traffic to total annual passenger traffic and then applies it to project annual traffic. The relationship of busy day to annual traffic depends largely on seasonal variations and passenger population profiles.

The hourly profile of the busy day is derived from the distribution of the busy-day traffic by time of day to determine the future peaking pattern and peak-hour traffic levels. This method is suitable to provide passenger demand forecasts that could be used adequately for planning purposes. The IATA also developed a model for international passenger forecasts at airports (4). The model formulation is

$$\text{Passengers} = a + b \times \text{GDP} + c \times \text{yield} + d \times \text{GDP of other countries} + \text{other explanatory variables} \tag{2.12}$$

or

$$\text{Passengers} = a + b \times \text{GDP/population} + d \times \text{population} + e \times \text{yield} + f \times \text{GDP of other countries} + \text{other explanatory variables} \tag{2.13}$$

where a, b, c, d, e, and f are coefficients.

More recently, major studies have resorted to modeling and simulation techniques to perform airport-level forecasting analysesbased on the specific facility and forecast component (passengers, aircraft, landside vehicles, etc.). Chapter 15 will provide a wider coverage of the use of modeling and simulation techniques for the various airport planning functions.

At this stage of the forecasting framework, airport forecasting techniques depend largely on the particular application for specific elements of the airport.

2.6 AIR TRIP DISTRIBUTION MODELS

The trip distribution model predicts the level of trip interchange between designated airport pairs once the level of generation of the air trip ending at the individual airport has been computed. The most widely used distribution model applied to the transport situation has been the gravity model. This model, analogous to Newton's law of gravity, has grown from knowledge developed in the social sciences that interactions between human settlements appear to be in accord with principles that are in many ways similar to the physical law of gravity. The gravity model in transport practice distributes trips between city pairs according to measures of the attractiveness of the cities, allowing for the impedance effects of cost, time, and other factors.

As early as 1943, use of the gravity model was advocated for predicting the air trip interchange between cities. This model takes the form

$$T_{ij} = \frac{k P_i P_j}{d_{ij}^x} \tag{2.14}$$

where

T_{ij} = travel by air passengers between cities i and j
P_i = population of the origin city
P_j = population of the destination city
d_{ij} = distance between i and j
k = a constant of proportionality
x = a calibrated constant

Using distance as the measure of impedance, it was found that the value of x appeared to vary from 1.3 to 1.8. Other forms of this model have been developed that attempt to define the measure of impedance in terms other than distance alone. Using travel cost, the following model was calibrated:

$$T_{ij} = \frac{kT_iT_j}{C_{ij}^x} \tag{2.15}$$

where

T_i = total air trips generated in city i
T_j = total air trips generated in city j
C_{ij} = cost of travel between i and j
K = a constant of proportionality
x = a calibrated constant

In a study of the U.S. airline interstate traffic, it was found that this model could be used only for city pairs less than 800 miles apart. For larger distances, traffic appears to be independent of both travel cost and distance and dependent only on the level of trip generation at either node. Thus, for greater air trip distances, the form of the model can be simplified to

$$T_{ij} = k(T_iT_j)^P \tag{2.16}$$

where p is a calibrated parameter.

A modified form of the gravity model was used in Canada:

$$T_{ij} = K \cdot \frac{P_i^{0.62} P_j^{0.35}}{D_{ij}^{0.56}} \cdot R_i^{4.88} \cdot A_j^{0.83} \cdot S_{ij}^{1.25}\, F_{ij}^{0.38}\, C_{h_i}^{-0.38}\, C_{h_j}^{-1.4} \tag{2.17}$$

where

P_i = population at i
D_{ij} = distance between i and j
R_i = indicator of road condition around city i
A_j = indicator of attraction to city j
S_{ij} = seats available between i and j
F_{ij} = service reliability indicator
C_{hi} = percent of manufacturing and retail employment of total employment at i

A predictive equation of a similar form was developed by the British Airports Authority for the Western European Airports Association:

$$Y_{it} = a_i(F_{it})^{\alpha i}\,(I_{it})^{\beta i}\,(1 + \gamma_i)^{t-1} \tag{2.18}$$

where

Y_{it} = number of air trips in year t in trip category i
i = trip category—cross-classified for business/leisure, European resident/nonresident, long haul/short haul
F = real cost of fares in year t
I = real income in year t
γ = an autonomous trend
α = elasticity of demand (fares)
β = elasticity of demand (income)
a = a regression constant

2.7 MODAL CHOICE MODELS

As previously stated, the analytical forecasting method has frequently been applied to mode-specific air trip generations that have been separately distributed. A more rational approach would be to generate non-mode-specific intercity movements, distribute these according to travel limitations, and finally determine modal selection by the application of modal choice models. It has been generally determined that *disaggregate models* which attempt to reflect individual travelers' choices rather than *aggregate* or *zonal models* give better results for modal choice analysis. A generalized cost disaggregate model is given here for illustrative purposes; it should be borne in mind, however, that many other disaggregate model types are available which, in the right context, have shown equal or better validity.

Many factors affect modal choice, such as convenience, comfort, and safety. Although such factors are often difficult to quantify, a simple method of allowing for them and for individual variability among travelers is to construct the model from parameters that reflect the degree of randomness of the traveler's choice. The generalized cost model assumes that the traveler will usually choose the mode with the lowest generalized cost, but there is a finite probability that some other mode will be selected. One model that uses this hypothesis is of the form

$$\frac{T_{ijk}}{T_{ij}} = \frac{\exp(-\alpha C_{ijk})}{\sum_{r=1}^{n} \exp(-\alpha C_{ijk})} \tag{2.19}$$

where

T_{ij} = total trips by all modes from i to j
T_{ijk} = trips by mode k from i to j
α = some calibration constant
C_{ijk} = generalized costs of travel from i to j by mode k
n = number of available modes

The generalized cost of any mode is the total of direct and indirect costs incurred in traveling. Theoretically, the generalized cost is capable of reflecting in monetary terms *all* factors affecting travel. In the absence of complete knowledge of social and attitudinal cost trade-offs, the generalized cost concept has its limitations. In practice, generalized cost is frequently expressed in terms of direct monetary costs and cost of travel time. Where this is so, and where two alternate modes p and q are being considered, equation 2.9 reduces to

$$\log\left[\frac{T_{ijp}}{T_{ijq}}\right] = -\alpha\left[(M_{ijp} - M_{ijq}) + \lambda(t_{ijp} - t_{ijq})\right] \tag{2.20}$$

where

α, λ = calibration constants
$M_{ijp} - M_{ijq}$ = difference in money costs for modes p and q for the journey from i to j
$t_{ijp} - t_{ijq}$ = difference in travel times by modes p and q for the journey from i to j

This form of the model has been successfully used to analyze the air transport's share of a short-haul market in competition with high-speed conventional rail travel and a high-speed tracked hovercraft mode.

2.8 GENERATION–DISTRIBUTION MODELS

Some analysts do not agree that the decision to make an air trip is separated from the decision of where to go, an implication of accepting the independent generation and distribution models. In an attempt to reflect the integrated decision process, combined generation–distribution models have been produced. Typically, two types are available: *mode-specific* and *multimode* models. Both are generally of the multiple regression type.

Mode-Specific Models

Air travel volumes can be generated and distributed directly between city pairs by means of mode-specific models. In this analysis technique, the generation of air travel is considered entirely separate from the demand levels of other intercity and interregional movements. These models are usually of the regression type, with predictive variables related to the socioeconomic characteristics of the population and the economic characteristics of the cities themselves.

One form of this type of model can be written as follows:

$$T_{ij} = r\, P_i^s P_j^t d_{ij}^u l_i^v l_j^w \tag{2.21}$$

where

T_{ij} = volume of air passenger traffic between city i and city j
P_i, P_j = populations of cities i and j
d_{ij} = distance between i and j
l_i, l_j = respective portions of the cities' populations with income in excess of $10,000 annually
r, s, t, u, v, w = regression-calibrated parameters
(In logarithmic form, the structure of the equation is of standard linear type.)

The structure of equation 2.21 can be extended to include other applicable variables, including the economic characteristics of the cities. An examination of the model indicates that it is "backward looking," specific to the mode concerned—the calibrated value of the regression constants reflecting the relative levels of air and other technologies at the time of calibration. New technological options or radical changes in existing systems cannot be accommodated within this form of model, making it of questionable utility in the long term.

The Canadian Transport Commission produced a mode-specific time trend analysis of the form

$$\frac{F_{ij}}{P_i P_j} = \alpha + \beta t + Q_{ij} \tag{2.22}$$

where

F_{ij} = air trips between i and j
P_i = population at i
t = time in years
Q_{ij} = factor to adjust for quantum effects, such as new surface links

A mode-specific econometric model has been produced of the form

$$T_{ij} = a(\alpha_i \text{GNP}_i)^b (\alpha_j \text{GNP}_j)^c \beta_{ij}^d \left(F_{ij} + A + \frac{B}{F_{ij} - C} \right) \tag{2.23}$$

where

T_{ij} = air traffic between stations i and j
α = station share of GNP
β = country pair relation index
F = economy fare
A, B, C = currency scale constants
a, b, c, d = regression constants

A two-category model has been developed for both the business and leisure categories of air trips (10). These models are

Business

$$\left(\frac{\Pi}{P}\right)_B = A + M f_{yB} \left[R_1 (Z_0,\ Z_D)^P_{y-i} + \frac{R_2}{1 + [K(\overline{F}/I)^q} \right] \tag{2.24}$$

Leisure

$$\left(\frac{\Pi}{P}\right)_L = A + M f_{yL} \left[\frac{1}{1 + [K(\overline{F}/I)^q} \right] \tag{2.25}$$

where

II = air trips in year y for the stated purpose
P = population at origin
A, M = constants
f_{yB} = f (income, station affinity, propensity to invest and trade) in year y for business
R_1, R_2 = constants
Z_0, Z_D = ratios in real terms of origin and destination countries' economies relative to base date

$\overline{F}$ = mean total effective fare (fare, supplements, and travel time)
I = mean income of households of potential travelers in origin country
K = constant reflection surface route saturation
p, q = constants

A number of distribution models have been developed using *growth factors*. However, these are simplistic models, and it is difficult to justify their use in long-term forecasting. The reader is referred to the literature (42) for a reasonably complete discussion of these models.

Multimodal Models

In an attempt to overcome the shortcomings of mode-specific models, multimodal models that can simultaneously predict the generation rates, distribution patterns, and modal choice of travelers have been introduced. Perhaps the best known multimodal model is the abstract mode model, which emphasizes modal characteristics and is inherently capable of representing any existing or hypothetical modes by a set of variables that completely describe the pertinent attributes of a transport mode for the type of travel being considered. For passenger transport, therefore, variables such as travel time, frequency of service, and indices of comfort and safety may be used. For each mode under consideration, the abstract mode model represents the characteristics in a ratio relative to the best mode available. These ratios are then used as predictive variables in the calibrated equation. In one of its forms, the model can be written in the following way:

$$T_{kij} = \alpha_0 P_i^{\alpha_1} P_j^{\alpha_2} Y_i^{\alpha_3} Y_j^{\alpha_4} M_i^{\alpha_5} M_j^{\alpha_6} N_{ij}^{\alpha_7} \times f_1(H_{ij}, H_{kij}),\ f_2(C_{ij}, C_{kij}),\ f_3(D_{ij}, D_{kij}) \ldots \tag{2.26}$$

where

$\alpha_0, \alpha_1, \ldots, \alpha_7$ = regression constants
P_i, P_i = populations of the two nodes
Y_i, Y_j = median incomes at the two nodes
M_i, M_j = institutional (industrial) indices of the two nodes
H_{ij} = least required travel time
H_{kij} = travel time by the kth mode
N_{ij} = number of modes between i and j
C_{ij} = least cost of travel between i and j
C_{kij} = travel cost by the kth mode
D_{ij} = best departure frequency from i to j
D_{kij} = departure frequency by the kth mode

The advantage of abstract mode models is that they can be used to predict demand for some novel transport system that does not now exist but for which a set of characteristics can be specified. Such applications include predicting demand for short-haul V/STOL transportation or for interurban third-level carrier transportation and in the projection of the impact of new technologies for which only the performance standards can be specified at the time of analysis.

The abstract mode model was used to assign trips by mode in the California Corridor Study (43). This model was applied to absolute levels of demand derived from the following regression models:

Business

$$\ln(T_{ij}) = -7.32 + 0.29\ln(P_i) + 0.37\ln(P_j) + 0.89\ln(Y_{ij}) - 0.33\ln(t_{ij}) \quad (2.27)$$

Leisure

$$\ln(T_{ij}) = -15.65 + 0.31\ln(P_i) + 0.42\ln(P_j) + 1.40\ln(Y_{ij}) \quad (2.28)$$

where

i = origin
j = destination
P = zonal population
Y_{ij} = average zonal mean income of zones i and j
t_{ij} = shortest time between i and j

2.9 AIR FREIGHT DEMAND FORECASTS

National Projections

Theoretically, the movement of freight by any mode is likely to be more amenable to analysis and prediction than passenger travel, because the element of subjective choice or personal taste is lessened where freight movement is concerned. Additionally, social variables, which have been found to be so important in passenger demand models, are absent in the analysis of freight movement, greatly simplifying the procedure. However, the forecasting of freight movement by all modes, including air, is currently in its infancy, reflecting the great scarcity of historical data at a necessary level of detail. Consequently, aggregated projections at the national level are more easily made than disaggregated forecasts of freight movement between specific locations.

Using regression techniques, excellent correlations can be achieved from equations of the form

$$F = f(\mathrm{GNP}, \mathrm{P_A}) \quad (2.29)$$

where

F = domestic scheduled air freight traffic (revenue ton-miles)
GNP = gross national product
P_A = air freight rates

Regional Projections

At the level of predicting actual regional freight movements, the lack of specific data on city pairs has prevented the calibration of satisfactory models. Whereas large sums have been expended on the collection and analysis of urban passenger movement data, and to a lesser degree intercity passenger movement data, a similar amount of detailed information relating to freight traffic is not available. Ideally, freight traffic can be considered as moving according to some cost minimization rationale. In fact, air freight appears to be responsive to some generalized cost function composed of the following elements:

Freight tariff
Time in transit
Frequency of service
Time of scheduling
Security of product
Reliability of service
Quality of service
Value of freight per unit weight

The two principal approaches to freight forecasting are regression analysis and input–output analysis.

Regression Analysis

Regression analysis has been applied in the hope that the method would be as successful for freight as it has been with respect to passenger movements. Successful calibration has not been possible, however, because of the lack of adequate data on movements between specific city pairs. It has been proposed that freight movement is likely to be strongly correlated to a surplus of specific commodities at the origin ends of the trips and a demand for the same commodities at the destination ends. In the absence of detailed knowledge of commodity supply and demand, surrogate variables describing the industrial makeup of the city pairs are used, in conjunction with variables descriptive of the level of air service. Experience with these models has been less than satisfactory.

Input–Output Analysis

In the United States, some effort has been made to use the interindustry model, a macroeconomic model sometimes designated as input–output analysis. This model can be used to determine the supply and demand of commodities of different types for individual sectors of industry. This information, in turn, can be applied to the industrial structure of specific city pairs to determine the generation of freight flows. The model is still at an embryonic stage.

Distribution and Modal-Split Models

Distribution of freight movements has been carried out using gravity models to distribute the demand between origins and destinations. These standard procedures are described in readily accessible reference works.

In the sequence of models, the generation and distribution stages are followed by commodity modal choice. The most successful *modal choice* model should be a cost minimization approach that includes freight rates, damage costs, security, travel times, inventory and warehousing costs, commodity deterioration, and en route handling costs.

In summary, the determination of air freight models of all types is complicated by a number of factors:

1. The majority of air freight moves in the bellies of wide-bodied aircraft. The availability of spare belly space at a particular airport is likely to have a very important effect on freight rates—a basic factor affecting the generation of air cargo.

2. At a number of airports, freight originating in the market area of one airport is often trucked by road to another airport, where it is uplifted. The decision to use long road sectors is determined by factors such as frequency of air service and available cargo rates at the point of uplift. These trucks are even assigned "flight numbers" when they move cargo from terminals at certain airports to the freight terminals at larger airports and international hubs (e.g., Chicago O'Hare, London Heathrow and Frankfurt).
3. Freight throughput at an airport may be artificially high with respect to originating or destined freight if the airline chooses to use the airport as a hub. In this case, large volumes of transfer freight will move either across the apron or through the terminal.

2.10 GENERAL AVIATION FORECASTS

A considerable amount of subjective judgment goes into making general aviation forecasts, which rely heavily on national trends and forecasts and, to the extent such are available, local historical records. Three basic types of forecast are normally made: (1) number of based aircraft and registered pilots, (2) number of aircraft operations, and (3) passenger forecasts.

The forecast of based aircraft and registered pilots calls for an inventory of presently based aircraft, registered pilots, historical growth trends, and, in the United States, employment of FAA National Forecast Growth Ratios for General Aviation Based Aircraft (given for various areas of the United States). As with passenger traffic, the FAA publishes its own forecasts of general aviation activity nationally, at hubs, and at individual airports.

Another approach is to use the step-down ratio method, applying these ratios to national aggregate forecasts using historic market shares.

The FAA forecasts the total general aviation fleet with the following models:

$$\Delta f_{t+1} = S^B_{t+1} + S^P_{t+1} - X_{t+1} + A_{t+1} - I_{t+1} \ldots \tag{2.30}$$

where

f = total active fleet
Δf_{t+1} = estimate of change in the active fleet between time t and time $t + 1$
S^B = sales of business aircraft
S^P = sales of personal aircraft
X = attrition
A = inactive-to-active status
I = active-to-inactive status

and

$$S^B_{t+1} = f_1\left(\frac{AP_{t+1}}{P_{t+1}},\ r_{t+1},\ W_{t+1}\right)\cdots \tag{2.31}$$

$$S^B_{t+1} = f_2\left(\frac{AP_{t+1}}{P_{t+1}},\ r_{t+1},\ Y_{t+1}\right)\cdots \tag{2.32}$$

where

AP = aircraft price index
P = implicit GNP deflator
r = rate of interest
Y = income
W = measure of business activity

The number of aircraft operations (local and itinerant) can be forecast from actual counts of present activities or, in the United States, from FAA surveys (Towered Airports) and by obtaining a relationship between the number of operations per based aircraft. If local data are not available, the following FAA data could be used:

	Annual operations per based aircraft		
Type	Typical low	Median	Typical high
Local operations	170	375	690
Itinerant operations (nontower airport)	125	210	450
Itinerant operations (tower airport)	225	425	745

Passenger forecasts are made by multiplying the average number of passengers per plane by half the total number of general aviation itinerant operations.

A brief treatment of modeling general aviation activity is contained in *Manual on Air Traffic Forecasting* (3). More detailed analysis of case studies is found in the TRB literature (e.g., 4, 6).

The FAA conducted analysis to estimate aircraft operations at small non-towered GA airports in the United States (44). It is typically difficult to estimate traffic at small non-towered airports that serve only GA traffic. The FAA Office of Aviation Policy and Plans, initiated development of an estimating model for GA operations at small airports based on the relationship between demographic characteristics of the area surrounding the airport, some airport measures such as based aircraft, and the GA aviation activity at the airport. This project was to identify common characteristics among a group of towered GA airports and then use these characteristics to build models of airport activity at non-towered, less monitored GA airports.

While this model is not designed as a forecast model per se, but combined with forecasts of the independent variables for the airport and its region it could provide an estimate of GA activity forecasts. The model is based on the assumption that aircraft activity at GA airports is related to demographic characteristics of the airport region along with certain operational characteristics of the airport. The region's demographic features are relatively easy to itemize and data are more readily available. The data set used to estimate the model contains 127 small towered GA airports, for which accurate tower counts exist, and 105 non-towered GA airports for which activity estimates have been made by state aviation authorities using various methods of sampling and extrapolation to a full year of data. For these airports data items used were developed from U.S. Census Bureau data and other databases.

The estimating equation, based on data from the 232 small towered and non-towered GA airports is:

$$\text{GAOPS} = -571 + 355\,\text{BA} - 0.46\,\text{BA2} - 40{,}510\,\%\text{in100mi} + 3{,}795\,\text{VITFSnum} + 0.001\,\text{Pop100} - 8{,}587\,\text{WACAORAK} + 24{,}102 + 13{,}674\,\text{TOWDUM} \tag{2.33}$$

where

BA : Based aircraft
BA^2 : Square of BA
%in100mi : Airport's percentage of BA within 100 mi
VITFSnum : Number of Part 141-certificated flight schools at airport
Pop100 : Population within 100 mi of airport
WACAORAK : Airports in California, Oregon, Washington, and Alaska
Pop25/100 : Ratio of population within 25 mi to population within 100 mi
TOWDUM : Tower at airport

The model statistical parametric results in terms of t-value are (45): Constant (−0.25); BA (8.41); BA2 (−3.83); %in 100mi (−2.79); VITFSnum (1.87); Pop100 (3.48); WACAORAK (−3.61); Pop25/100; (2.67) and TOWDUM (6.44). The R^2 value of the model is (0.743).

The model was then assessed against actual filing data for 2,789 GA airports in the United States. This GA airport activity estimating model provided valuable new information to state or regional planning organizations with an interest in GA, and could provide a direct connection between the level of activity data at a small GA airport and the demographic features of the airport's environs.

2.11 ROUTE CHOICE MODELS

Another important subject of demand modeling is predicting airline traffic through existing hubs or even potential hubs. The very large, relative volumes of transit and transfer traffic cannot be predicted satisfactorily using the techniques previously described in this chapter. The trips are generated externally to the hub and are not dependent on the socioeconomic characteristics of the area or region in which the hub is situated. Instead, the hub attracts traffic which is related to the level of air service provided by the hubbing facility. Variables which have been used to describe this service level are:

- Frequency of departures
- Connection time at the hub
- Capacity of route in terms of available seats
- Average journey time through the hub

The models which have been calibrated to describe and to forecast route choice are extensive and are of complex mathematical formulation. A model calibrated in the United Kingdom on British CAA data was of the form (46)

$$p(a, r) = p(r/a),\ p(a) \tag{2.34}$$

$$p(r/a) = \frac{\exp\left[V\,(a, r)\right]}{\exp\,\Phi^R(a)} \tag{2.35}$$

$$p(a) = \frac{\exp[\delta^R \Phi^R(a)]}{\sum_{a^* E A} \exp[\delta^R \Phi^R(a^*)]} \tag{2.36}$$

where

A = set of departure airports
$p(a, r)$ = probability of a passenger using a route r served by a departure airport a
$p(r/a)$ = conditional probability of choosing a route served from a
$p(a)$ = marginal probability of a
Φ^R = expected maximum utility (EMU) or inclusive value from a set of routes R
R = set of routes available from each airport
δ^R = inclusive value (or EMU) coefficient, which measures the correlation among the random terms due to route-type similarities at a departure airport, a
V = utility function of form
= β_1 (access time) + β_2 (weekly flight frequency on a route)
+ β_3 (average connection time at hub airport)
+ β_4 (weekly available aircraft seats on a route)
+ β_5 (average journey time)
+ β_6 (route specific constant)

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3

Characteristics of Aircraft As They Affect Airports*

3.1 RELATIONSHIPS BETWEEN AIRCRAFT AND AIRPORTS

In a conventional air transport system, aircraft and airports are dependent on each other in providing a service for the passenger. In the past, the system evolved largely with separate planning of the airport, route structuring, and aircraft technology. Advances in technology, the major factor in the growth of the mode, have been quickly utilized by the airlines in expanding their route structures and improving their efficiency in terms of real cost per seat kilometer supplied. Those responsible for the provision of airports have sought to plan, design, and construct the facilities necessary to ensure that they were not left behind in full participation in this high-growth industry.

Advances in engine and airframe technology have allowed significant reduction in the real cost of air travel and at the same time have led to improvements in system performance. These improvements in speed, range, ticket price, comfort, and reliability have been responsible for the high growth rates. Historically, the operating costs of the aircraft have constituted 85% of the operating costs of the entire air transport system; the airports have contributed 10%, and the remaining 5% has been spent on navigation charges and overheads of governmental control. This has resulted in a natural tendency for the airports to accommodate any changes in aircraft design and performance that could maintain the trend to lower aircraft direct operating cost (DOC). The result is illustrated in Figure 3.1, which shows how the runway lengths of major international airports would have had to change to conform to the requirements of the expected operational fleet. Up until the early 1960s, runway lengths were continually increasing. With the widespread introduction of turbofan aircraft and the gradual retirement of pure jet equipment, runway length requirements first stabilized and subsequently gradually decreased. The widely adopted policy of permitting aircraft DOC to dominate the design of the air transport system was reversed in the late 1960s because of a number of factors. Environmental considerations, focused, in the first place, on the neighborhood of the airport, caused compromises between, on the one hand, the design of aircraft and, on the other, the scale and location of the airport. In the 1990s much speculation took place about the design of future aircraft carrying 800–1000 passengers, but in 2009, the Airbus 380 with a maximum certified capacity of 853 passengers was introduced into service. There had been considerable resistance from airport operators to the introduction of aircraft with double-decked access or greatly increased wingspans. Rising

*Originally authored by Robert.E.Caves, the chapter in this edition has been updated by Michael Makariou.

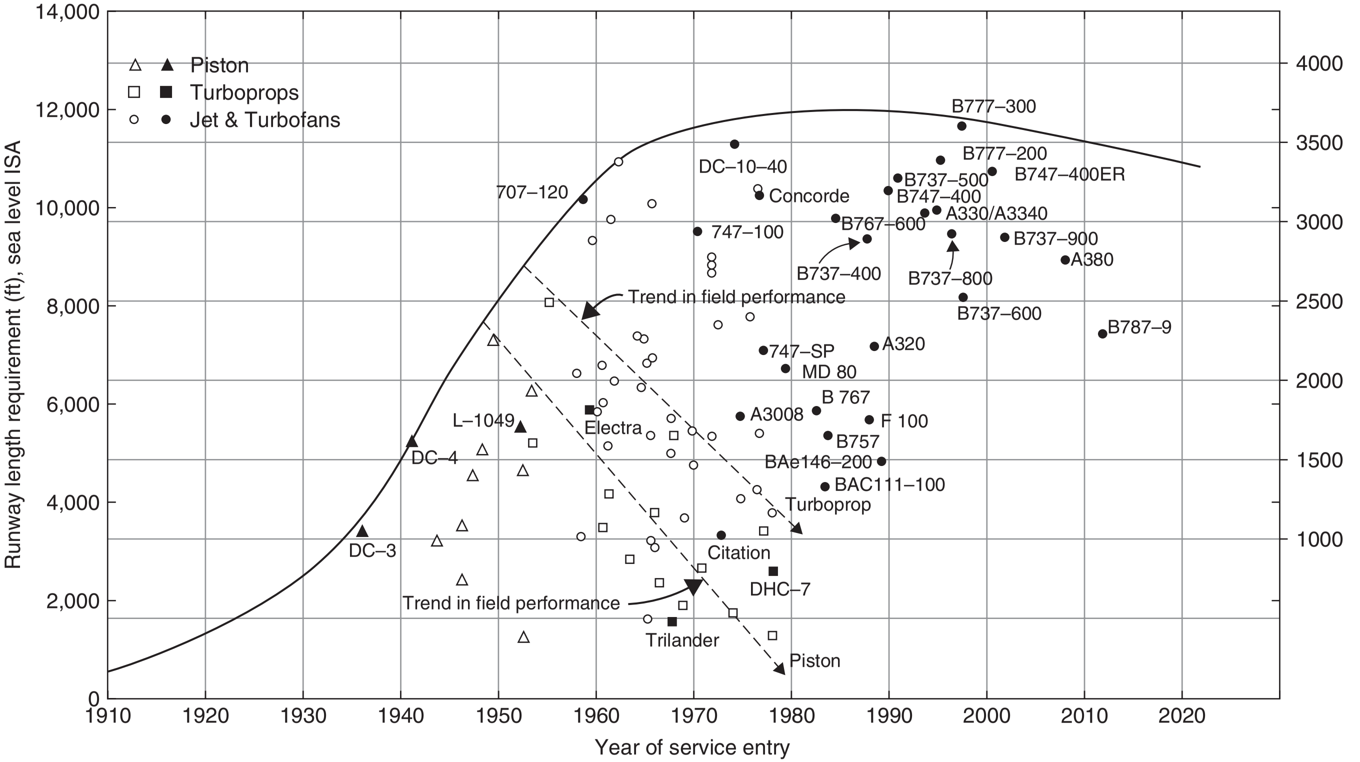

Figure 3.1 Trends in runway length.

land values and construction costs increased the airport contribution to the total system capital costs, which was already considerably greater than its contribution to operating costs. The increasing cost and scarcity of capital added importance to the correct definition of the role of the airport to the total system. Additionally, there developed a tendency to bring into the air route system more and more airports with relatively low frequency operation and relatively short stage lengths. The low utilization of such facilities implies a greater contribution of the airports to the total system cost and made it unreasonable for aircraft designers to call for continued increases of runway length.

Short-range aircraft need less runway than the long-range type, since there is a smaller fuel requirement. In addition, advances in the technology of producing high lift for takeoff and landing allow a further reduction in the runway requirement without too much penalty in DOC. Therefore, the pressures from the airport to reduce runway length requirements can be met by both the aircraft manufacturer and the operator. New runways are often shorter, where the main market is for short-range operations.

At the same time, the growth in runway length for long-range operations has leveled off as new demands for increased range no longer appear* and because the operating costs for this type of flight are acceptably low. This peaking of runway length requirement is depicted in Figure 3.1.

Runway length is only one of the many areas in which the requirements of aircraft cost, performance, or design affect airport layout. Other important areas are the number and orientation of required runways, the structural and geometric design of pavements, including taxiways, exits, and aprons, and the location and configuration of cargo and passenger terminals. All contribute to or control airport layout and capacity requirements. These aspects, together with aspects of noise control, are discussed in this and subsequent chapters.

3.2 THE INFLUENCE OF AIRCRAFT DESIGN ON RUNWAY LENGTH

All commercial aircraft design has its roots in the development of propulsion systems and the application of aerodynamic theory. In parallel with advances in type and efficiency of aircraft power plants (Figure 3.2) have come increases in absolute power. Aerodynamic advances have been made allowing the full use of propulsive improvements. In particular, speed capability has increased (Figure 3.3). After the introduction of the supersonic Concorde into commercial service in 1976, it became clear that supersonic flight was not commercially viable. This meant that the development of air transport aircraft for the period 1970–2010 was concentrated on top cruising speeds within the range of 0.9–0.85 Mach. The combination of improvements in speed and absolute size has resulted in the upward trend in seat mile per hour productivity within the envelope shown in Figure 3.4. Combined with improvements in engine fuel efficiency and other economies of scale, these factors have generated a significant long-term reduction in real costs per passenger kilometer and tonne kilometer.

In the days of the DC-3, a wing design that gave economical cruising flight also allowed a reasonably short field length, because the aircraft could sustain flight at quite a low speed.

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*Between short- and long-haul designs, the proportion of empty to maximum weight varies from 63 to 49%, while the proportion of fuel to maximum weight varies from 20 to 42%, though some of this difference is due to the smaller size of the shorter range aircraft.

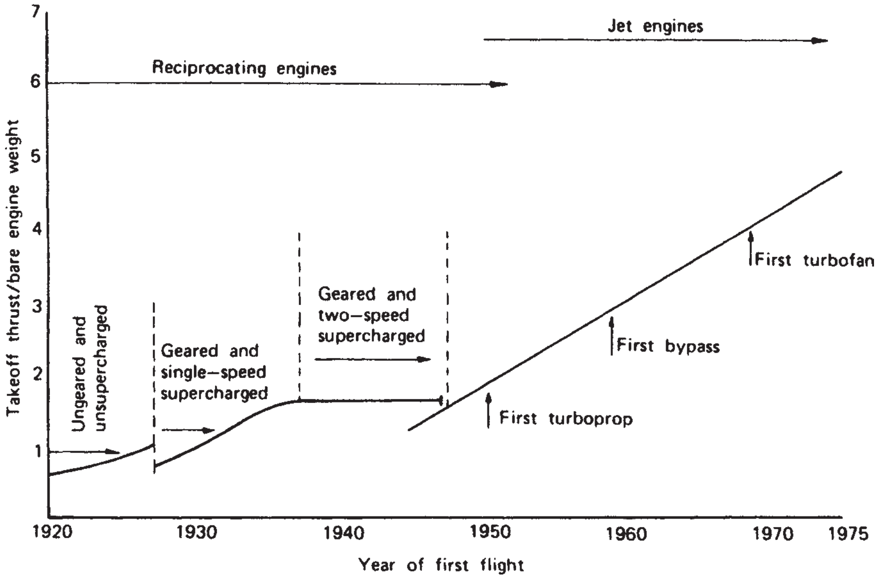

Figure 3.2 Trends in ratios of takeoff thrust to bare engine weight.

For level flight,

$$\text{lift } (= \text{weight})\ \alpha\ \rho\ V^2 S C_L \tag{3.1}$$

where

ρ = air density
V = forward speed of the aircraft
S = area of the wing
C_L = coefficient of lift (nondimensional); approximately proportional to the angle of attack of the wing

or

$$\frac{W}{S} \propto \rho V^2 C_L$$

where

W = Aircraft weight
W/S = wing loading

Thus, at a given value of C_L, higher speeds allow a smaller wing, and hence lower weight and drag. Unfortunately, high-speed wings tend to have a lower maximum value of C_L (at which the wing stalls and loses lift abruptly), so the ratio of cruise speed to stall speed is naturally lower, and this leads to much higher takeoff and approach speeds. Even if it were possible to have infinitely long runways, high approach speeds would be unacceptable because of problems associated with landing gear design, pilot judgment, airspace requirements, and air traffic control. Hence, high-lift devices are employed to reduce the stalling speed by increasing the effective wing area and by increasing the maximum value of C_L.

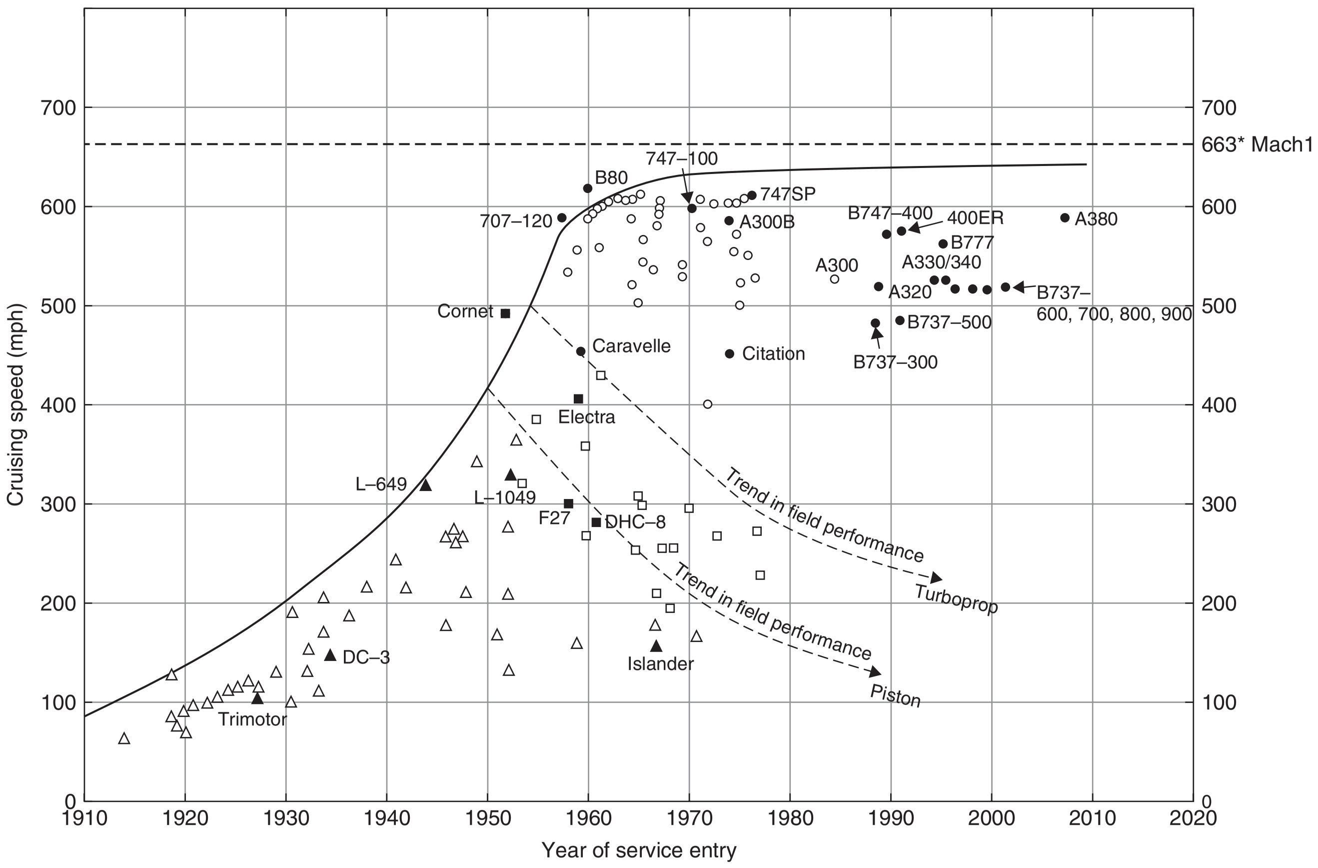

Figure 3.3 Trends in cruising speeds of subsonic passenger transport aircraft.

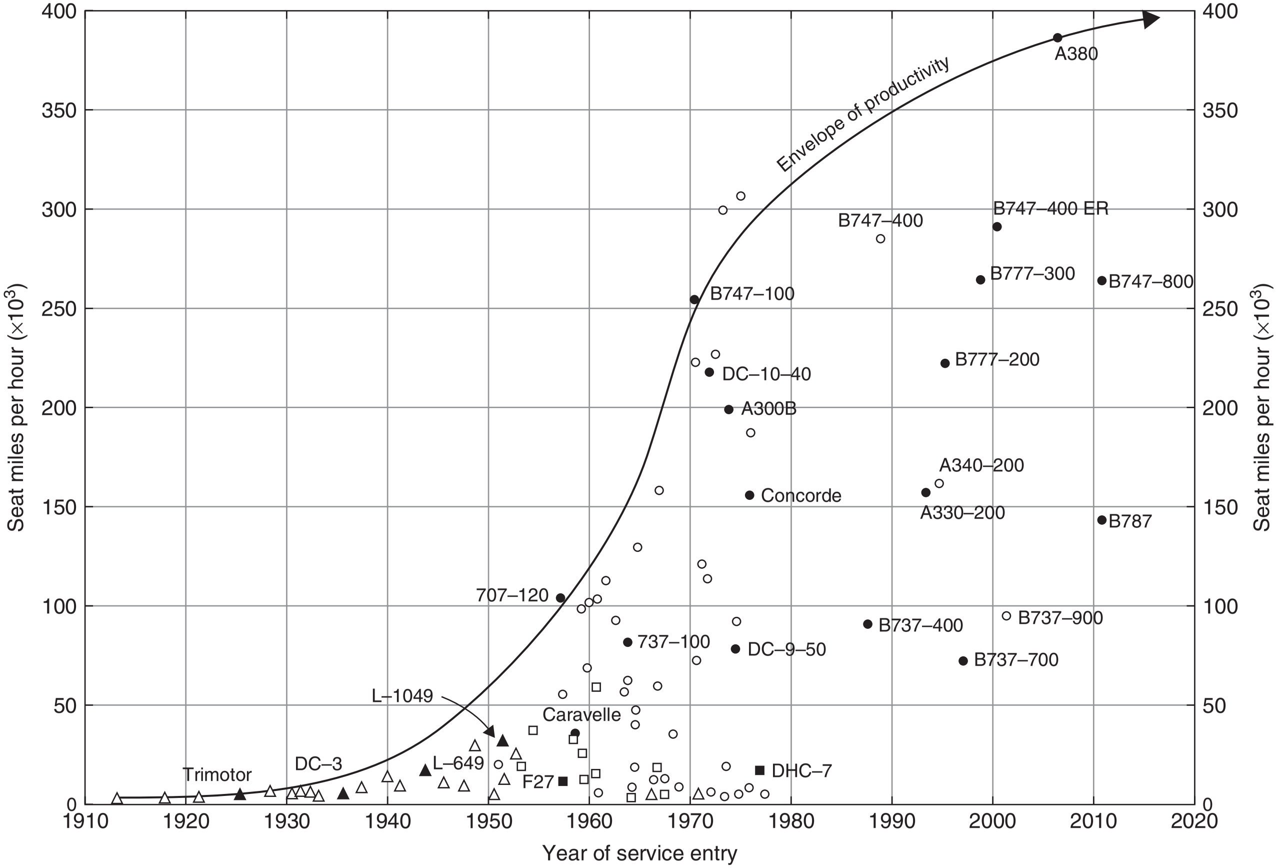

Figure 3.4 Trends in productivity in terms of passenger seat miles per hour.

A measure of the scale of penalty involved in compromises between aircraft design and runway length provision can be gained from the estimate that a twin turbofan aircraft designed for a 1000-nautical-mi (1850-km) range operating from a 6000-ft (1830-m) runway is penalized by approximately 23%, compared with an aircraft of similar specification designed to unlimited field length.* The penalty arises from a combination of increased wing area, the high-lift devices, extra thrust for takeoff, and extra fuel. The high-lift devices have more influence on the landing field length, and the extra thrust is of more value on takeoff. The increase in wing area provides a lower minimum flying speed, regardless of the amount of flap or slat being used, thus reducing both the takeoff and landing field length requirements. The takeoff usually leads to the greater field requirement, except with aircraft designed exclusively for short stage lengths; in the latter case, the maximum landing weight is usually very similar to the maximum takeoff weight.

Figures 3.5 and 3.6 illustrate the tendencies for aircraft designed to different field lengths to use different power-to-weight ratios and wing loadings. From the range of types of powerplant and categories of operation selected, it can be seen that propeller-driven aircraft achieve adequate field performance without increased thrust-to-weight ratio because of their use of relatively low wing loadings and the high static efficiency of their low disc loading.† Similarly, the helicopter achieves vertical takeoff with the same installed power as a light conventional aircraft of the same weight. On the other hand, pure jet aircraft require much higher installed thrust if their takeoff field length is to be reduced substantially, with commensurate reductions in wing loading, or more powerful flaps if the landing field length is to be similarly reduced.

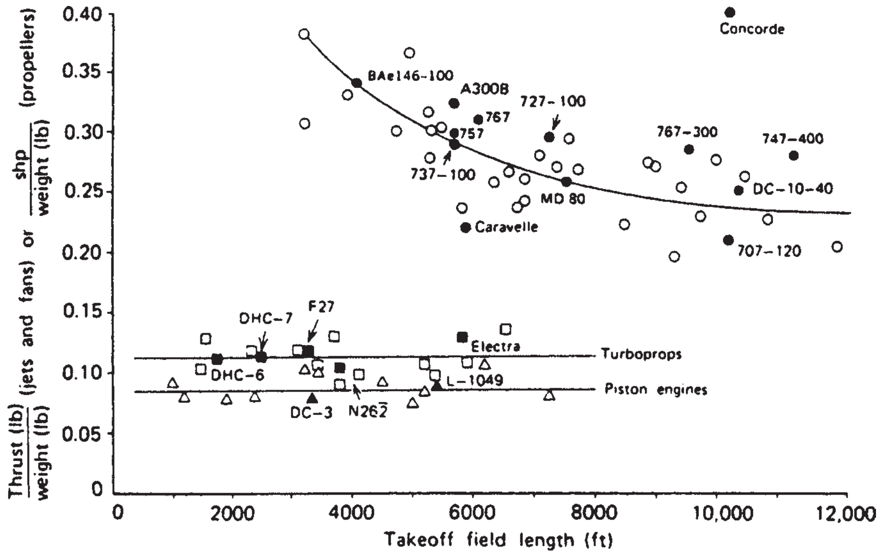

Figure 3.5 Effect of power-to-weight ratio on field length.

*In this case, "productivity" is defined as scat miles per hour per pound all-up-weight (AUW).

†Disc loading is the thrust developed by a fan per unit frontal swept area. Static efficiency is inversely proportional to disc loading.

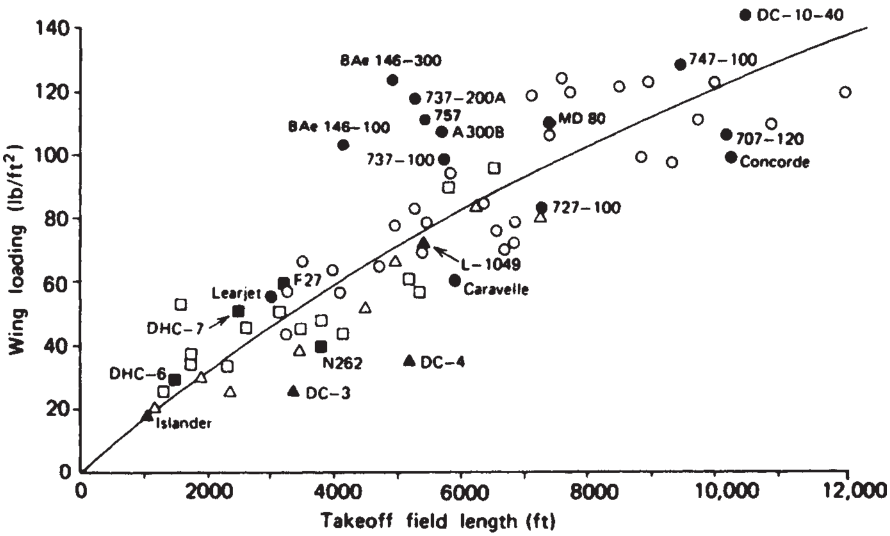

Figure 3.6 Effect of wing loading on field length.

Requirements of Current Aircraft Types

In the previous discussion, we have attempted to indicate the interactions that take place in aircraft design between the field length and other factors. There are fundamentally three different types of interaction. With long-range aircraft, a long takeoff is dictated by the large fuel requirements. Medium- and short-range aircraft for trunk and local airline operation have to compromise their cruise performance with the need to use a large number of medium-length fields. Aircraft for feeder and general aviation roles normally operate over short ranges where cruise speed is not essential; thus, a low wing loading is permissible, and they can operate with short field lengths without a significant design penalty.

Tables 3.1a, b, and c present the characteristics of a wide range of present-day aircraft. The variation in Federal Air Regulation (FAR) Landing and Takeoff Distances illustrates the preceding discussion. It is important to realize that the speeds, field lengths, weights, and maximum stage lengths given are all for quite specific conditions of operation, which are held constant over the range of aircraft types for ease of comparison. Cases of variation from these specific conditions having an important effect on the field length requirements are discussed in detail below.

Field Length Regulations—Air Transport Aircraft

The field lengths listed in Table 3.1 are determined not only on the basis of the aircraft's design capability but also by the safety regulations made by the responsible bodies in the individual member countries of the ICAO. In the United States, the regulating authority is the FAA. The ICAO issues worldwide advisories that are similar in philosophy and content to the FAA regulations. Field length requirements for a given class of aircraft are based on the performance of several critical and rigidly specified operations.

Table 3.1a Aircraft Characteristics of Air Carriers: Powerplant, Dimensions, and Number of Passengers

		Dimensions (m)						Number of
Aircraft Type	Powerplant	Span	Length	Height (max)	Turning Radius[a]	Wheel Base	Track	Passengers (Average)
Short/Medium Haul								
B737-300	2 × 22,000 lb	28.88	32.18	11.15	14.1 (65°)	12.45	5.23	128 (2-class)
B737-400	2 × 23,500 lb	28.88	35.23	11.15	16 (65°)	14.27	5.23	146 (2-class)
B737-900	2 × 27,300 lb	35.79	40.67	12.37	19.2 (65°)	17.17	5.72	177 (2-class)
A 310-200	2 × 53,200 lb	43.89	46.66	15.82	31.67	12.47	9.6	265
A320	2 × 27,000 lb	34.1	37.57	12.45	14.3 (65°)	12.64	7.59	164
A321	2 × 30,000 lb	34.1	44.5	12.65	14.3 (65°)	16.9	7.59	200
MD 90-30		32.87	43.03	9.5	26.2 (65°)	23.52	5.08	172
B757-200	2 × 37,400 lb	38.06	47.32	13.74	20.6 (65°)	18.29	7.32	186
F28-2000	2 × 9,850 lb	23.56	29.62	8.87	17.68	10.33	5.03	79
BAe146-200	4 × 6,700 lb	26.33	28.56	8.63	12.56	11.22	4.72	106
Long Haul								
747-400	4 × 58,000 lb	64.94	70.67	19.51	26.3 (55°)	25.62	11	416 (3-class)
B747-400ER	4 × 59,500 lb	64.94	70.67	19.51	26.3 (55°)	25.62	11	416 (3-class)
B777-200	2 × 84,300 lb	60.93	63.73	18.76	29.9 (60°)	25.88	10.97	305 (3-class)
B777-300	2 × 98,000 lb	60.93	73.86	18.76	35.9 (60°)	31.22	10.97	368 (3-class)
B767-200	2 × 52,000 lb	47.57	48.51	16.13	23.0 (60°)	19.69	9.3	296 (2-class)
B767-300	2 × 60,600 lb	47.57	54.94	16.03	26.8 (60°)	22.76	9.3	261 (2-class)
B767-300ER	2 × 61,500 lb	47.57	54.94	16.03	26.8 (60°)	22.76	9.3	296 (2-class)
B767-400ER	2 × 60,600 lb	51.92	61.37	17.01	30.7 (60°)	26.2	9.3	296 (2-class)
B787-9	2 × 53,000 lb	60.12	55.91	16.91		23.78	9.8	224
A330-300	2 × 72,000 lb	60.304	63.689	17.18	27.4 (60°)	25.37	10.684	335
A340-500	4 × 56,000 lb	63.45	67.93	17.53	32.3 (65°)	27.583	10.684	313 (3-class)
A340-600	4 × 60,000 lb	63.45	75.362	17.43	38.2 (65°)	33.637	10.864	380 (3-class)
A380-800	4 × 80,000 lb	79.75	72.727	24.1	39.6 (55°)	31.727	12.456	555 (3-class)
Commuters								
Brasilia	2 × 1,500 eshp	19.69	19.72	6.31	17.8	6.8	6.07	30
SAAB 2000	2 × 3,096 kW	24.77	27.28	7.72	12.5	7.14	6.71	50–58
F27-500	2 × 2,140 eshp	29.01	25.08	28.68.72	20.1	9.63	7.22	56
DHC-7	4 × 1,174 eshp	28.35	24.48	7.99	18.9	8.38	7.16	54
DHC-8- 100	2 × 2,000 eshp	25.89	22.25	7.49	9.22 (60°)	7.95	7.88	56
ATR 72-500	2 × 2,475 eshp	27.05	27.17	7.65	NA	10.77	4.01	66

[a]Max nose wheel steering angles between 55° and 65°.
Source: References 5, 6, manufacturers' brochures.

Table 3.1b Aircraft Characteristics of Air Carriers: Weight, Field Length, Cruise Speed, and Payload

Aircraft Type	Weight (lb × 1000)			FAR Field Length (m) International Standard Atmosphere ISA Sea Level, 15°C		Cruise Speed (knots)	Payload Range: International Standard Atmosphere, Still Air Zero Rwy Gradient (Note 1)			
							Range at Max Payload		Max Range Payload	
	Takeoff (max)	Landing (max)	Empty, Operating	Takeoff	Landing		Nautical mi	lb × 1000	Nautical mi	lb × 1000
Short/Medium Haul										
B737-300	139.5	115.8	72.54	2200	1680	427	1950	34	2750	9
B737-400	150	124	74.17	2550	1880	450	1740	45	2500	35
B737-900	174.2	146.3	94.58	2300	2100	450	900	45.4	2900	23
A310-200	291	261	169.5	1600	1400	488	2210	69.7	4430	27.1
A320-200	166.5	142.2	82.1	2050	1460	450	1880	45.6	2680	34
A321-200	196.2	166.5	103.6	2750	1625	450	1350	54	2350	38
MD 90-30	156	142	88.17	2150	1850	438	1200	41.8	2200	29
B757-200	220	198	129.8	1890	1470	494	1200	64.0	4660	11.8
F 28 2000										
BAe146-200	88.3	77	47.2	1510	1060	419	1,535	22.1	1646	20.9
Long Haul										
B747-400	875	630	396.3	3000	2400	493	5200	148.7	7000	91
B474-400ER	910	652	406.9	3350	2500	495	6200	148.1	8000	78
B777-200	632.5	455	299	3400	1840	490	5800	131	8650	56
B777-300	660	524	351.7	3250	2175	490	3600	143.3	5500	96
B767-200	300	270	178.3	1722	1435	470	2220	67.7	4900	15.9
B767-300	350	300	189.75	2600	1720	470	2250	88.25	4400	51
B767-300ER	412	320	198.44	3200	1910	470	4100	90	6400	46
B767-400ER	450	350	229	3120	2170	470	3800	101	5500	61
B787-9	547	NA	254	NA	NA	487	8000	NA	NA	NA

(*continues*)

Table 3.1b (*continued*)

Aircraft Type	Weight (lb × 1000) Takeoff (max)	Weight (lb × 1000) Landing (max)	Weight (lb × 1000) Empty, Operating	FAR Field Length (m) International Standard Atmosphere ISA Sea Level, 15°C Takeoff	FAR Field Length (m) International Standard Atmosphere ISA Sea Level, 15°C Landing	Cruise Speed (knots)	Payload Range: International Standard Atmosphere, Still Air Zero Rwy Gradient (Note 1) Range at Max Payload Nautical mi	Range at Max Payload lb × 1000	Max Range Payload Nautical mi	Max Range Payload lb × 1000
A330-300	478.4	394.6	279.3	2250	1740	473	3300	115	5500	62
A340-500	804.7	520.3	370.1	3150	2000	479	7000	54	9100	23
A340-600	804.7	560	384.2	3150	2125	479	5600	145.5	7850	69.5
A380-800	1234.6	851	610.4	2900	1900	495	6500	185.5	8800	76
Commuters										
Brasilia	21.7	21.7	12.3	1080	1220	287	575	6.0	1570	3.2
SAAB 2000	50.27	48.5	30.2	1300	1380	NA	820	50.26	1280	10.5
F27-500	45	42	26.3	1670	1000	248	825	13.2	2180	5.66
DHC-D7	41	39	24.4	550	550	238	637	11.1	1740	6.44
DHC8-100	34	33.9	22	1100	880	238	540	9	11.7	6.9
ATR 72-500	49.6	49.3	28.55	1290	1070	276	300	16.65	NA	NA

[a]Standard reserves for holding and diversion included. NA, not available, Jan 2010. Landing Distances: Flaps 30°, wet runway.
Source: References 5, 6, manufacturers' brochures.

Table 3.1c Characteristics of Selected General Aviation Aircraft

Aircraft	Length, ft	Span, ft	Height, ft	No. of Passengers	Maximum Takeoff Weight, lb	Maximum Landing Weight, lb	Empty Operating Weight, lb	FAR Takeoff Length, m	FAR Landing Length	Range nm
Gulfstream 150	56.76	55.58	19.09	8	26,100	21,700	15,100	1,524	878 m	2950
Gulfstream 650	99.74	99.57	25.33	18	99,600	83,500	54,000	1,829	914 m	7000
Hawker 850XP	51.18	54.33	18.08	8	28,000	23,350	18,450	1,534	808 m	2642
Learjet 40XR	55.56	47.78	14.13	6	21,000	19,200	13,861	1,426	811 m	1723
Beech Super King	43.83	54.5	14.33	13	12,500	15,000	9,110	1,006	442 m	1400-1974
Air 300L	13.36 m	16.61 m	4.36 m		5,672 kg	6,806 kg	4,133 kg			
Beech 400A	48.25	54.5	14.33	8	16,100	15,700	10,250			
	13.36 m	16.61 m	4.36 m		7,305 kg	7,123 kg	4,651 kg	1308	1072 m	1900
Twin Otter	51.7	65	18.6	20	12,500	12,500	6,700	366	320 m	560
Cessna Mustang	40.58	43.17	13.42	4–6	8,645		5,300	949	729 m	1167
	12.37 m	13.16 m	4.09 m		39,22 kg		2,405 kg			
Cessna	50.17	53.33	15.17	6–8	13,870	12,750	8,700	970	845 m	1875
Citation CJ3+	15.29 m	16.25 m	4.62 m		6,293 kg	5,785 kg	3,947 kg			
Cessna Citation X	72.33	63.92	19.25	8–10	36,100	31,800	21,700	1567	1040 m	5950
	22.05 m	19.48 m	5.86 m		16,397 kg	14,428 kg	9,846 kg			
Dassault Falcon 7X	76.08	86	25.8	8–12	69,000		34,072	1678	690 m	5950
	23.19 m	26.21 m	7.86 m		31,307 kg		15,459 kg			
Dornier 228-212	47.63	49.5	15.83	8–12	14,550	13,448	8,243	793	450 m	600-1080
	14.52 m	15.09 m	4.82 m		6,602 kg	6,102 kg	3,740 kg			
Embraer 110	49.58	50.28	16.17	18–21	13,010	12,563	8,005	975	430 m	400-920
Bandeirante	15.11 m	15.32 m	4.92		5,903 kg	5,700 kg	3,632 kg			

In essence, an aircraft type is required to demonstrate the field length required for the following cases: (a) to complete a takeoff to 35 ft (11 m) altitude with all engines operating, (b) to complete a takeoff to 35 ft (11 m) altitude with an engine failure at a critical point, (c) to stop after aborting a takeoff with an engine failure at the same critical point, and (d) to stop after landing from a height of 50 ft (15 m).

The demonstrations take place under carefully controlled conditions of flying speed, aircraft weight and configuration, and airfield altitude and temperature. Safety margins are then added to these demonstrated distances to allow for variation in pilot performance, aircraft performance, and environmental conditions in service. The margins are typically 15% in the all-engine-operating takeoff case and 67% in the landing case; the difference is due mostly to the extra difficulty of controlling and monitoring an approach compared with the relatively fixed and known conditions on takeoff. It is also recognized that the in-service performance of old aircraft, while conforming to adequate maintenance procedures, will be less than the performance of new aircraft under certification demonstrations.

Extra margins are implicit in the procedure just described, insofar as most airports accepting commercial flights do not have obstructions at the ends of their fields and most airfields have either visual or electronic guidance on the approach path. However, experience has shown that margins of this order are necessary if a satisfactorily low rate of hazardous incidents associated with field length is to be maintained. In this way, a required field length is assigned to each certificated aircraft, for every practical combination of variations in weight, altitude, and temperature, and the information is published in the official flight manual as a series of charts. This information is collated by the FAA (2) and the ICAO (3). Figure 3.7 is a modified example taken from the FAA's runway length requirements for airport design. The example shown indicates the runway lengths required at 1000 ft elevation and STD + 15C for a B737-900 takeoff with maximum design takeoff weight (174,200 lb) and for takeoff with a restricted takeoff weight of 150,000 lb.* The FAA provides a companion chart for calculating the landing runway length required.

Published field length requirements can be used for the following purposes:

1. Checking the ability of an aircraft to take a specified payload from, or to land at, a specified airfield in specified environmental conditions
2. Calculating the allowable maximum payload that may be moved under those specific conditions when the payload is limited by available field lengths
3. Planning the field lengths that must be provided at an airport to allow operation of a specific aircraft type from that airport to specific destinations on a specified percentage of occasions annually (determined by local environmental history), with a specified percentage of its maximum payload

This chapter is mostly concerned with the last of these purposes. In this case, the altitude and temperature are fixed, and the runway slope and obstacles below the flight path are largely predetermined. It is unwise to rely on any advantage from wind effects, and equipment is provided to ensure that aircraft performance is not compromised by runway surface conditions. Then the main variables are runway length, aircraft type,

*All major manufacturers include runway design information in the airport design manuals for each of their aircraft types, but the actual approved field lengths are to be found in the individual operator's flight manual.

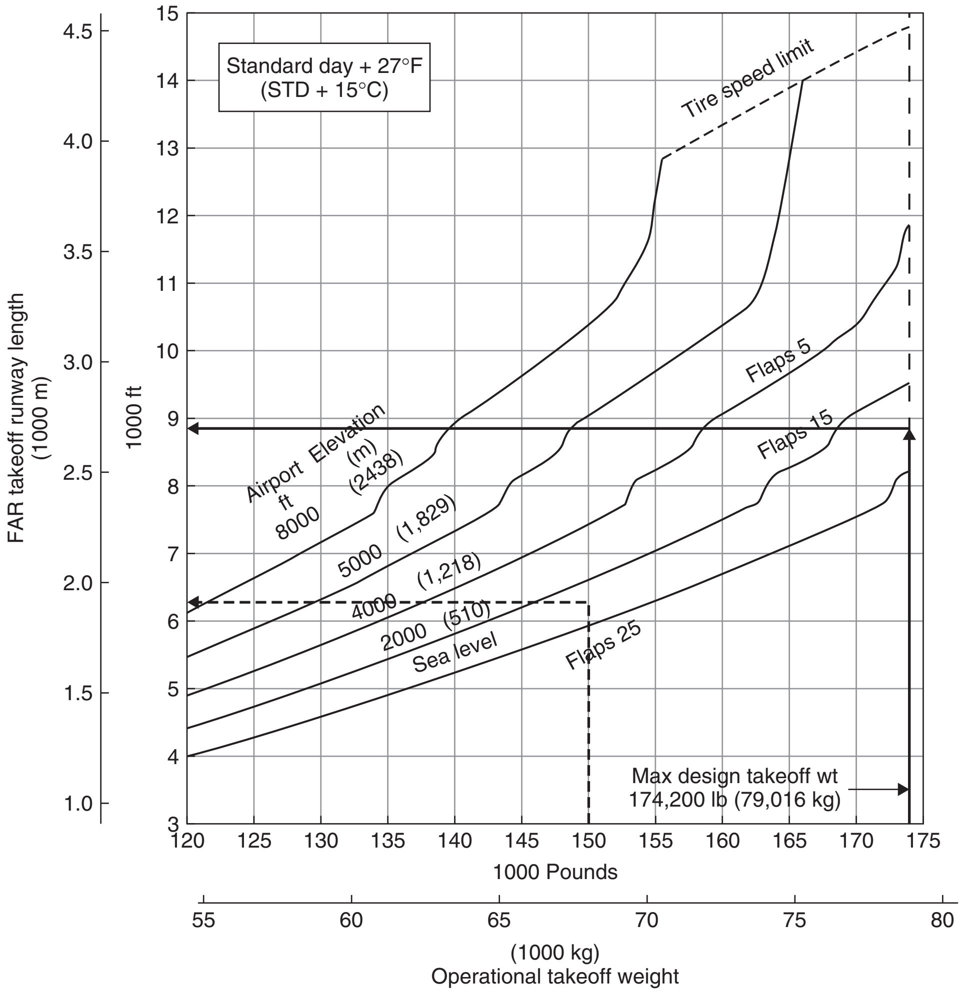

Figure 3.7 Takeoff runway length chart for Boeing 737-900 (1).

and aircraft weight, the weight being adjustable between useful payload and fuel, as described below.

There are, however, two further variables to be considered in defining the field length requirement. The takeoff distances that must be demonstrated for transport category aircraft are presented in Figure 3.8; the speeds to be controlled during the demonstration are symbolized as follows:

V_1 = takeoff decision speed chosen by the aircraft manufacturers: $>1.10V_{mc}$, <speed at which brakes overload, $<V_R$, $<1.10\ V_s$

V_{mc} = minimum control speed: minimum speed at which engine failure can occur and still allow straight flight at this speed in a fully controlled manner

V_{LOF} = liftoff speed: $\geq 1.1\ V_{mu}$ ($\geq 1.05V_{mu}$ with one engine out)

V_{mu} = minimum unstick speed: >minimum speed that allows safe continuation of the takeoff

V_2 = takeoff safety speed at 35 ft (11 m) $\geq$ $1.2V_s$, $\geq 1.1V_{mc}$

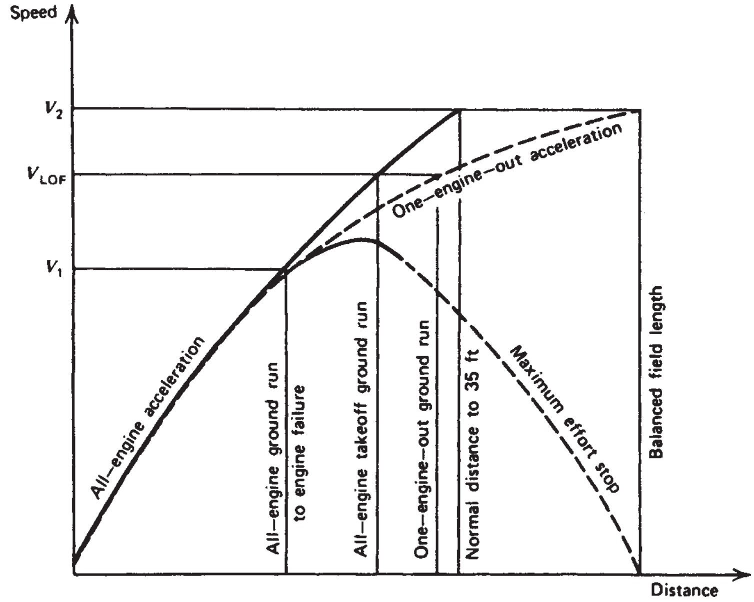

Figure 3.8 Takeoff field length demonstration requirements for transport category aircraft (2, 3).

V_s = stall speed in takeoff configuration
V_R = speed at which nosewheel can be lifted from runway and $\geq V_1$, $\geq 1.05\ V_{mc}$

The first variable is V_1, which can be chosen by the manufacturer within the limits of controllability, rotation speed, and brake failure. If the engine fails before this speed is reached, the pilot must abort the takeoff; if failure occurs at or above this speed, the pilot must continue the takeoff, despite the loss of power. When only a normal hard runway is available, the minimum engine-out runway requirement is obtained if V_1 is chosen so that the distance needed to stop is equal to the distance to reach 35 ft (11 m). This is called the *balanced field length.* The field length in this case is determined as the larger of the balanced field length and 115% of the all-engine distance to a height of 35 ft (11 m). This is the only definition applicable to piston-engine aircraft.

Turbojet engines have proved to be so reliable that engine failure on takeoff has become very uncommon. This has allowed the introduction of a second variable, namely, the ability to substitute stopways and clearways for some portions of the hard runway. Stopways and clearways are defined in the U.S. Code of Federal Regulations (CFR), Title 14, Part 1 (4, 5).

A stopway is defined as "an area beyond the runway, not less in width than the width of the runway, centrally located about the extended centerline of the runway, and designated by the airport authorities for use in decelerating the aircraft during an aborted takeoff. To be considered as such, the stopway must be capable of supporting the aircraft without inducing structural damage to it." A clearway, on the other hand, is defined as follows:

> An area beyond the runway not less than 500 feet (150 m) wide, centrally located about the extended centerline of the runway, and under the control of the airport

authorities. The clearway is expressed in terms of a clearway plane, extending from the end of the runway with an upward slope not exceeding 1.25% above which no object nor any portion of the terrain protrudes, except that threshold lights may protrude above the plane if their height above the end of the runway is not greater than 26 inches (66 cm) and if they are located to each side of the runway.

Similar definitions for both the stopway and the clearway are given in Annex 14 (6). A clearway may not be longer than half the difference between 115% of the distance between the liftoff point and the point at which 35 ft (11 m) altitude is reached for a normal all-engine takeoff or longer than half the difference between the liftoff point and the point at which 35 ft (11 m) altitude is reached for an engine-out takeoff. A stopway may be used as a substitute only for the part of the accelerate-stop distance that is greater than the full-strength runway requirement determined from clearway allowances; that is, the hard runway must extend for the full length of the takeoff run, defined as the point equidistant between the point at which V_{LOF} is reached and the point at which a height of 35 ft (11 m) is attained. The use of stopways and clearways in the declaration of available field lengths is shown in Figure 3.9. Also shown is the way in which the demonstrated performance is converted to the factored performance as scheduled in the aircraft's flight manual.

The takeoff field lengths scheduled in the flight manual and listed in Table 3.1b must be the greater of the demonstrated engine-out accelerate-stop distance, the demonstrated engine-out distance to 35 ft (11 m) altitude, or 115% of the demonstrated all-engine distance to 35 ft (11 m) altitude. The takeoff decision speed (V_1) may be chosen by the manufacturer, within the limits noted in Figure 3.10, but the speed must be used for both the aborted and the continued takeoff.

This flexibility of choice is extended to the pilot who is faced with a particular runway situation, so that the greater the takeoff distance available, relative to the emergency

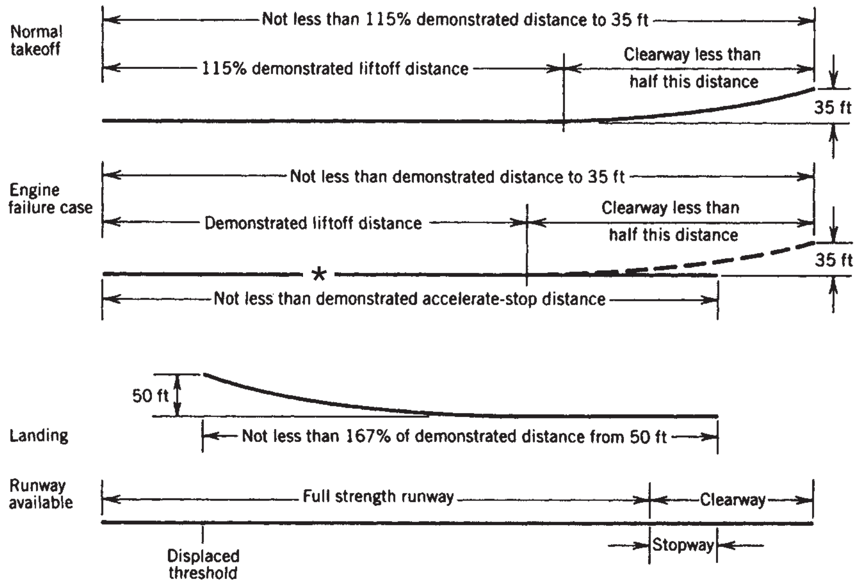

Figure 3.9 Field length definitions (the asterisk on the horizontal axis of the middle graph indicates engine failure at speed V_1).

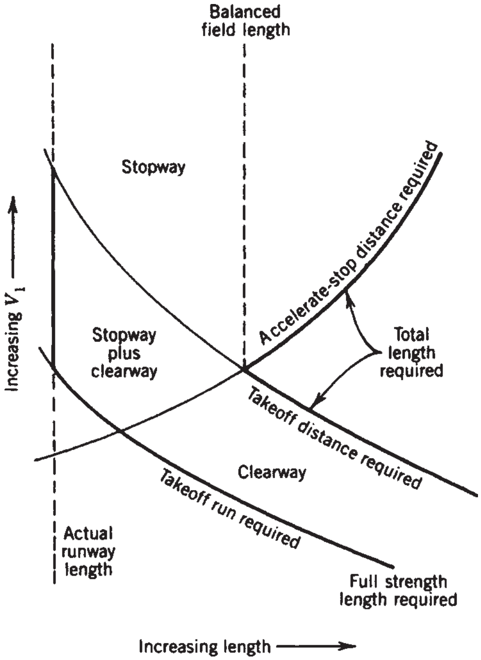

Figure 3.10 Use of unbalanced field performance.

stop distance available, the lower the pilot will choose his or her V_1 speed. Similarly, the airport planner can take advantage of these alternatives. It is frequently advantageous to use a clearway, because it saves on full-strength runway without penalizing the operation. Then a low decision speed can be chosen to keep stopway requirements to a minimum. Conversely, a high V_1 will give an even shorter full-strength runway requirement at the expense of a long stopway in the engine failure case, but the normal takeoff or landing cases may then become critical from the point of view of the length of full-strength runway. These choices are depicted in Figure 3.10. Every airport constitutes an individual case for consideration. The runway length requirements depend on the geography and weather at the airport, the possible critical speeds of the aircraft, and the fuel requirements for the critical flight plan.

Field Length Regulations—General Aviation Aircraft*

Many general aviation aircraft used for executive business, air taxi, and commuter operation are now certified in the United States under Federal Aviation Regulations, Part 25, and so must meet the same field length requirements as those applicable to

†It is the responsibility of individual countries to certify aircraft appearing on their own register. Developed countries, such as the United States, the United Kingdom, France, Germany, and so on, have their own certification procedures. Small countries often avoid the costs of certification by accepting the certification of the FAA or some other authority, such as the CAA in the United Kingdom or the French Ministry of Civil Aviation. This applies both to air transport and general aviation categories of aircraft. The examples given here quote FAA requirements, but these can be considered typical.

aircraft greater than 12,500 lb AUW and/or 30 seats, as described earlier. Other aircraft are certificated under Federal Aviation Regulations, Part 23 (8), which requires only demonstration of all-engine takeoff distance to 50 ft altitude and landing from 50 ft altitude for aircraft weighing between 6000 and 12,500 lb. No specific demonstration is required for aircraft below 6000 lb, but Table 3.1c gives some data relating to normal takeoff and landing distances to 50 ft to assist in runway design.

Reference 2 provides guidance on the recommended runway lengths for turbojet-powered airplanes of 60,000 lb or less maximum certified takeoff weight. In that circular, the FAA presents temperature- and altitude-dependent curves to cover 75 and 100% of the basic turbojet fleet at 60 and 90% load factors. That fleet includes Bombardiers, Sabreliners, Cessna Citations, and Falcons. Load factors greater than 90% are not considered, because the likelihood of that load occurring on a day when this category of aircraft is not climb limited is very small. For those airports expected to accommodate general aviation aircraft over 60,000 lb, the runway length requirement is calculated on the critical aircraft as it is at a commercial airfield.

Reference 7 gives the runway lengths recommended as a basis for planning the various classes of utility airports as well as the effects of altitude and temperature.

Restrictions on Payload-Range Performance

It is important to realize that the field lengths given in Table 3.1 refer to maximum take-off and landing weights at sea level and 59°F (15°C) (ISA). Equation 3.1 (Section 3.2) indicates that lift is proportional to air density. Since air density falls with increase of either altitude or temperature, for operation at maximum takoff or landing weights, higher takeoff and landing speeds must be used, requiring greater field length. If additional field lengths are not possible, landings and takeoffs must be carried out at lower weights to compensate for the lower generated lifts. This is demonstrated in Figure 3.7 and in Table 3.2. The illustrations refer to transport category operation, but the effects on general aviation are equally substantial. The situation is complicated by the effect of

Table 3.2 Increases in Field Length (ft × 1000) due to Changes in Altitude and Temperature

	Takeoff				Landing			
	Sea Level		4000 ft		Sea Level		4000 ft	
Aircraft	ISA	ISA + 15°C	ISA	ISA + 15°C	ISA	ISA + 15°C	ISA	ISA + 15°C
B747-400	3000	3150	4000	4200	2400	2400	2650	2650
B767-300	2600	3400	4400[a]	4400[b]	1720	1720	1900	1900
A340-600	3150		3900	3900[a]	2125	2125	2350	2350
767-200	1720	1860	2350	2620	1450	1450	1630	1630
B737-900	2300	2400	3150	3100[a]	2100	2100	2300	2300
A321-200	2750	2900	3800	3850[a]	1625	1625	1830	1830
MD 90-30	2150	2275	2650	2800	1850	1850	2800	2800
De Havilland Dash8	1300	1440	1640	2000	1050	1050	1150	1150

[a]Break energy limitation, reduced TOW in some cases.
[b]Take-off weight limitation.
Source: Manufacturers' data.

low-density air on engine performance, which tends to produce a greater deterioration in the takeoff case, unless the engine is flat rated (i.e., its output at high air densities is deliberately limited to avoid overloading its components). Therefore, under hot and high conditions, it becomes necessary to use longer field lengths or to reduce weight. In addition, the hot and high cases frequently make it difficult to meet the requirements for engine-out climb gradients at a given weight, even if the runway is long enough to meet the field length regulations at that weight.

The previous discussion has shown how the payload range can be compromised by runway length and by altitude and temperature. The allowable operation weights, hence the payload-range capability, can also be affected by runway strength limitations. This is illustrated in Figure 3.11, which indicates the relative effects of strength and length limitations for a given set of operating conditions as well as the reduction in potential profit margin. However, these limitations only apply for more than occasional use above the pavement's structural limits.

Weight Components

It is not always difficult to reduce weight to meet runway requirements, because aircraft usually are flexible in the makeup of their maximum weight, as indicated by the following definitions:

1. Empty operating weight is a constant weight for a type, made up of all items except payload and fuel.

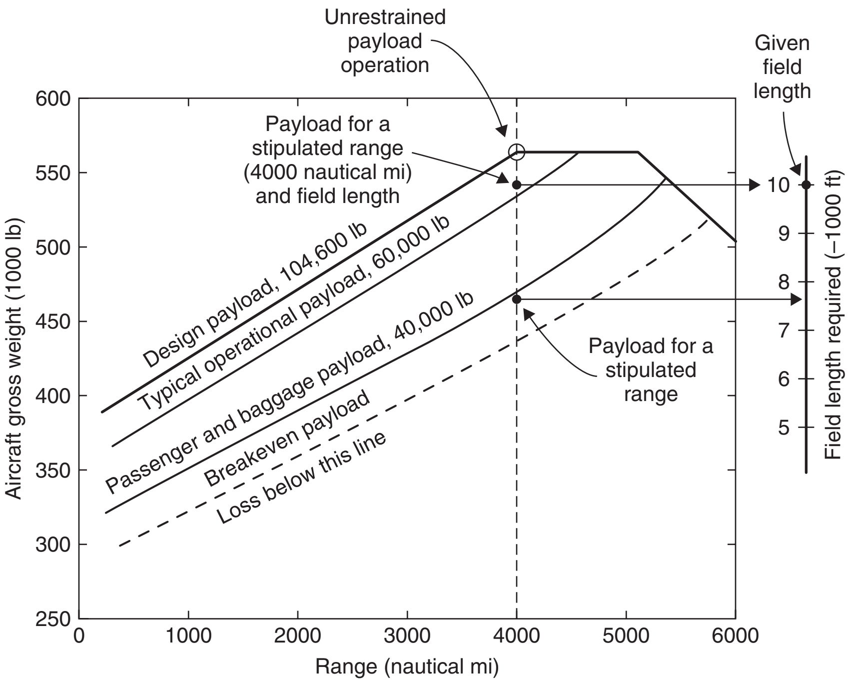

Figure 3.11 Typical aircraft gross weight versus payload-range chart.

2. Zero fuel weight is the sum of empty operating weight and the maximum payload, the latter normally being volume limited.
3. Maximum takeoff weight is determined by structural limits and performance requirements and is made up of the empty operating weight and a flexible combination of payload and fuel.
4. Maximum ramp weight is usually slightly higher than the maximum takeoff weight so that the fuel required for queueing and taxiing does not prejudice the load that can be lifted for the flight.
5. Maximum landing weight is less than the maximum takeoff weight by an amount dependent on a reasonable mean expectancy of the weight of fuel burned during a flight. Thus, the landing gear can be designed for lower landing loads without prejudice to the aircraft's lifting ability, on condition that sufficient fuel will always be burned or jettisoned before a landing is attempted.

Tables 3.1b and 3.1c list the maximum takeoff, maximum landing, and empty operating weights.

It can be seen that there is flexibility in both the size and the makeup of the difference between the takeoff weight and the empty operating weight. This is usually expressed in terms of a payload-range diagram (Figure 3.12). The payload is the useful load that may be carried—passengers, cargo, or mail. It is normally volume limited but may on occasion be limited by structural, weight, or balance factors. The fuel is limited by volume or by the maximum ramp weight. Some fuel is always needed, even for a zero-range flight for ground taxiing and reserves, the latter depending on whether the flight is to be under visual or instrument flight rules (VFR or IFR).* A further reserve is required as a function of range to allow for winds and loss of engine efficiency.

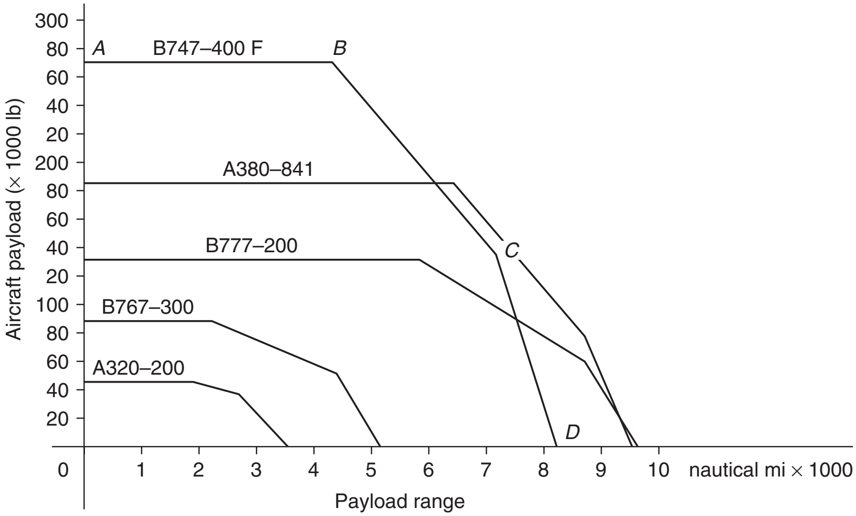

Figure 3.12 Payload ranges of various commercial aircraft. (*Source:* Boeing Airplane Company and Airbus Industrie)

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*These terms are defined in Section 6.2.

For short ranges and low payloads, the aircraft may take off with a weight below the maximum takeoff weight. Indeed, even if maximum payload is to be carried, the aircraft may still take off below the maximum takeoff weight for the short ranges over which the payload remains constant (A–B in Figure 3.12). Above this range, the aircraft must use its maximum takeoff weight, and the more fuel it needs to carry, the less payload it can accept (B–C). Finally, it is operating with full tanks, and the only extra range capability comes from the slight reduction of drag if even less payload is carried (C–D). Thus, the lack of runway for maximum weight takeoff will not necessarily penalize the operator if he or she has a smaller payload or range for a particular stage than is average for the aircraft type under consideration. It would not, however, be wise to rely too much on this in airport planning, since traffic normally is expected to grow and the operator may prefer to carry extra fuel rather than buy it elsewhere.

The foregoing discussion of field length applies in principle to all types of aircraft, though the detail is mainly concerned with conventional transport category aircraft. Reduced and short takeoff and landing (R/STOL) designs generally find that the landing case can be as limiting as the takeoff case. This is normally true of general aviation designs, which naturally have these R/STOL characteristics. Such aircraft have less rigorous requirements to meet but are more sensitive to environmental effects and generally have less flexibility with regard to payload and fuel. As a first approximation, it may be assumed that a 10% increase in takeoff run can be caused by a 5% increase in weight, a 1000-ft (305-m) increase in altitude, a 5°C increase in temperature, a 2% increase in runway slope, or a tail wind of 5% of the unstick speed. Also, long grass, soft ground, or snow can lengthen the takeoff run by 25%.

Following the air crash at Munich in the late 1950s, the FAA carried out tests on the effect of slush on runways with respect to takeoff length required for jet aircraft. Using a four-engine Convair on a carefully prepared runway, it was found that 2 cm (3/4 in.) of slush effected a drag more than equivalent to the loss of one engine. It was further found that 3.5 cm (1-3/8 in.) of slush was almost equivalent to the loss of two engines and 4.5 cm (1-7/8 in.) to three engines.

3.3 OTHER AIRPORT LAYOUT FACTORS

Aircraft characteristics significantly affect other airport layout factors, including:

The number, orientation, and configuration of runways
The types and strengths of pavements
The dimensions of parking aprons, taxiways, holding bays, and so forth
The design of passenger and cargo terminal areas

Crosswinds: Number of Runways

The number of runways required is influenced both by the number of each type of aircraft to be accepted and by their capability to operate in crosswinds. The former is largely a capacity problem and is covered in Chapter 7. The latter is a problem which is related to the design of the aircraft itself. It is more difficult to compensate for a given crosswind without incurring too severe a penalty in other areas of design. This is because there is an increase in the angular difference between the resultant direction of airflow and the required track on the ground. The individual member countries require that, for certification, transport category aircraft must demonstrate their ability to operate in crosswinds of 25 knots.* In the United States, this is laid down in CFR, Title 14, Part 25. Other categories of aircraft with lower flying speeds and shorter field lengths have less crosswind capability. This is reflected in ICAO airport requirements (6, 9), which call for runways to be usable for 95% of the time in the maximum crosswinds listed in Table 3.3.

These crosswind limits on runways are for design purposes. They are quite conservative in comparison with the 25-knot speed used in transport aircraft design to allow for variation in runway surface conditions. In general aviation, where combinations of sideslip, crab, and use of crosswind landing gear can allow operation in 20-knot crosswinds, the airport design criteria are more conservative: It is frequently more difficult to taxi in crosswind than to land (10).

The validity of the criterion of 95% usability is debatable. Not only does it appear low, but also the criterion remains constant over all categories of airports, whereas one might have expected that the investment in other areas to improve operational reliability at major airports would have called for commensurate improvement in the area of crosswinds.

Crosswinds: Orientation and Configuration of Runways

Once the decision has been made that the aircraft using the airport will require one or more crosswind runways for safe operation, the *orientation* of these runways and their physical location or *configuration* on the ground must be determined. These matters are covered elsewhere in this text: for orientation, see Section 7.17; for configuration, see Section 5.8.

Runway and Taxiway Strength and Surface

The strength requirement is a function of absolute weight, weight per wheel, pressure per wheel, and frequency of operation. In addition, the type of surface that is acceptable depends on the jet exhaust or slipstream effects and the vulnerability of intakes and flying surfaces to damage from debris thrown up by tires. In aircraft intended for shorter fields at low frequencies, the designers generally attempt to minimize aircraft sensitivity

Table 3.3 Maximum Crosswinds Permissible for Different Runway Lengths and Aircraft Types

Reference field length[a] (m)	1500 and over	1200-1500	1200 and less
Maximum permissible crosswind component in kts	20 (37 kph)	13 (24 kph)	10 (19 kph)

[a]Balanced field length at maximum takeoff weight with standard atmospheric conditions at sea level (see this chapter: Field length regulations).
Source: Annex 14.

*knot = 1 nautical mi/hr = 1.15 statute mi/hr = 1.85 km/hr.

to rough surfaces* and to minimize the weight and pressure per wheel. In this way, the least expensive surface can be used. However, this approach leads to increased empty weight and drag from the landing gear housing and is thus less appropriate to high-speed, long-range designs. The only economic solution to increasing size for these aircraft is to increase the number of wheels per bogie and the number of bogies, particularly for the main wheels, which, between them, take approximately 95% of the aircraft weight.

Taxiways, Exits, Parking Aprons, Holding Bays, And So On: Limitations due to Aircraft Dimensions

The principal dimensions of the more common aircraft are given in Table 3.1. The spacing of taxiways and nose-in bays is determined largely by the wingspan. The length is important in determining queueing distances, spacing of pretakeoff waiting areas, and the length of loading bays. The height to the top of the tail fin is of interest in sizing maintenance hangars and also, together with the other dimensions, in the location of electronic aids to minimize any interference due to reflection. The primary use of the minimum radius swept by the extremity of the aircraft is in determining the size of the apron and parking space. The pivot point can be derived by projecting through the axes of the main wheels and the axis of the nosewheel at its maximum angle, which gives a reference point from which the minimum radius swept by the landing gear can be found. The minimum radius on taxiways and turning points is based on this, though in practice the more important criterion is the minimum radius that can be negotiated at a given taxi speed. The width of the taxiways is influenced by the track width between the wheels, and the size of the full-strength apron and waiting area surfaces is related to the wheelbase (i.e., the distance between the nose and main wheels).

Cargo Implications

The layout of the facilities for handling cargo is influenced by all the parameters that determine the airside design to the passenger handling terminal. However, the increasing average size of aircraft is influencing the degree to which cargo can be considered separately from passenger handling.

As will be explained in the later chapter covering air cargo facilities, by 2010 air cargo was carried in containers in a mixture of aircraft: all-freighter wide and narrow bodies, in wide- and narrow-body combination aircraft, and as belly loads in all-passenger aircraft. A very small proportion of cargo continued to be carried uncontainerized in all-freight or combination aircraft where runway lengths available at airports precluded the use of large aircraft.

With the introduction of wide-bodied aircraft, much cargo was carried in the bellies of passenger aircraft, where operators found there was otherwise unused space. Because this freight was loaded and unloaded on the passenger aprons, cargo activity had little effect on cargo aprons. With the increasing passenger loads and increasing

*As an example, the now discontinued MBB VFW-614 had its engines placed over the wing primarily to avoid ground ingestion problems. A more common solution for smaller jets is to mount the engines on the rear fuselage above wing level.

freight flows, more aircraft were introduced for all freight operations and cargo aprons acquired increasing usage, requiring designs reflecting the presence of freight versions of passenger transport aircraft. This trend has increased with the widespread use of the all-freight 747F and the successful 777F.

3.4 FACTORS AFFECTING AIRPORT CAPACITY

The characteristics of aircraft using an airport have an important effect on the capacity of runway systems as well as that of passenger processing terminal facilities.

Runway Capacity

The capacity of a given runway under given meteorological conditions and control procedures depends in part on the average aircraft size and the mix of types of aircraft using the runway (see Chapter 7). The variation in capacity with fleet mix is due to differences in the approach and climbout speeds of the various aircraft and to the vorticity generated in the wake of large aircraft. The vorticity gives rise to control problems for smaller aircraft attempting to fly through its effect.

Lift is produced by the achievement of a pressure on the upper surface of a wing that is lower than the pressure on the lower surface. This produces a tendency for air to flow up around the wing tips. At the same time, the lift generated by the pressure differential must be balanced by a downward component of momentum in the airstream behind the wing. The combined effect of these forces is for a pair of vortices to roll up behind and below each wing tip, the radii of the cones increasing with distance downstream. The effect of these vortices is severe enough to have caused a DC-9 to bank through 90° while attempting to follow a DC-10 in to land (11).

Much research has been done to contain the effect of the vortices. The most promising approach—namely, to prevent the vortices from developing—requires modifying the wing producing the vortices without destroying the lift or increasing the drag.

The progress being made in this direction is illustrated by changes in the level of rolling moment required by a Learjet to overcome the vorticity generated by a Boeing 747 in the landing configuration in the three cases appearing in Figure 3.13. The spoiler reduces the rolling moment required below that available when the separation between the aircraft exceeds 0.5 nautical mi. This is achieved with no loss of maximum lift and only a 4% increase in drag. There is little inducement, however, for operators of large aircraft to go to the expense of fitting devices, though there is some hope that wing-tip "sails" might offer a reduction in vortex strength while actively improving the aerodynamic performance of the wing. Thus, in the short term, either the separation between large aircraft and following small aircraft must be increased, with consequent loss of runway capacity, or the smaller aircraft must be segregated to other airfields. This rather extreme measure would also avoid the loss of capacity caused by differences in approach speed. However, it is clearly very inconvenient to airline operations if connecting flights are involved.

Alternatively, because small aircraft usually require short runways only, a parallel runway can be utilized. However, unless runway separations are very large, this solution may not entirely overcome the vorticity problem, in that vortices tend to drift laterally in crosswind situations.

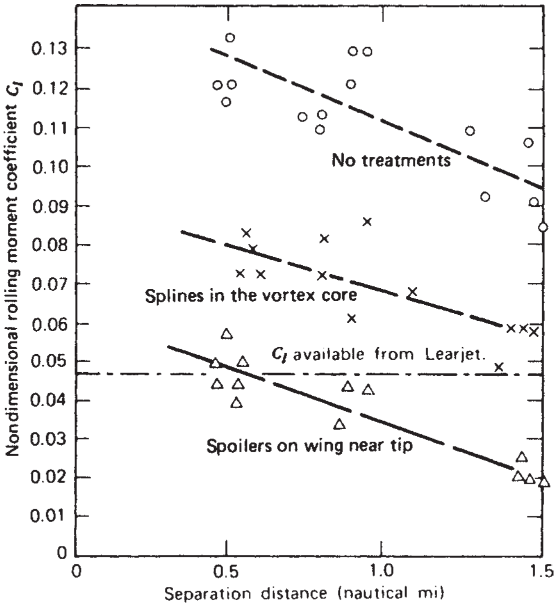

Figure 3.13 Effect of the wake of a Boeing 747 on a Learjet (11).

The runway capacity in terms of operations per hour is a function of aircraft size. The smaller aircraft can be accommodated at a higher rate, particularly in VFR conditions (see Chapter 7). This is because of their lower runway occupancy time and their ability to perform tighter maneuvers in the air. Both these advantages stem from their lower takeoff and approach speeds.

Terminal Capacity

The advent of large aircraft has tended to transfer the capacity problem from the runway to the passenger processing terminal. Problems arise particularly in the areas of:

1. Apron requirements
2. Location of airbridges
3. Access to upper decks of wide-bodied aircraft
4. Baggage handling
5. Handling large batches inside the terminal
6. Security

These matters are discussed in Chapter 10.

3.5 NOISE

The noise generated by aircraft creates problems in making decisions regarding airport layout and capacity. The correct assessment of future noise patterns, to minimize the effect on surrounding communities, is essential to the optimal layout of the runways.

Failure in this regard may result in capacity problems due to curfews and maximum limits on allowable noise exposure.

The FAA noise regulations (FAR, Part 36:20) came into force in 1969 for stage 1 jet-powered aircraft with bypass ratios greater than 2, such as B707s, DC8s, and B737-100s. In 1973, they were modified to apply to all aircraft manufactured after that date. The stage 2 regulations did not vary with the number of engines. Stage 2–compliant aircraft included B727s, B747-100s, DC9s, and B737-200s. These have subsequently been modified to meet stage 3 requirements or have been retired. Stage 3 regulations, applicable to aircraft certified after 1977, were approximately 8–12 dB lower than stage 2 levels, representing a substantial improvement in noise emission. Aircraft built to meet stage 3 requirements include the MD90s, Airbus 300s, B757s, MD80s, B767F, and later models. Stage 4 requirements conform to the Chapter 4 standards adopted by the ICAO in March 2002, which required that the cumulative EPNdB of the three measuring points was reduced by 10 dB. These standards are met by aircraft such as the B777 and the A380. Both in timing and in their variation with weight, the regulations are carefully tailored to demand only that which current technology can provide, without undue economic penalty. ICAO certification requirements are almost identical to those stated in FAA, Part 36, with ICAO Chapters 2, 3, and 4 corresponding to FAA stages 2, 3, and 4.

The first-generation jet aircraft (stage 1, Chapter 1) are now banned from operation in the United States and other developed countries, although they can still be found flying in the Third World. In the United States, airports have already also excluded all stage 2 aircraft that have not been modified to conform to stage 3 standards, which are shown in Figure 3.14.

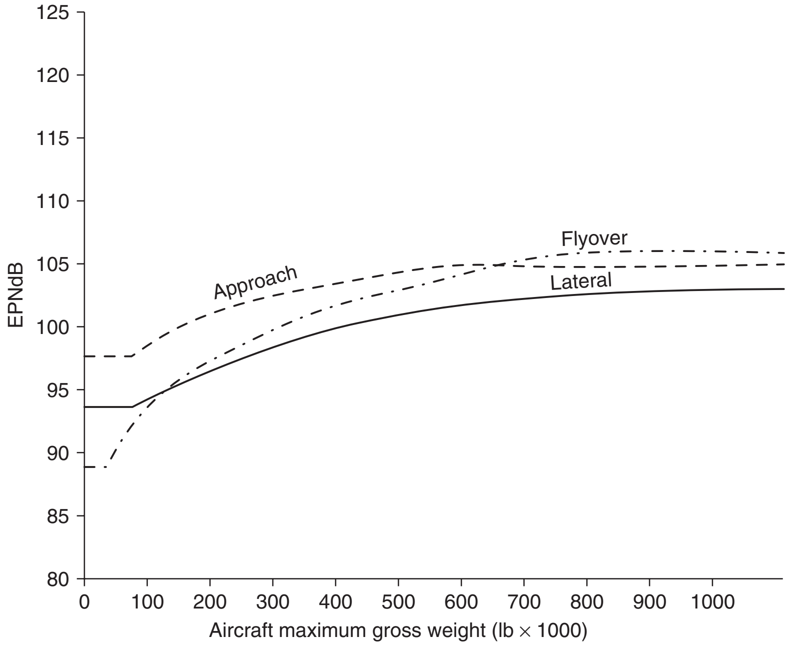

Figure 3.14 Approach, flyover, and lateral noise limits, stage 3, Chapter 3.

At the beginning of the 1990s, there were international (ICAO, ECAC*) and national (FAA) programs which legislated the phasing out of all Chapter 2 aircraft over a 10-year period, with the objective of having only Chapter 3 aircraft or better operating within the areas under their jurisdictions by 2002.

Several U.S. manufacturers marketed "hush kits" for stage 2 aircraft such as Boeing 727s, 737-200s, and DC9s which were just capable of meeting stage 3 requirements, making full use of allowable trade-offs among approach, takeoff, and sideline noise constraints. Hush kitting, because of its marginality with respect to requirements, was not as effective as reengining as a solution to noncompliant aircraft. For example, stage 1 BAC1-11s and Boeing 727s reengined with Rolls Royce Tay engines easily complied with stage 3 regulations. As stage 4 standards are implemented, the use of hush kits will be discontinued as older aircraft are retired from service. Table 3.4 shows the noise ratings of selected aircraft and indicates the dramatic improvement in noise emission from modern aircraft.

The trend toward twin jets such as the 767 and the Airbus for medium- and even long-haul operations is good for the noise problems of airports. Because such aircraft must have sufficient takeoff and climb-out power with one engine nonfunctional, the climb rate under normal operation is very high; see Figure 3.15. This is allowed for in the noise certification limits. As fleets move increasingly to twin-engine aircraft, the adverse noise impact tends to shrink back toward the boundary of the airport itself.

A problem which has grown in recent years with respect to noise impact is the proliferation of local noise regulations, especially those relating to nighttime operations.

Table 3.4 Noise Emissions from Air Transport Aircraft

Manufacturer	Model	ENPdB Takeoff	ANPdB Approach
Concorde (no longer flying, for reference only)		112.9	109.5
Airbus	A-300B	79.1	90.9
	A-310-308	75.6	88.9
	A-320-231	70.3	83.1
British Aerospace	BAe 146-300A	73.4	87.2
Boeing	707-300B/C	94.0	98.4
	727-100	85.0	96.0
	737-200	85.2	91.1
	737-700	66.3	88.0
	737-900	72.1	85.5
	747-100	100.5	97.8
	747-400F	86.8	93.0
	757-300	75.1	85.6
	767-300ER	81.5	89.2
	777-300	82.9	90.7
Bombardier	DHC-8-402	62.5	81.7
Cessna	Citation VII	65.4	81.6
Embraer	EMB145B	72.5	63.1
Fokker	F70	65.4	78.6

Source: FAA AC 36-3H, Estimated Airplane Noise Levels in A-weighted decibels, April 2002.

*European Civil Aviation Commission.

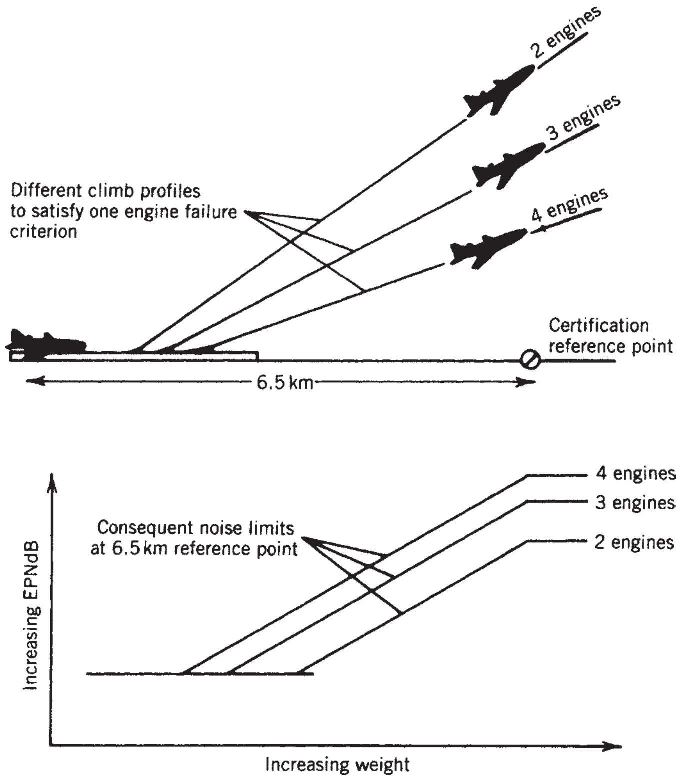

Figure 3.15 Stage 3 noise certification requirements.

These regulations involve both restrictions and curfews. A number of communities have arranged that airports have night quota systems aimed at preventing increases in nighttime noise exposure (or noise "dose"). Such a quota system operates or is proposed on a 24-hour basis, for example, at Minneapolis St. Paul Airport and at some downtown airports (such as London City Airport) to prevent excessive noise exposure of the community. Under this type of restriction more aircraft operations can be permitted using quieter aircraft provided that the dose in the form of overall total noise energy does not increase. In Europe, at London and Edinburgh, for example, aircraft are designated into NN/C and NN/B classifications. Typically NN/C aircraft have a 95-EPNdB noise footprint of less than 5.2 km^2. NN/B aircraft have footprints at the same level of between 5.2 and 10.4 km^2. The noise dose on a community is maintained at a constant level or decreased by increasing the number of NN/C aircraft operations while decreasing those in the NN/B category.

3.6 FUTURE TRENDS IN AIRCRAFT DESIGN

It is apparent from the material presented in this chapter that design has, in the past, improved productivity by increasing aircraft speed and size. The air transport product has now become much more diverse, with particular emphasis on lowering aircraft-mile costs as well as seat-mile costs.

The introduction of the turbofan has helped to allow a more efficient match between cruise performance and field performance, thus relieving the pressure on runway length (see Figure 3.1). The long runways required by the pure jets are no longer necessary and will not return in the future.

While it is undoubtedly feasible technologically, it is unlikely that the once forecast logarithmic growth of speed with time (Figure 3.16) will have any significant role in commercial air transport. In the 1960s and the early 1970s, two aircraft manufacturers had programs to build supersonic passenger aircraft. The Concorde, which commenced

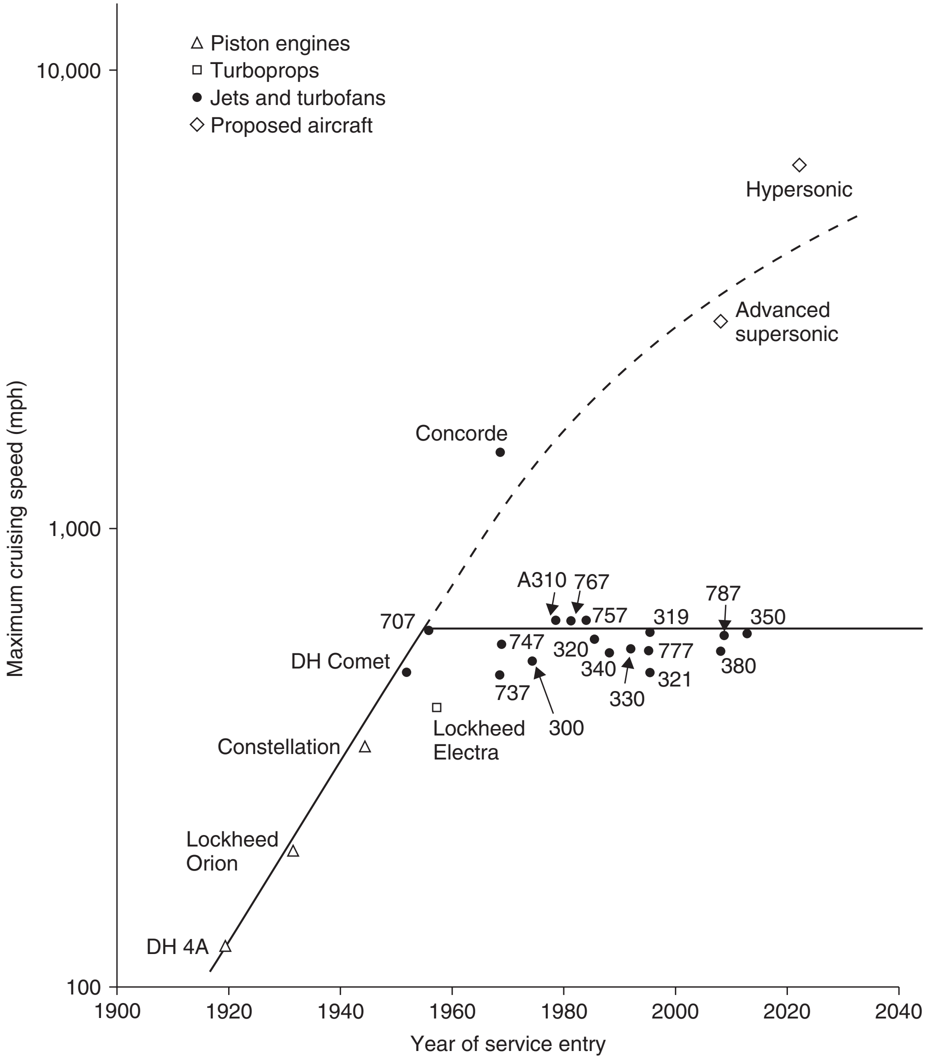

Figure 3.16 Historic and projected development in air transport speed.

scheduled service in 1973, proved to be extremely uneconomic and was unable to recover development costs. The larger and faster Boeing 2707-200SST, planned to come into service in 1975, never progressed beyond incomplete prototypes and the program was abandoned in 1971. The Concorde itself flew its last service flight in October 2003. Only 14 aircraft were bought by two airlines; these were British Airways, then owned by the British government, and Air France, owned by the French government.

Many advances in aerodynamics, structures, propulsion, systems, and control technology moved in the 1980s and 1990s from development stage to production. These advances have allowed a continuous improvement in fuel efficiency in terms of fuel burn per seat mile. The remarkable improvement in fuel efficiency by the turn of the century is shown in Figure 3.17.

The continued search for fuel efficiency is causing more attention to be focused on turboprops, particularly for the short-haul market. They provide an easy way of obtaining the short field lengths that these markets need in order to:

1. Serve the very many smaller airports that could not justify runway expenditure for low-density operations.
2. Reduce noise footprint areas at airports close to built-up areas.
3. Increase runway capacity with the use of early turnoffs, parallel STOL runways, and stub runways, thus supplementing the trend toward more frequent services with smaller aircraft in this time-sensitive sector of the market.

The potential demand for ever larger aircraft exists on the routes that have adequate frequency already. Airbus decided to respond to this by offering the A380, a double-decked wide body that in single-class configuration carries up to 853 passengers. This

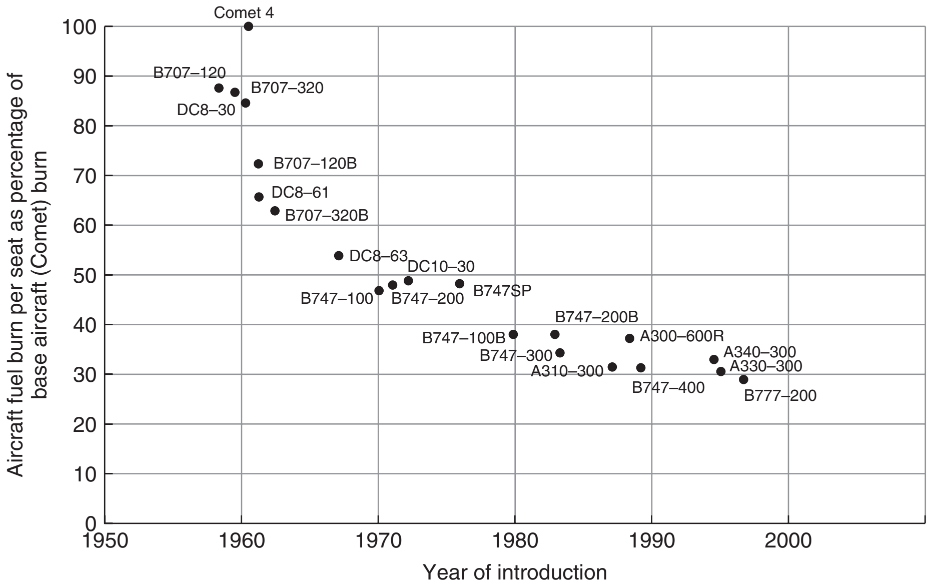

Figure 3.17 Improvement in fuel consumption efficiency of air transport aircraft (12).

aircraft entered service in 2007. Very high capacity is likely also to be offered in the form of standard seating in extended upper decks of the Boeing 747.

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4

Airport System Planning

The airport is one node in a larger system. The planning of the airport has to carefully consider its role, function, and interaction within the entire system. Neglecting to do so will adversely impact its future development. It is therefore important to understand the relationship between the airports within the system, their planning, and ways to harmonize the planning of the airport within its system and with the larger aviation system and other interacting systems.

4.1 AVIATION SYSTEM PLANNING

Aviation system planning is a process aimed at translating goals and policies into programs that would guide the evolution of the aviation system. The process is a *continuous* one and it includes monitoring the development of the system and replanning its evolution. It should be a *comprehensive* one due to the sheer number of entities in the interacting systems. It should also be a *coordinated* process in order to have all parties and stakeholders of the systems involved interactively in their planning. The aviation system planning process covers national and state systems and can be applied to components of other systems or subsystems.

The aviation system is composed of a number of components and subsystems, including:

- Airways
- Operating system
- Airports
- Airlines
- Aircraft
- Air passengers
- Air cargo

Ideally, the planning of the airport system should be subsumed into an aviation system planning exercise. In practice, this may not be feasible in certain countries, as the system would be very large and sophisticated, system components may not be well developed or even exist, advanced technology required is not available, or the country lacks the institutional and constitutional make-up. Only in a developed country with the above components established and mature can a comprehensive, continuous, and coordinated aviation system planning be applied.

4.2 LEVELS OF PLANNING

It is generally recognized that there are three levels at which planning is conducted:

1. *Strategic Level*. At this level long-term structures are examined and the adequacy of various structures and system interactions is determined to assess how well they fit the identified goals and objectives. It is at this level where procedures, timelines, and interaction modalities are set out that will lead to an optimum long-term plan with an ideal structure for the system and its future performance.
2. *Tactical Level*. At this level short- and medium-term courses of action are examined and the plan that would best fit the overall strategic goals is determined. The plan would include tasks, procedures, timelines, entities involved, and the particular courses of action in the short and medium terms.
3. *Project Level*. This level identifies details of executing a tactical plan to carry out a well-defined project of a specific nature and clear objectives. The plan would explicitly state its components, including the timeline, the budget, management procedures governing interaction between parties, and the specific outcome of the plan.

These three planning levels can be applied to an idealized 3C planning structure for aviation system planning and airport system planning. Planning levels that start from a national strategic aviation system plan, to a tactical airport system plan, and then to a project-level airport master plan represent the best approach to guarantee that the airport development will consider all aspects of the aviation system. While the airport system plan is strategic in nature, it is actually tactical in context. It is a process designed to optimize and harmonize the role of individual airports for best system performance. It is also designed to provide public funds to all airports, considering what each needs to perform adequately in the medium term as well as to ultimately maintain an efficient national airport system.

The airport master planning process is multifaceted and brings strategic and tactical planning perspectives to a project—the airport. It is strategic in that the plan is long term vis-à-vis the airport's ultimate role in the system. It is tactical in that it specifies short- to medium-term steps the airport is required to take to reach the strategic goals of the aviation and airport system plans. The master plan is, after all, a project-level plan to determine specific development phases the airport is required to undertake to reach its ultimate goal.

4.3 PLANNING AIRPORT SYSTEMS UNDER DIFFERENT STATES OF INDUSTRY

It is important to recognize some structural and contextual intricacies of system interactions and effects these interactions may have on the system planning process, procedures, and activities. Strong interactions exist between the national economic and political landscape, stakeholders' perceived outlook of the systems, as well as technological changes and advancements in the industry and their collective impacts on the planning process. There are seemingly inexhaustible scenarios for the structure of the aviation planning process. These scenarios are dependent on government monopoly and laws dictating all activities in the system and an unregulated, deregulated, liberalized environment where all elements in the system play by the rules of the free market economy and promote privatization. The scenarios to be examined include:

1. Government-regulated monopoly
2. Deregulated free market
3. Public–private partnership (PPP)
4. Global partnership with foreign enterprise

In the United States, the air transportation system matured as it passed through these phases.

Government-Regulated Monopoly

Theoretically, a governmental monopoly in a regulated air transport system should, with skilled planning, lead to an optimal system which has been evaluated as providing the best service to the nation within the context of available resources. Provided that the system can be modeled in terms of output with respect to national goals, the determination of an optimal system should be feasible. Such a hypothesis, however, assumes a number of factors, including:

- Adequate planning skills at the national level
- A broadly accepted method of evaluating available options
- A broadly accepted basis of national resource allocation
- Lack of political interference in the development of an optimal system
- Isolation of the national system from serious interference caused by international perturbations
- Lack of corruption in the government and its administration

In practice, in countries that adopt centralized planning and administration, many problems have been encountered, including:

- Lack of innovation and development of new ideas or new technology
- Lack of risk taking by civil servants with no motivation to enter into courses of action with uncertain outcomes
- A career structure for professionals which bases advancement on length of service and not performance
- Inadequate response to the needs of clients or customers, that is, the airlines or passengers

During government regulation of the airline industry prior to airline deregulation in the United States in 1978, government regulations on the air transport industry resulted in:

- Limited access to medium to small markets and communities.
- The existence of “international gateways” where international flights served few airports in the United States, namely, New York, Miami, Dallas-Fort Worth, Los Angeles, and Chicago.

- The primary airline hubs in the system where connecting and interlining take place were limited to Chicago, Atlanta, Chicago, Dallas-Fort Worth, and to a lesser extent St. Louis and Denver.
- Airline competition was minimal and had no impact on entering new markets or on airfares that were preset by government.
- Most air transportation activity was concentrated in the primary airports, where two-thirds of U.S. enplanements were in the top 24 primary airports (1) and one-quarter of all airline passengers boarded their flights in five primary airports: two airline hubs (Atlanta and Chicago O'Hare), two international gateways (New York JFK and Los Angeles), and one that is both (Dallas-Fort Worth).

Deregulated Free Market

The U.S. Congress passed the Airlines Deregulation Act of 1978 ending 40 years of air transportation regulation for domestic services that started with the Civil Aeronautics Act of 1938. About the same time, Congress passed the International Air Transportation Competition Act of 1979, which endorsed the policy of ratifying bilateral air transport agreements with foreign governments that increased competition in international air transportation. These two acts, albeit separately, ushered the onset of a deregulated environment for the airline industry in the United States based on entirely free market principles (2).

Between 1938 and 1978, phenomenal growth in both U.S. domestic and international air transportation took place. Domestic air passengers grew from just over 1 million in 1938 to more than 267 million in 1978. This growth elevated the U.S. air transport industry from obscurity to one of the major industries in the nation, particularly after World War II.

Despite the remarkable advance and market growth under the regulatory scheme established in 1938, broad public satisfaction with the airline system started to diminish fueled by desire to bring in free competition to the industry and general public distrust of government regulation. Starting in the early 1970s, several political, economic, and regulatory developments brought the dawn of deregulation in 1978, and it was a different air transport market landscape afterward. Domestic airline deregulation occurred in two phases (3):

- From 1978 to 1985, air travel was characterized by an explosion of new airlines entering the market with ensuing intense price wars resulting in financial disaster and demise of most new airlines.
- Beyond 1985, the wave of new airline entry into the market was reversed with consolidation and mergers of airlines resulting in a smaller number of airlines in the market.

The free market approach was considered by its proponents to have several overall advantages:

- Access to finance in the normal commercial financial markets
- Introduction of competition, bringing lowest costs to passengers and maximum service levels

- A market-driven approach, with management objectives responsive to passenger consumerism

Opponents of airline deregulation presented a number of potential problems:

- Airlines have no long-term commitment to either routes or airports, which brings an inherent instability to the system.
- The system can be subject to very large changes in transport supply, in terms of airline provision, at very short notice.
- There has been a tendency toward the development of a few very large megacarriers rather than many smaller and highly competitive operations. Small carriers have found themselves subject to predatory competition.
- Most airports are small corporate and financial entities in comparison with airlines. They find themselves subject to great pressure to conform to the airlines' requirements.
- Airports which are entirely privatized can have goals which are not aviation oriented and which, furthermore, may conflict directly with aviation needs.
- The transfer of the airport public authority to private ownership entails the transfer of large amounts of sunk public capital and assets, the value of which on the open market is almost impossible to assess correctly. The private entities are prime targets for asset stripping, takeovers, and non-aviation-oriented management.

Public–Private Partnership

After 1978, the deregulated environment continued for most of two decades during which the air transport system witnessed another monumental growth in air passengers passing through airports and boarding flights. While the airline industry financed its own growth, the national airspace system, both airports and air traffic control (ATC)-airways systems, were mostly financed by federal and state governments. During the 1990s, a huge investment was required to upgrade the air transportation system infrastructure to facilitate the significant growth safely and economically.

Federal capital expenditures on airports were financed through taxation legislated back in 1933 and 1941. It was soon realized that funding levels were too low to satisfy the level of development and expansion of the system desired by industry. The air transport industry lobbied Congress and government to establish a new collaborative perspective to funding the needs of the air transport system infrastructure development and airport capacity expansion. The Airport and Airway Development Act of 1970 established the Airport and Airway Trust Fund. Between 1960 and 1982, cumulative public and private investment in U.S. airports was $25 billion, and the federal share was about one-third. The Airport and Airway Improvement Act of 1982 combined the Planning Grant Program (PGP) and Airport Development Air Program (ADAP) into a single normally multiyear grant: the Airport Improvement Program (AIP). The AIP was authorized by the Airport and Airway Improvement Act of 1982 (4). Since the original authorization the Act has been amended in 1994, 1996, 1999, 2000, 2001, 2002, and again in 2003, to change the annual authorizations for fiscal year 1994 through 2007 as well as numerous other program changes.

The Act's broad objective is to assist in the development of a nationwide system of public-use airports adequate to meet the current needs and the projected growth of civil aviation through funding for airport planning and development projects at airports included in the National Plan of Integrated Airport Systems (NPIAS). In this respect, the AIP is the United States federal grant program dedicated to provide funds to airports to help improve safety and efficiency. Improvement projects relate to runways, taxiways, ramps, lighting, signage, weather stations, NAVAIDs, land acquisition, and some areas of planning. The money is raised through taxes on airplane tickets sold to the public and a tax on aviation fuel. In 2009, funds under the AIP went to 389 NPIAS airports totaling $2.2 billion, averaging $5.5 million per airport. The AIP program also funded improvements to 1,121 general-aviation airports in communities with no airline service, totaling $832 million averaging $742,000 per airport (4).

Therefore, in the context of the entire US air transportation system, funding forms a partnership between the private and public components of the system.

This approach was a middle-of-the-road attempt to bring about the advantages of the two previous approaches. Most countries which are moving toward deregulation and privatization are doing so by forging a "partnership" between the public sector and private entrepreneurs. This may be carried out by adopting a number of models, the most common of which include the following:

1. Private airlines, public airports (U.S. model)
2. Private airlines, large private airports, small public airports (U.K. model)
3. Large semiprivate airlines, small private airlines; large semipublic airports, small public airports (German and French models, respectively)

The best structure of aviation administration is a matter of political choice, but some form of mixed public–private approach appears to be desirable if, on the one hand, the rigidity of total public ownership is to be avoided and, on the other hand, the volatility and destructive nature of the totally free competitive market are to be avoided.

Global Partnership with Foreign Enterprise

This approach is similar to the last two given above but with the introduction of foreign investment with the national private enterprise in the development of airports. This form of public and foreign enterprise partnership prevailed with the proliferation of globalization that swept the world during the last decade of the twentieth century. While each country may have varying levels of government control and regulation of foreign capital's entry into local markets resulting in partial or total ownership of national infrastructure assets such as airports, this introduction was mostly accepted by government regulators when carried out under special legal instruments such as build-operate-transfer (BOT) contracts or the partnership of national and foreign enterprise.

4.4 EFFECT OF AIRLINE HUBS AND DEREGULATION ON U.S. AIRPORT SYSTEM

The concept of airline hub-and-spoke operation is not new; there were airline hubs before deregulation and they continued afterward. But as airlines gained the route flexibility of deregulation, they placed a degree of emphasis on "hubbing" that far exceeded prior expectations (2). This strong emphasis by airlines on hubbing has deep roots in basic principles of airline economics. At the dawn of deregulation, there were about 50,000 city-pairs in the U.S. airport system, but only 2% could generate enough local traffic to support the nonstop air service in the new deregulated environment. The airlines' response was to offer connecting and one-stop service to "thin markets," and it was hubs that could provide the effective and economically feasible means of achieving that.

The benefits to all of airlines that adopted hubbing include:

- Air access benefits to the residents of hub cities, which are usually the larger metropolitan areas and business centers.
- Enhanced international service to the hubs and to the many airports serving as their spokes, bypassing traditional international gateways.
- Enhanced domestic service to small cities that as spokes to the airline hubs provided far improved service over the previous point-to-point system.
- Competition between hubs (actually between airlines) would bring greater benefits to smaller communities through a wider choice of carriers, more service frequency with convenient connections, and perhaps more reasonable airfares.
- The airline hub, by its definition, connects flights of the hubbing airline. Therefore, on-line connections at the hub have the advantage of shorter (preset) layover times, reduced walking distance in the terminal, and greater reliability of baggage transfer. Statistics showed that in 1978 one-seventh of all passengers made interline connections, but this dropped to less than 3% in 1988.

In a totally deregulated environment, however, airport system planning is not possible. Because the level of service provided by airlines is largely responsible for the generation of air transport demand at an airport, private-sector airline decisions control demand levels in the system. Airline service provision to a large degree determines the number of air transport trips that would be generated, their origin and destination airports, and the location of transit or transfers. The methodology used by airport system planners can model the effect of airline decisions reasonably well by use of airport choice and route choice models. Planners cannot, however, with any certainty predict how airlines will make their choices of service provision in a business environment replete with bankruptcies, mergers, takeovers, global influence, and financial restructuring. It can be deduced therefore that airport system planning will only work where there is some level of regulation.

Deregulation in the United States was devised essentially to allow airlines to provide service where they wanted at any price they wished. In 1975, the Kennedy Report on "Civil Aeronautics Board Practices and Procedures" outlined the main advantages to be offered by deregulation:

(a) *Free route entry and exit* to foster more efficient utilization of equipment, more rational route structuring, and better targeting of subsidy for essential services

(b) *Real price competition* which would result in lower fares, greater choice of products and airline, and elimination of costly "service competition"

The architect of airline deregulation, Alfred Kahn was convinced that "increased competition should make for a leaner, more efficient scheduled operation." He foresaw that unbridled competition needed control but stated:

> One does not assure the survival of a regime of competition by a policy of mere laissez-faire. This is why we have antitrust laws . . . . The preservation of a competitive market structure sometimes requires us to protect suppliers from the application by more powerful rivals of competitive tactics that deny them an opportunity to compete for reasons that have nothing to do with their comparative efficiency in serving the public.

The following conclusions can be drawn from the first decade of domestic deregulation:

1. Exit/entry freedom has allowed many new entries into the industry and has led to route rationalization and better allocation of subsidies to essential services. Many of the new entries (over three-quarters) have disappeared because of financial failure or takeovers. Many communities have lost jet service as major carriers have dropped services in low-density markets. Hub-and-spoke systems have proliferated in the United States with the advent of deregulation and by the mid-1980s US airlines established their permanent hubs at airports around the United States. Figure 4.1 illustrates the U.S. hub system in 1986, with the airline and its share of total airport traffic is indicated against each hub airport.

2. Freedom in pricing has produced lower fares on some dense routes but much higher fares on sparse routes. Free competition in pricing has also produced an extremely complex tariff structure which requires computer access. Price/cost disparities have also appeared in point-to-point fares.

3. The carriers have faced severe financial difficulties in spite of better management efficiency and lower costs. There has been a tendency for carriers with financial problems to be absorbed into a few megacarriers.

The effect of hubbing on individual airports can be seen in the context of Figure 4.2, which indicates how the activities of three U.S. airlines (American Airlines, Northwest, and TWA) have been concentrated into a few main hubs, with major concentration at one facility (3). In some cases, the buildup of traffic at an individual airport has been entirely unexpected in terms of long-term master planning. For example, Charlotte, the hub for former Piedmont Airlines, experienced tripling of passenger enplanements in six years coinciding with deregulation, as shown in Figure 4.3. The situation for Raleigh-Durham, which American Airlines turned into its hub in 1978, was more dramatic (3). As shown in Figure 4.4(a), passenger enplanements shot up by more than threefold in five years. Aircraft movement growth at the airport was more pronounced, as shown in Figure 4.4(b). American Airlines flights at Raleigh-Durham were responsible for more than doubling total aircraft movement at the airport in five years.

In other cases, there have been significant and sudden drops in traffic due to a failure of an airline or to some change in airline operating strategy. One such airport casualty was Raleigh-Durham itself, as American Airlines dropped it as a hub a few years later, and traffic levels at the airport went down to its prehub levels. Figure 4.5 shows the

*Based on combined 2 Qtr. 1986 passengers from proposed mergers TAC-Texas Air Corp.

Figure 4.1 Major U.S. airline hubs existing in 1986.

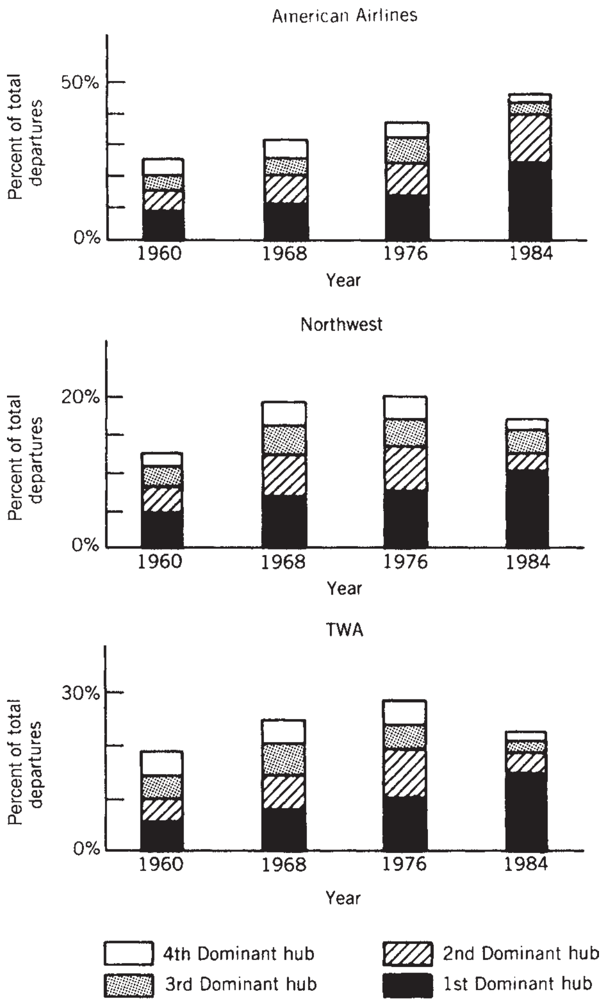


Figure 4.2 Trends in concentration of airline activity at various U.S. hubs (3).

significant drop in traffic at Newark after 1986 due to the failure of People Express. The abrupt drop in Kansas City traffic after 1979 when TWA moved its hubbing operation is shown in Figure 4.6. The hiatus in long-term growth in Atlanta's traffic after 1979 was due to deregulation itself, which permitted the monopoly of Atlanta's southeast hub to be broken by the development of other hubs within the region (mainly Charlotte and Raliegh-Durham), as shown in Figure 4.7. Atlanta Hartsfield Airport today is the busiest airport in the world.

De Neufville and Barber (5) have examined the effects of volatility of airport traffic in a deregulated environment. One consequence is that capital expended on facility expansion is invested at greater risk. If this development fund has to be generated by revenue bonding, the interest rate paid must be consequentially higher and bond flotation becomes more difficult. To reduce risk, De Neufville and Barber recommend

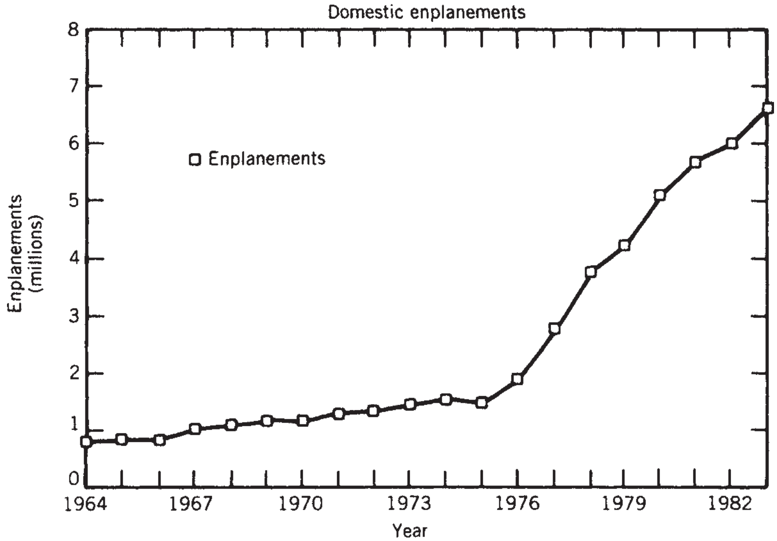


Figure 4.3 Enplanements at Charlotte, S.C., 1964–1983 (3).

planning for shorter term horizons and designing facilities in a more flexible manner to serve a range of future needs to minimize the risk of obsolescence.

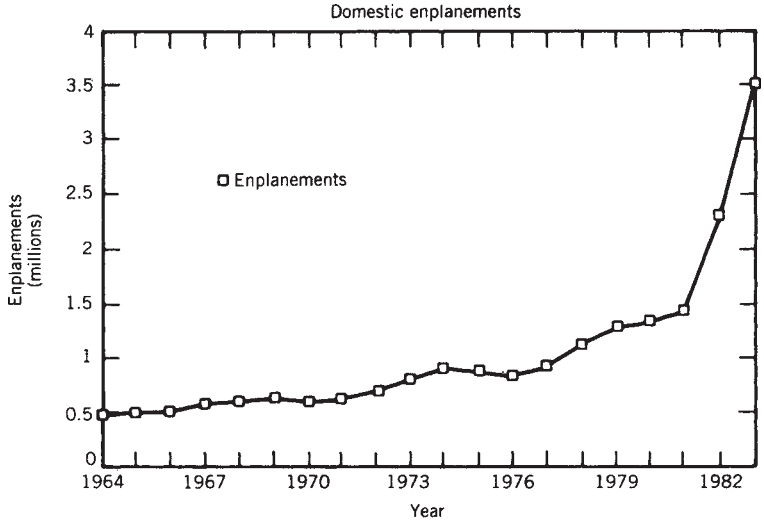
4.5 AIR TRANSPORT PLANNING IN THE UNITED STATES

U.S. air transportation system planning has matured and settled constitutionally (laws enacted) and institutionally (government entities responsible for applying the laws) into several interacting plans. While these plans are federal, the states have input and feedback is secured, as well as the other system stakeholders.

National Plan of Integrated Airport Systems (6)

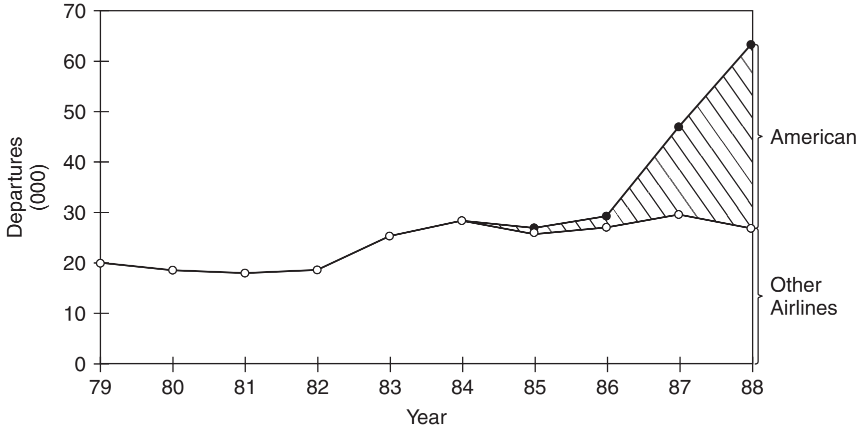
The National Plan of Integrated Airport Systems (NPIAS) identifies more than 3,400 existing and proposed airports that are significant to national air transportation in the United States. It serves as the mechanism for airports to receive federal grants under the Airport Improvement Program (AIP) and to estimate the amount of AIP money needed to fund infrastructure development projects that will bring these airports up to current design standards and add capacity to congested airports in the U.S. airport system. The FAA is required to provide Congress with a five-year estimate of AIP eligible development every two years.

Genesis of NPIAS. In 1984, the U.S. Congress published a report (1) to examine present conditions and future needs of the U.S. airports. This study was conducted by a special advisory panel of experts in industry, government, and academe. The study looked at the system level of airports and examined the classification of airports in the national system. Airports are identified and classified in terms of ownership, purpose, traffic volume, type of aircraft served, public access and service, and eligibility for federal aid.



(a)

Figure 4.4(a) Enplanements at Raleigh-Durham, N.C., 1964–1983 (3).



(b)

Figure 4.4(b) Aircraft movements at Raleigh-Durham, N.C., 1979–1988 (3).

The inventory and classification of airports (by size and function) in the United States started in the early 1970s when the FAA issued the National Airport System Plan (NASP), a 10-year plan that was part of its compliance with the Airport and Airway Development Act of 1970. As part of the FAA compliance with the Airport and Airway Improvement Act of 1982 (Public Law 97-248), which reflected strengthened congressional commitment to airport planning and development, a new classification and planning process emerged: the NPIAS. The NPIAS was first published in 1984 and set to be issued every two years to cover airport development needs over five-year increments.

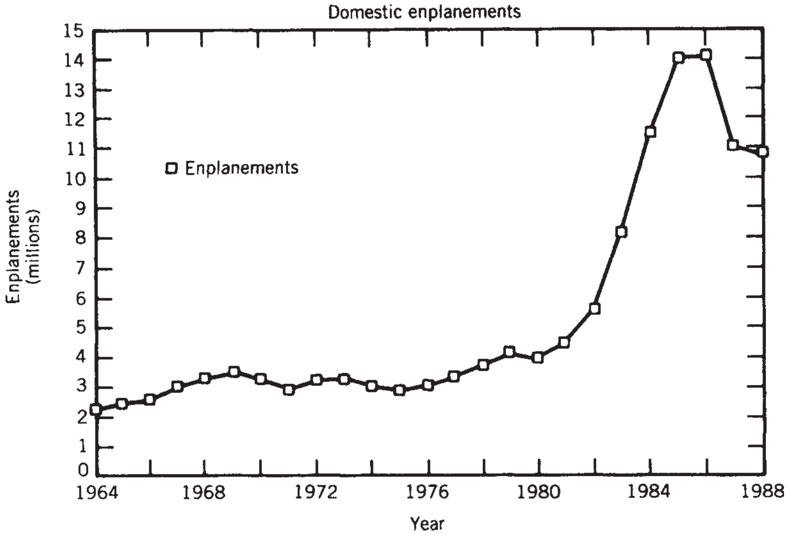


Figure 4.5 Enplanements at Newark, N.J., 1964–1988 (3).

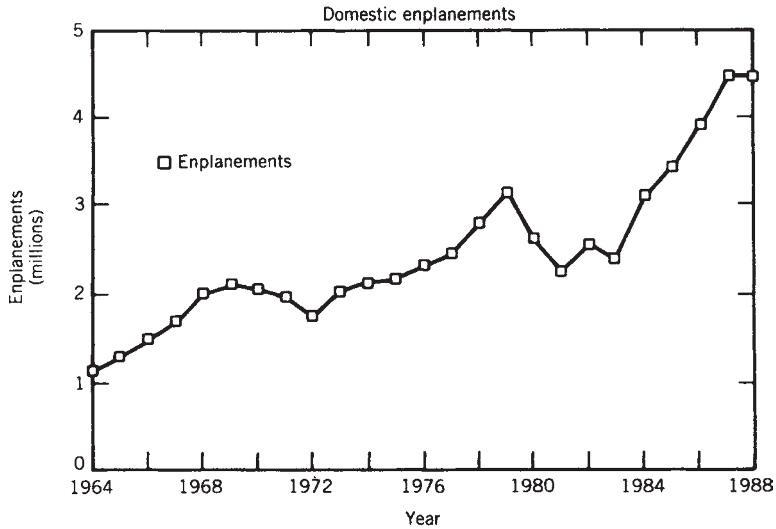


Figure 4.6 Enplanements at Kansas City, 1964–1988 (3).

Rationale for NPIAS. Given the high cost and long lead time for building new or improving existing airports, system-level planning of the entire U.S. airport system needs to be undertaken. Moreover, the need to develop individual airports in the system must be carefully weighed according to societal needs and plans. Planning could not be undertaken singularly for one airport in isolation of others in the same system connected within the same network, where all airports are part of the national transportation system. Therefore, airport planning involves government at all levels as well as other industries and public and private organizations.

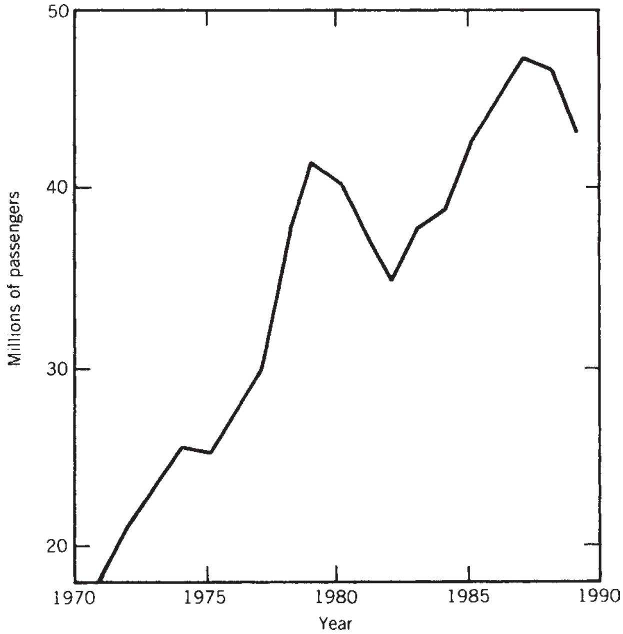


Figure 4.7 Total passengers at Atlanta Hartsfield International Airport, 1970–1989 (3).

The purpose and uses of the NPIAS, as required by law, are:

- It is a legal requirement of the FAA to report to Congress every other year.
- It defines the national airport system and the roles of individual airports and is reported to Congress, the public, and international organizations.
- It identifies airport development needs to meet their required role.
- It is utilized by Congress in discussions of total airport development needs and funding authorization.
- It is used by federal auditors to examine funding applications and by industry to monitor airport development grants.
- It is used as a base template for reporting airport condition and performance in the system.

The NPIAS represents the outlook to the U.S. airport system planning that emerged at the time the law was enacted to ensure adequate balance between different levels of planning.

The outlook of this airport system plan considers the following levels:

- Airport master plans on the airport local level.
- Regional airport plans, typically including all public airports within the county or metropolitan boundary.
- State airport (or aviation) plans. As the U.S. transportation system plans are taken down to the state level (AIP airport funding is on the state level), each state would have to initiate its own airport plan.
- National airport system plan, that is, the NPIAS.

NPIAS Airport Categories. The NPIAS comprises all commercial service airports, all reliever airports, and selected general aviation airports. The only airports eligible for AIP funding under the NPIAS are public-use airports that serve civil aviation. In the Airport and Airway Improvement Act of 1982, the definition for airports refers to "any area of land or water used or intended for landing or takeoff of aircraft." Within the four categories of airports listed below, the special types of facilities included are seaplane bases, heliports, and facilities to accommodate tilt rotor aircraft. An airport includes "an appurtenant area used or intended for airport buildings, facilities, as well as rights of way together with the buildings and facilities."

The U.S. airport system is the largest and most complex in the world. In 1982 there were 15,831 airports on the FAA records—4,805 publicly owned airports, 1,970 privately owned airports open to public use, and 9,056 private, nonpublic airports. The 2009 NPIAS report (6) indicates that these numbers have changed to 19,815, 4150, 1040, and 14,625; respectively. These numbers constitute almost half of the world's total registered airports. Figure 4.8 depicts the NPIAS inventory public and nonpublic airports in the United States.

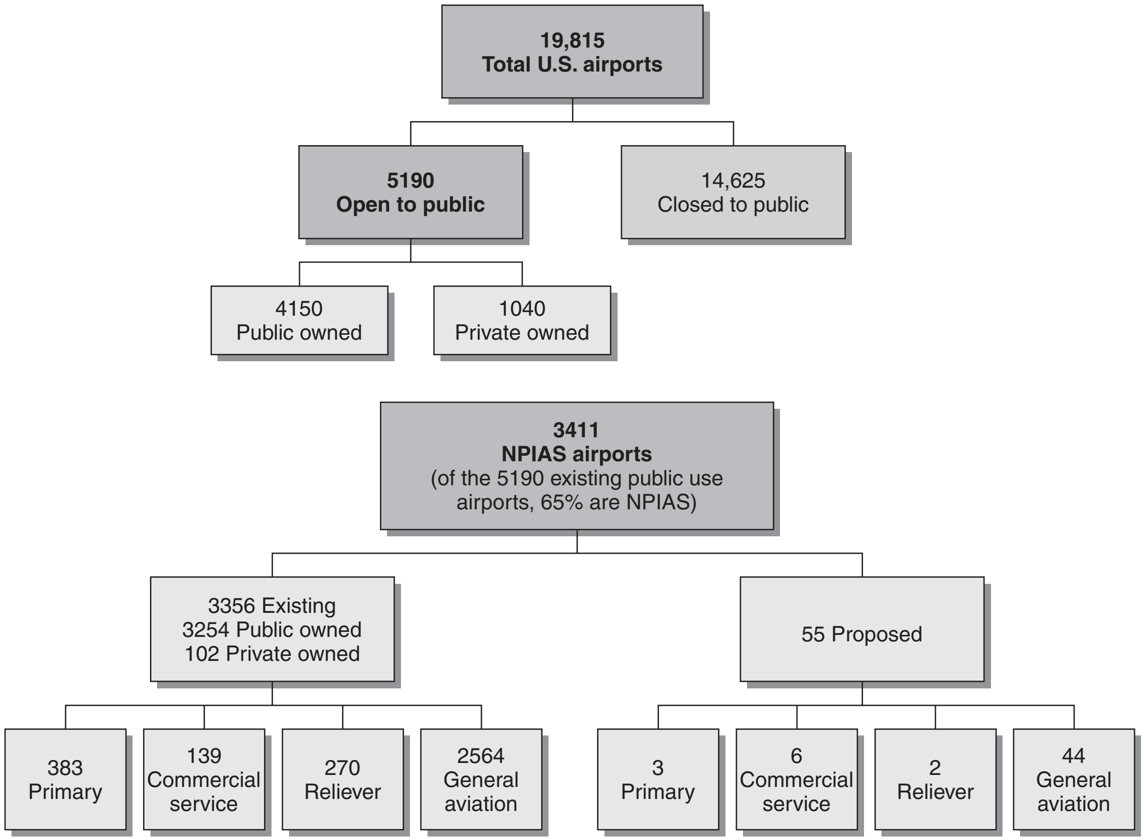


Figure 4.8 NPIAS inventory of public and nonpublic U.S. airports (6).

The 1982 law defines airports by categories of airport activities, including commercial service, primary, cargo service, reliever, and general aviation airports. These categories are defined as follows:

1. *Commercial service airports* are publicly owned airports that have at least 2500 passenger boardings per calendar year and receive scheduled passenger service. Passenger boardings refer to "revenue passenger enplanements on an aircraft in service in air commerce whether or not in scheduled service." Commercial airports are divided into:
   (a) *Nonprimary commercial service airports* having between 2500 and 10,000 passenger enplanements annually.
   (b) *Primary airports* having more than 10,000 annual passenger enplanements. Hub categories for primary airports are defined as a percentage of total U.S. annual passenger enplanements. Certain formulas are used for the definition of airport categories based on statutory provisions cited as described in the law.
2. *Cargo service airports* are airports that, in addition to any other air transportation services that may be available, are served by aircraft providing air service in intrastate, interstate, and foreign air transportation of only cargo with a total annual landed weight of more than 100 million pounds. An airport may be both a commercial service and a cargo service airport.
3. *Reliever airports* are airports designated by the FAA to relieve congestion at commercial service airports and to provide improved general aviation access to the overall community. These may be publicly or privately-owned.
4. *General aviation airports*, the largest single group of airports in the U.S. system, include all the other airports commonly described as such by the law. This category also includes privately owned, public-use airports that enplane 2500 or more passengers annually and receive scheduled airline service.

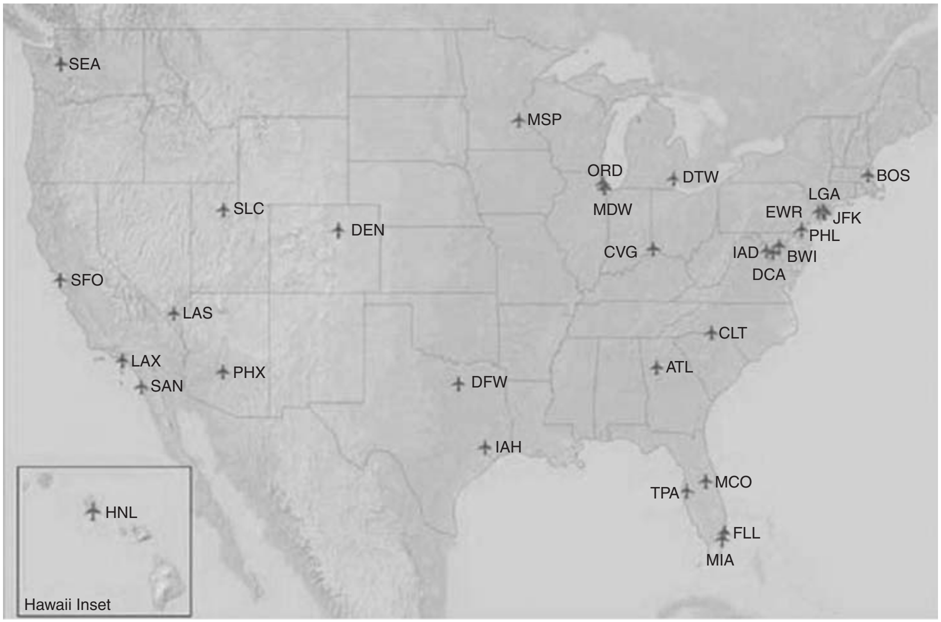
Airport Hub Type. The term "hub" is used by the FAA specifically to identify very busy commercial service airports as measured by passenger enplanements. In this context it is different and unrelated to the term used by the airline industry.

Primary commercial service airports are grouped into four categories:

- *Large hubs* (*L*) are those airports that each account for at least 1% of total U.S. passenger enplanements.
- *Medium hubs* (*M*) are airports handling between 0.25 and 1.0% of total U.S. passenger enplanements.
- *Small hubs* (*S*) are airports handling between 0.05 and 0.25% of total U.S. passenger enplanements.
- *Nonhubs* (*N*) are airports handling less than 0.05% of total U.S. enplanements but more than 10,000 annual enplanements.

Figures 4.9(a)–4.9(g) depict the above NPIAS categories graphically on the United States map (6):

- Large hub airports (Figure 4.9a)
- Medium hub airports (Figure 4.9b)



(a)

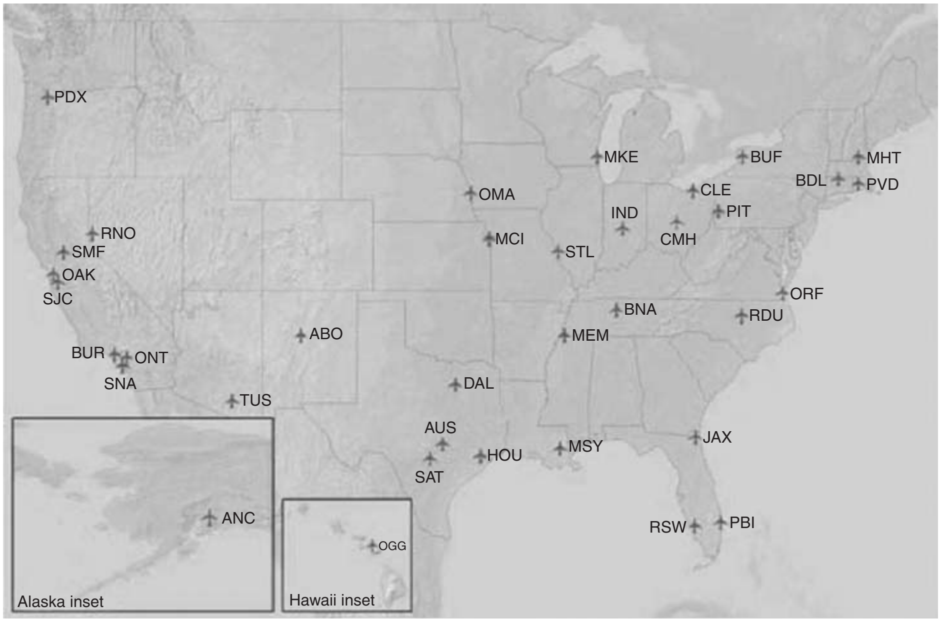
Figure 4.9(a) U.S. large hub airports, 2008 NPIAS (6).

- Small hub airports (Figure 4.9c)
- Nonhub primary airports (Figure 4.9d)
- Nonprimary commercial service airports (Figure 4.9e)
- Reliever airports (Figure 4.9f)
- General aviation airports (Figure 4.9g)

In summary, the FAA has established a system to maintain and continuously update the NPIAS database, which is used to organize preparation of the periodic NPIAS reports to Congress. This system provides necessary guidance and sets forth policies and procedures for the continuous formulation, maintenance, and periodic publication of the NPIAS (7).

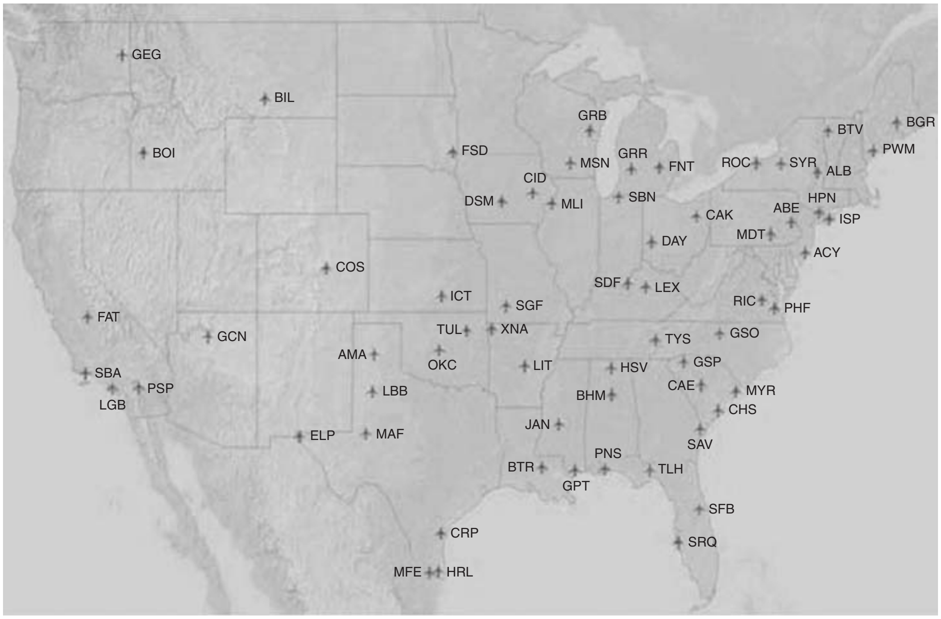
Airport Development Needs. Types of airport development needs that the NPIAS covers include:

1. *Airfield*, which includes the runways, taxiways, and aprons, for example:
   (a) Pavement extension and rehabilitation
   (b) Runway and taxiway lighting, markings, and movement control
2. *Buildings*, expanding and rehabilitating airport terminals
3. *Noise mitigation* costs (Part 150)
4. *Airport safety*, including aircraft rescue and fire fighting (ARFF) structures and equipment, SRE, safety areas, runway protection zone (RPZ), etc.
5. *Airport roadways* for access and service



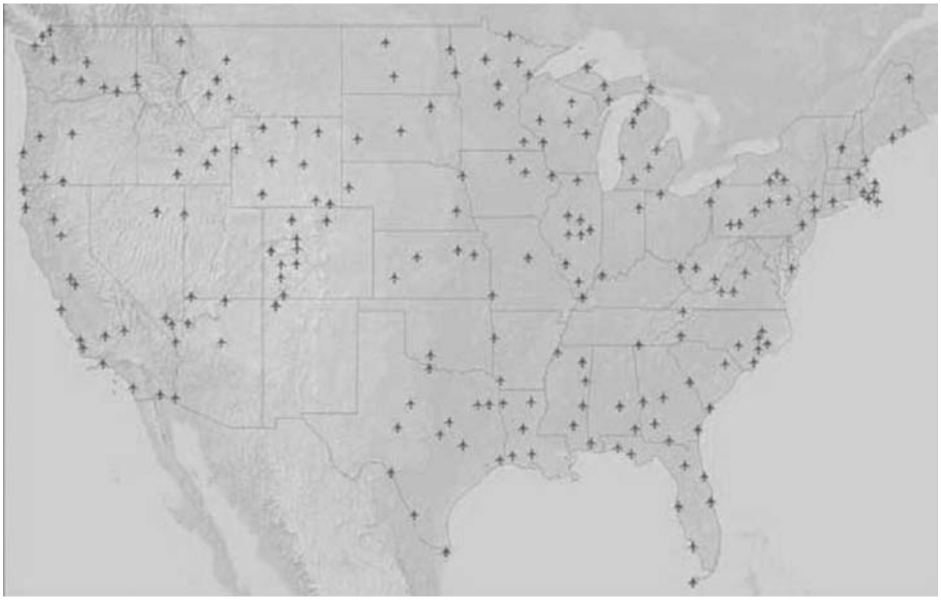
(b)

Figure 4.9(b) U.S. medium hub airports, 2008 NPIAS (6).



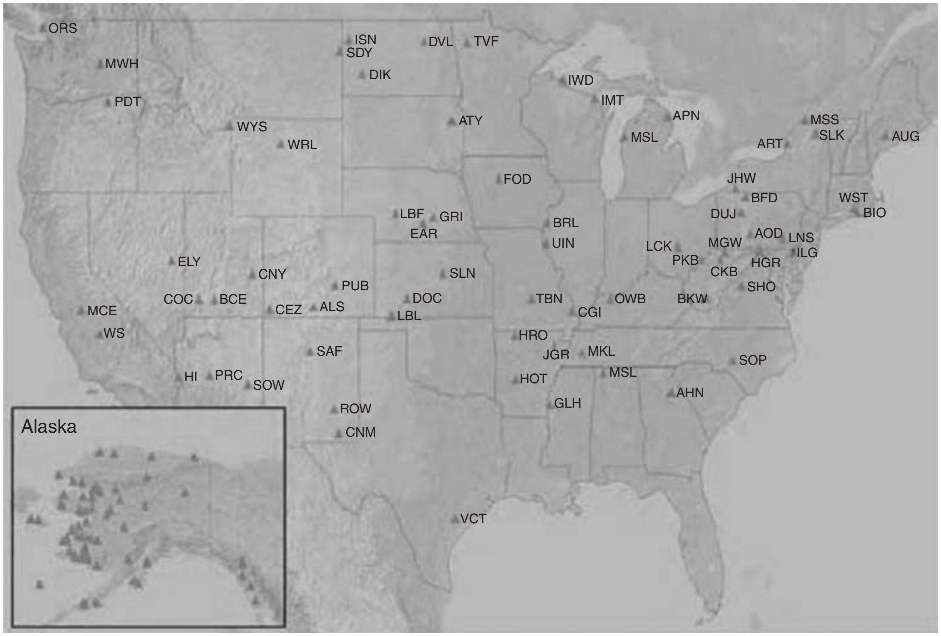
(c)

Figure 4.9(c) U.S. small hub airports, 2008 NPIAS (6).



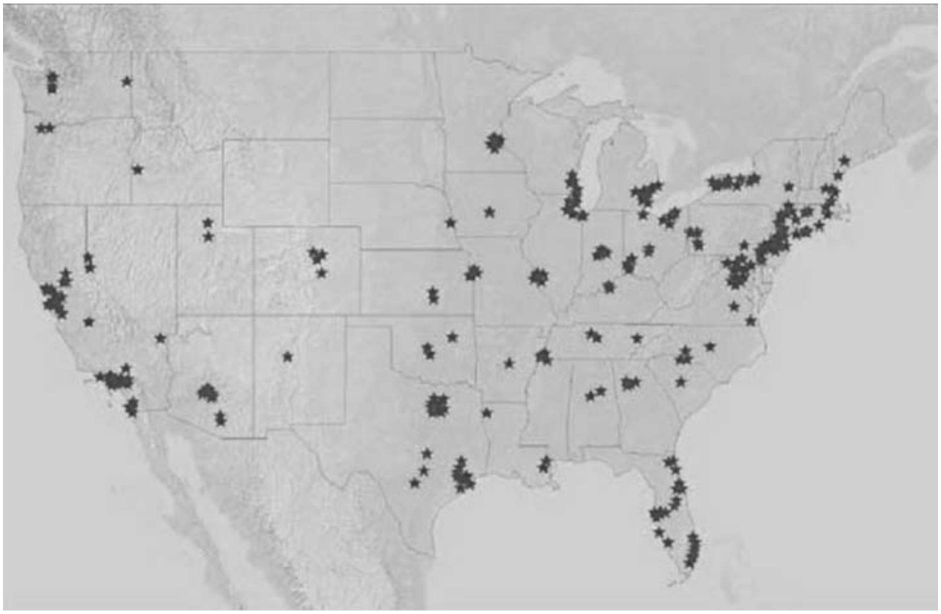
(d)

Figure 4.9(d) U.S. nonhub primary airports, 2008 NPIAS (6).



(e)

Figure 4.9(e) U.S. nonprimary commercial service airports, 2008 NPIAS (6).



(f)

Figure 4.9(f) U.S. reliever airports, 2008 NPIAS (6).

(g)

Figure 4.9(g) U.S. general aviation airports, 2008 NPIAS (6).

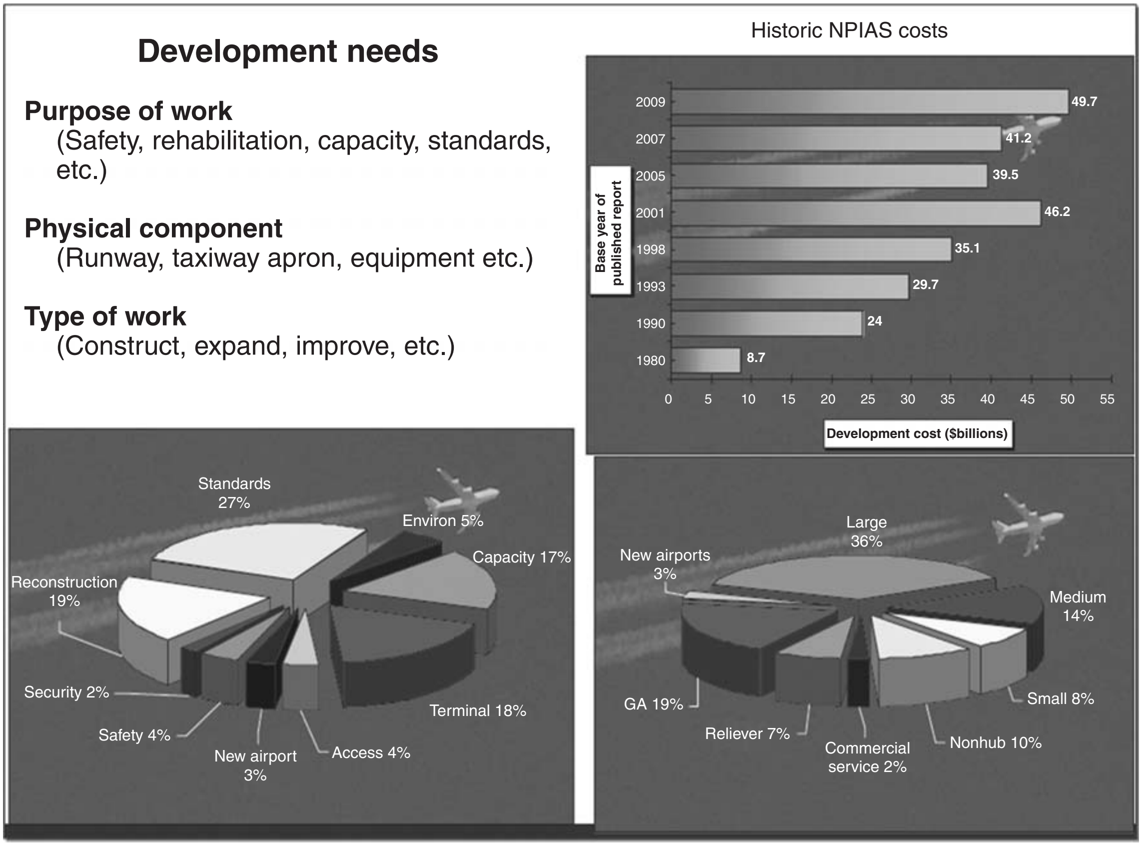


Figure 4.10 NPIAS airport development needs and costs (6).

Summary of 2009 NPIAS Report. The NPIAS report provides the aggregation of the field formulation and data inventory of all airports under the NPIAS in the United States (6). It includes the total costs of the development needs for all airports eligible for AIP funding. Figure 4.10 depicts the summary of airport development needs and costs in the 2009 NPIAS report.

The 2009 NPIAS report summary indicates that:

1. There are 3411 public-use airports that are projected to have AIP-eligible development needs of $49.7 billion during the five-year period 2009–2013.
   (a) Cost estimates of airport development for this report are 21% higher by $8.5 billion than the previous NPIAS report, reflecting rising construction costs.
   (b) Development estimates increased for all categories of airports
2. Approximately 61% of the development cost is slated to rehabilitate existing airport pavements to keep the airports up to standards.
3. Approximately 39% of the development cost is slated to accommodate growth in travel demand, with more passengers and cargo and larger and heavier aircraft.

However, the U.S. air transport industry believes that the above airport development fund allocations are not sufficient to maintain adequate air transport system performance, or provide the airport infrastructure required for future growth. In direct response to the NPIAS 2009–2013 report, the U.S. airport industry published an airport capital needs survey of what the industry believes are realistic capital needs (8). Airports Council International- North America (ACI-NA) argues that the NPIAS fund allocations are almost half of what the industry needs realistically to maintain system performance. Given the steady growth in passenger, air cargo, and aircraft movements over the years, increase of annual inflation of approximately +2.8% during this NPIAS period, and significant escalation of construction costs since 2003 of approximately +6% annually, the industry projects a different picture. Based on this 2008–2009 extensive survey of 95 airports of hub airports ACI estimates that assuming 1.5% construction costs escalation during the NPIAS period, airport capital needs is $94.3 billion, versus a NPIAS estimate of only $49.7 billion. The ACI capital need is broken down to $55.3 billion for large hubs and $13.3 billion for medium hubs. In comparison with NPIAS, numbers, the capital needs estimates by ACI indicate 194% and 78% differential for large and medium hubs, respectively (8).

National Airspace System Plan

While the NPIAS represents the "ground infrastructure component" of the entire air transportation system in the United States, the National Airspace System (NAS) represents the "airspace infrastructure component" of this system. In essence, these two with the airlines operating within this system form the three pillars of the U.S. air transportation system.

Recognizing the gradual and piecemeal evolution of this system over more than six decades, with the resulting inefficiencies, redundancies, and impediments to growth and safety, the FAA initiated a major effort to establish a modern, integrated, efficient, and safe system with the objective of adequately responding to the needs and requirements of the air transport industry and the entire economy to improve air commerce over the long term.

The NAS is comprised of a complex network of interconnected systems and subsystems as well as the people who operate, maintain, and use the system and detailed operational procedures and certification (9), in addition to airports that operate in harmony and function collectively to provide safe, expeditious, and efficient flying environment to the user.

The objectives of the NAS plan include (a) upgrading the infrastructure (both airspace and airports-airside) to enhance overall capacity of the system, (b) improving the system's safety by providing new safety and security features, and (c) incorporating new technological capabilities into the existing system to enhance efficiency. The complex composition of the U.S. NAS is defined by these facts: There are around 4000 airports in the NAS (and NPIAS), more than 400 of which are considered primary. The top 100 primary airports handle more than 650 million passengers on flights flown by more than 600,000 active pilots operating close to 300,000 aircraft. Over 33,000 FAA employees are actively involved in monitoring and controlling flying aircraft throughput the NAS.

To provide full representation of the entire system, the FAA has developed the model to provide the structure, description, and interrelationships of the complete architecture of the NAS. This model identifies FAA services for a "National Aerospace System," which includes the airports on the ground, airspace, and outer space. The NAS architecture is composed of the following "services":

1. Air traffic services (ATS)
2. Airport operation and management
3. Safety and security
4. Certification
5. Business management of the system

In the FAA effort to develop the NAS architecture, the focus was mainly on air traffic services (ATS), which includes the air traffic control (ATC), air traffic management (ATM), and air navigation functions of communication, navigation and surveillance (CNS/ATM) that are covered in Chapter 6.

The airport operation and management service of the NAS architecture considers the entire airport system plan to ensure that both the air and ground elements work in harmony. An airport basically revolves around three distinct functions: change of mode between air and ground, processing of entities using the airport, and change of movement type for passengers and freight (10). Airports are intrinsic components of the NAS, inseparable from its other components. Therefore, there is always an important overlap between the airport and airspace, a consideration that should not be overlooked or neglected when a new airport is designed. Figure 4.11(a) depicts this fact.

The airports component of the NAS architecture is based on the functional view of airports within the system, broken down into subsystems that function in line with the primary functional performance of the airport and its role in the system. Figure 4.11(b) depicts a schematic of the logical components of the airport function within the system.

These components are (11):

1. *Aircraft operations*, which covers surface movement support, airfield safety, obstruction limitation control, and airport emergency and security
2. *Aircraft ground service and maintenance*, which includes aircraft gate-ramp service operation, aircraft fueling, aircraft deicing and hazmat control, ground service vehicle access and control, and cargo operations
3. *Airport infrastructure development*, which includes airport planning, engineering design, development funding and financial assistance, environmental compliance (in conformance with the National Environmental Protection Act, NEPA), construction management and oversight, and project acceptance and commissioning
4. *Airport operations management*, which covers airside operations management, landside operations management, airport emergency management, and airport financial management
5. *Airport infrastructure and information management*, which covers system planning information system, airport infrastructure-GIS information system, airport safety information system, and airport activity information system

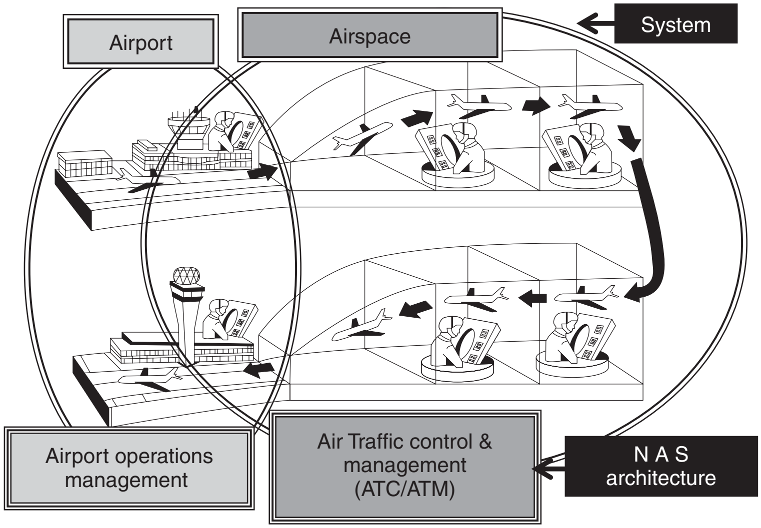


Figure 4.11(a) Graphical representation of systems interaction (airport–airspace) and respective NAS architecture services (airport management and ATS (8).

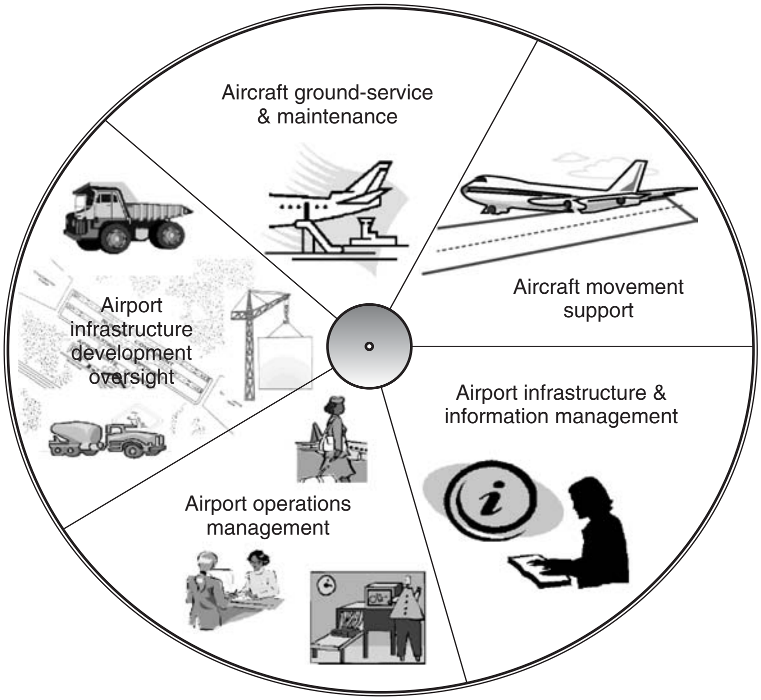


Figure 4.11(b) Schematic of logical components of the airport by function (10).

4.6 AIRPORT SYSTEM PLANNING IN EUROPE

United Kingdom: London Airport System

The London area provides a useful case study in airport system planning. In the late 1980s, it became apparent that the demand for air transport at the four London area airports was growing at a faster rate than capacity was expanding. The four airports serving the London area are Heathrow, 16 miles west of central London; Gatwick, 25 miles south of central London; Luton, 27 miles north of central London; and Stansted, 31 miles northeast of central London.

Terminal capacities of the individual airports (in terms of million passengers per annum) were forecast as follows:

Heathrow: 45 mppa in 1990, 50 mppa in 1995, 86 mppa in 2005, and ultimately 86 mppa in 2015
Gatwick: 26 mppa in 1995, 32 mppa in 2005, and ultimately 41 mppa in 2015
Stansted: 9 mppa in 1995, 21 mppa in 2005, and ultimately 35 mppa in 2015
Luton: 5 mppa in 1995, 10 mppa in 2005. However, Luton was eventually removed from the London airport plan and included in the East England airport plan.

However, the three major London airports, Heathrow, Gatwick, and Stansted, all under BAA Airports Company, have serious constraints on expansion. There is strong public opposition to building new runways for Heathrow. Gatwick Airport's capacity is constrained by the availability of only a single runway; it is therefore fruitless to increase terminal capacity beyond 30 mppa. The 5-mppa passenger limit at Luton is due mainly to the airport's proximity to Stanstead. Air traffic airspace control limits the number of air traffic movements (ATMs) to Luton as the new London airport, Stansted, continues to expand.

The UK Civil Aviation Authority, which has the responsibility of advising the British government on matters of aviation policy, undertook a study in the late 1980s to examine the impact of different airport expansion policies on air transport demand (12). Using 1987 as the base year, forecasts of total U.K. travel were developed for the years 2000 and 2005. For the latter year, the forecasts were made for three different assumptions:

1. *Scenario A*. Stansted airport would be permitted to expand to accommodate all traffic that naturally flowed to it when the London airports had reached capacity.
2. *Scenario B.* Stansted would be limited in its growth to a capacity of 20 mppa, but other airports in the southeast area of England could expand to take diverted traffic.
3. *Scenario C.* Stansted would be limited to 20 mppa and other southeast airports would not be able to take significant additional traffic.

Under these different assumptions, traffic is expected to divert from the London area and the southeast area. For example, significant traffic was diverted from the London airports to the East Midlands and Birmingham airports, 120 miles north and 100 miles northwest, respectively, of the London area. It is interesting to note that, under the most severe conditions of constraint in the year 2005, the CAA estimated that 16.6 mppa would be lost to air transport, either not made because passengers could not find a convenient airport or made by some other transport mode. This amounts to over 8% of all forecast trips.

A follow-up to the original plan was conducted in 2003, as the White Paper prepared by the Department for Transport (13). This White Paper sets out a sustainable long-term strategy for the development of air travel and airport capacity in the United Kingdom to 2030. While government's primary role is one of enabler and regulator, it is not the primary provider of civil airport capacity and does not authorize or preclude any particular development in any airport. Government in this document essentially sets out a policy framework against which all stakeholders could carry out their own development plans and take guidance on future planning of the airport system, collectively. While recognizing the huge socioeconomic benefits expansion of air travel has brought to economy and to the people, it also sets policies on striking a balance with the impacts of air travel and airports, particularly environmental.

The White Paper prescribes a range of measures to be applied nationally and locally that includes new legislative actions and creative economic instruments as well as improved technology and stringent planning conditions attached to airport development. The government's underpinning objectives here are to limit and reduce noise impacts over time, ensure air quality and other environmental standards are met, and minimize other local environmental impacts.

The main policy highlights of this paper include:

- Failing to provide additional capacity when and where it is needed would significantly damage the economy and national and regional prosperity.
- Taking advantage of the affordability of air travel and opportunities it brings to respond to the people's desire to travel further and more often by air.
- Seeking to reduce and minimize impacts of airports on nearby communities and on the natural environment.
- Ensuring that overall price of air travel reflects all its environmental and social impacts and that air transport industry pays the external costs its activities impose on society at large.
- Minimizing needs for airport development in new locations by making best use of existing capacity and increasing capacity at existing airports.
- Fully respecting rights and interests of individuals and communities affected by airport development.
- While providing assurance to all concerned in the planning of future airport capacity, sufficient flexibility is recognized and adapted to the uncertainties inherent in long-term planning.

For the South East England-London area, the White Paper concluded that while there is no strong case for developing a second international hub airport close to Heathrow, there is urgent need for additional runway capacity in the South East region. In fact, the White Paper stated that provision should be made for two new runways in this region by 2030; the first would be at Stansted and the second either at Heathrow or at Gatwick after 2019.

Based on the White Paper guidance, a capital investment program was developed by BAA for the phased capacity expansion of the three London area Airports (Table 4.1).

Table 4.1 Capital Investment Program for Capacity Expansion at the London Airports

	Million pound sterling (2005 prices) in year			
Year	Heathrow	Gatwick	Stansted	Total
2004–2005 (actual)	1133	131	23	1287
2005–2006	1236	100	50	1389
2006–2007	998	93	67	1,160
2007–2008	491	75	91	658
2008–2009	576	65	78	715
2009–2010	607	63	60	730
2010–2011	441	62	59	562
2011–2012	291	60	60	411
2012–2013	200	59	25	284
2013–2014	405	55	34	494
2014–2015	380	53	25	458
Total	5625	685	550	6860

Source: Ref. 13.

Since 2003, the government commissioned two studies to follow up on the White Paper—the Stern Review and the Eddington Study were undertaken and published in late 2006 (14). There has been progress since then, including:

- Better use of capacity, both in airspace and on runways, particularly in the congested London area
- Tangible improvements in passenger terminal development and refurbishment
- Improvement in engagement with local government and communities over airport development with long-term proposals and environmental mitigation measures
- Enactment of the Civil Aviation Act of 2006, which strengthened control powers over aircraft noise and local air quality, with industry making measurable progress in reducing those impacts
- Inclusion of aviation in the European Union Emissions Carbon Trading Scheme

4.7 AIRPORT SYSTEM PLAN ANALYSIS

Several analyses may be conducted as part of the entire effort to develop the airport system plan. These are discussed in this section.

Determine Individual Airport's Share of the System

Total demand at an airport is constituted of origin and destination (OD) traffic plus the number of transit and transfer passengers. The former can be modeled by airport choice models, while the latter is predicted by route choice models. These rather advanced forms of demand models are covered in Chapter 2.

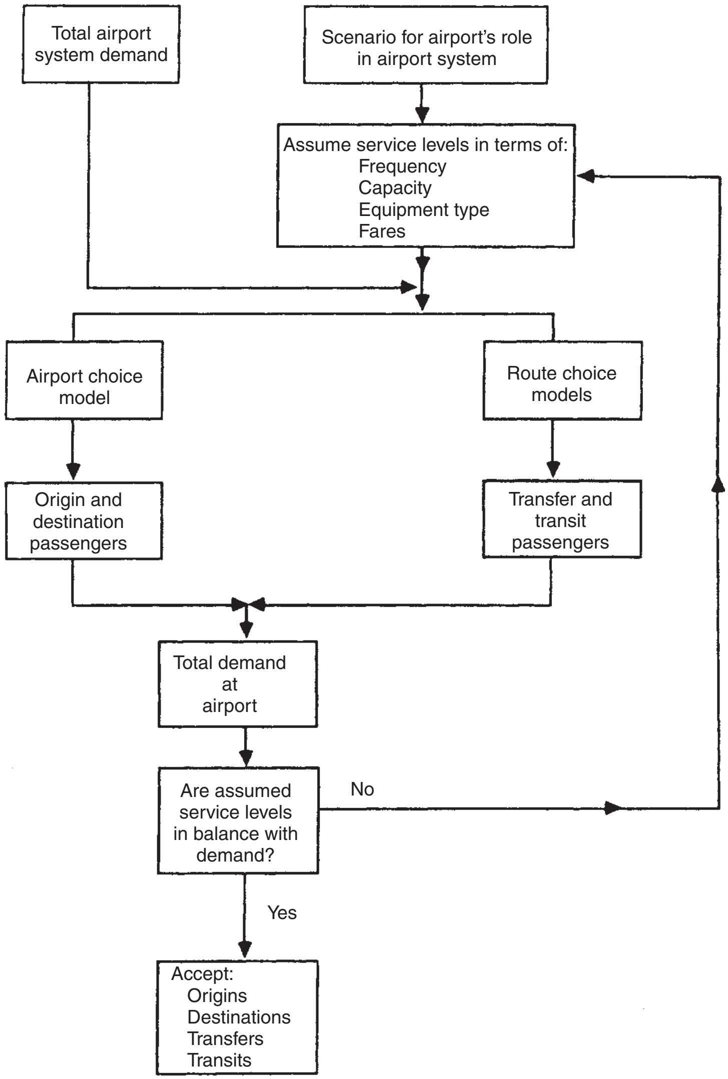


Figure 4.12 Flow chart of analysis for airport systems planning.

The process used to determine an individual airport's share of the airport system total is depicted in Figure 4.12. The process indicates the steps for predicting an individual airport's share of total system traffic when scenario analysis is used:

- A scenario for the development of the airport is set out in conjunction with scenarios for all other airports in the system.
- Airline service is postulated in terms of frequencies, capacity, equipment type (jet or turboprop), and fare levels.
- Originating and destined passengers are predicted using airport choice models.
- Transfer and transit passengers are predicted using route choice models.

- The total demand at the airport is compared with the airline supply levels assumed. When these are in balance, the demand obtained is accepted.

Develop the Comprehensive Airport System Plan

Where a comprehensive airport system plan is to be carried out, the required commitment of resources is likely to be extensive, especially in countries with well-developed air transport networks. The FAA has issued guidelines for preparing the airport system plan, including the metropolitan, regional, and state aviation plans (15). Federal law defines "integrated airport system planning" as "developing for planning purposes, information, and guidance to decide the extent, kind, location, and timing of airport development needed in a specific area to establish a viable, balanced, and integrated system of public-use airports." This includes four main elements: (a) system needs identification; (b) systemwide development cost estimate; (c) studies, surveys, and other planning actions to decide which aeronautical needs should be met by a system of airports; and (d) standards prescribed by a state, except standards for safety of approaches, for airport development at nonprimary public-use airports. Therefore, the primary purpose of airport system planning is to study the performance and interaction of an entire aviation system to understand the interrelationship of the member airports. The system evaluated in the plan can be the airports of a metropolitan area, a region (Figure 4.13), a state (Figure 4.14), or several bordering states.

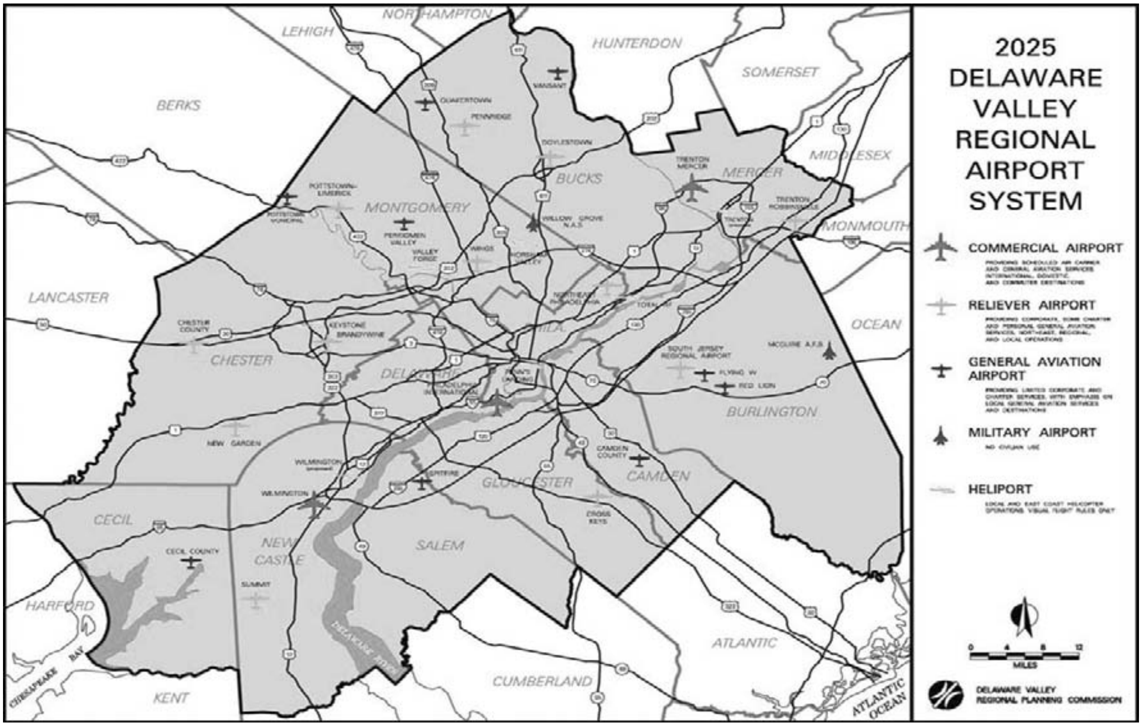


Figure 4.13 Sample of a regional airport system (15).

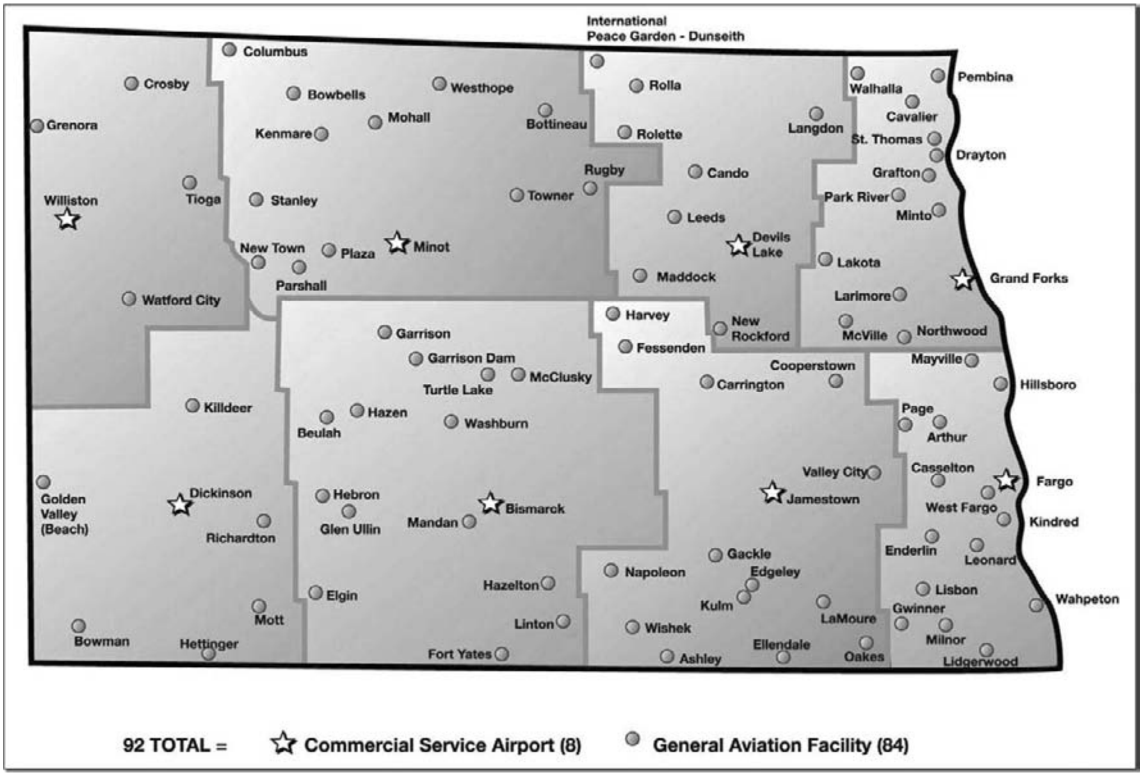


Figure 4.14 Sample of a state airport system plan (15).

The airport system plan augments the NPIAS, which the FAA prepared in 1984 and periodically updates (16) to replace the earlier National Airport System Plan. The NPIAS integrates local airport master plans with state aviation system plans, as shown in Figure 4.15. The whole plan is updated by a continuous planning process (shown in Figure 4.16), whereby interim and formal plan updates are prepared as reappraisal determines them to be necessary.

While the NPIAS provides an overall structure which forecasts reasonably well overall demand and indicates the way in which this demand can be accommodated, it does not, however, provide for the dynamic forces industry experts on the system. To assess industry dynamics, De Neufville and Barber (4) provided a methodological approach incorporating dramatic upheavals of the industry, such as deregulation and industry consolidation. The major reason is that the basic structure and building blocks of the NPIAS are essentially local airport plans. Nonetheless, the NPIAS format has performed reasonably well over the years in the U.S. context of a well-developed air transport mode. It should not, however, be used as a model for countries or states where the mode is not well developed; the bottom-up approach could in such cases lead to ill-constructed airport system plans. Even in the United States, which has a highly developed network, in the late 1980s considerable pressure was exerted to move from the traditional FAA method of airport systems planning to a more strongly centralized approach (17).

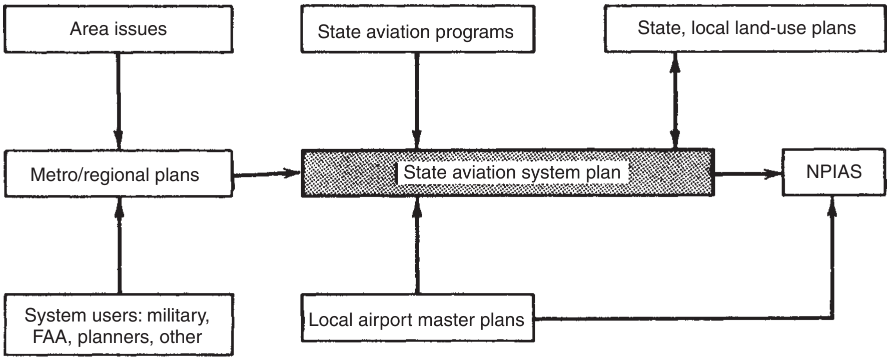


Figure 4.15 Planning relationships for state aviation plan (15).

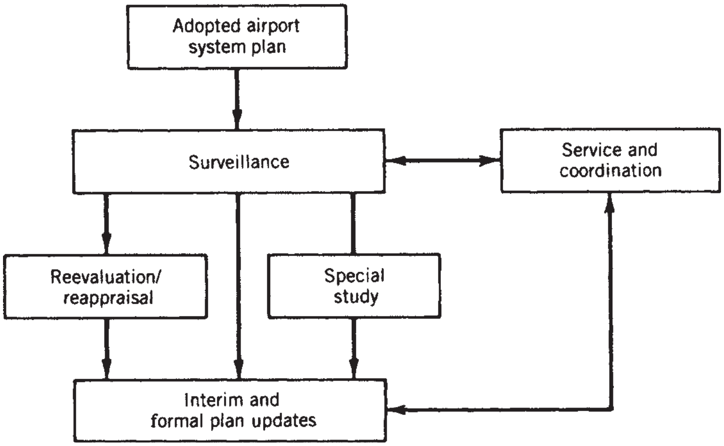


Figure 4.16 Continuous airport system planning process (15).

After several years of investigation into the problems involved, the Committee for the Study of Long Term Airport Capacity Needs recommended the following actions by the U.S. government to urgently improve the U.S. airport system (18):

- Setting up of a long-term strategic planning process with the FAA
- Immediate physical improvements to airport and aviation facilities to support a strategic planning process
- Definition of a set of short- and long-term goals for aviation
- Inauguration of a broad and greatly expanded research and development program in designated aviation areas

In coming to these conclusions, the committee looked at the future U.S. airport system by examining eight options for accommodating air travel demand (18):

- Make incremental capacity improvements at existing airports.
- Create new hubs at presently underused airports.
- Add new airports in metropolitan areas with high-traffic volume.

- Develop new airports dedicated to be transfer points (wayports).
- Apply administrative and regulatory techniques.
- Employ economic measures to redistribute demand and resources.
- Promote development of new aviation technology.
- Develop high-speed surface transportation technology.

These options were set within nine base scenarios of differing technological development and socioeconomic conditions. Finally, the committee examined and evaluated the following strategies of system development (18):

Strategy A: Continue on present course.
Strategy B: Build more airports in high-volume metropolitan areas.
Strategy C: Centralize system management.
Strategy D: Build an expanded, centrally managed system, using new airports in metropolitan areas with high volume.
Strategy E: Adopt a market approach with new airports, using economic measures to manage and allocate existing and new capacity.
Strategy F: Reconfigure the airport system, using new airports to serve as transfer points.
Strategy G: Revolutionize intercity transportation by introduction of new air and surface technology.

The strategies which offered the most promise for the satisfaction of future demand levels were found to be D, E, and G. If eventually adopted, these recommendations will have prompted a significant move of U.S. aviation planning in the direction of a strongly centralized or "top-down" philosophy.

Figure 4.17 depicts the top-down planning approach used for smaller secondary airport systems where much development is still likely to take place (4). This approach has a number of identifiable steps:

- The extent of the system to be considered should be identified.
- Existing airports and potential sites should be inventoried. This can be done at a more superficial level than required for the master planning of individual facilities (see Chapter 5).
- Develop scenarios for the roles to be played by different airports.
- Estimate total system demand under different demand growth scenarios (e.g., high, most likely, low).
- Develop scenarios for the various airports in a number of future systems. Synthesize the very numerous combinations into a small, robust set of options which best covers the range of options.
- Examine each scenario based on the following:
  - Estimate air service levels in terms of capacity, frequency, and cost.
  - Distribute systemwide demand using airport choice and route choice models (see Sections 2.10 and 2.17, respectively).
  - Ensure that demand and supply, in terms of service levels, are in reasonable balance.
  - Determine financial, economic, and environmental feasibility.

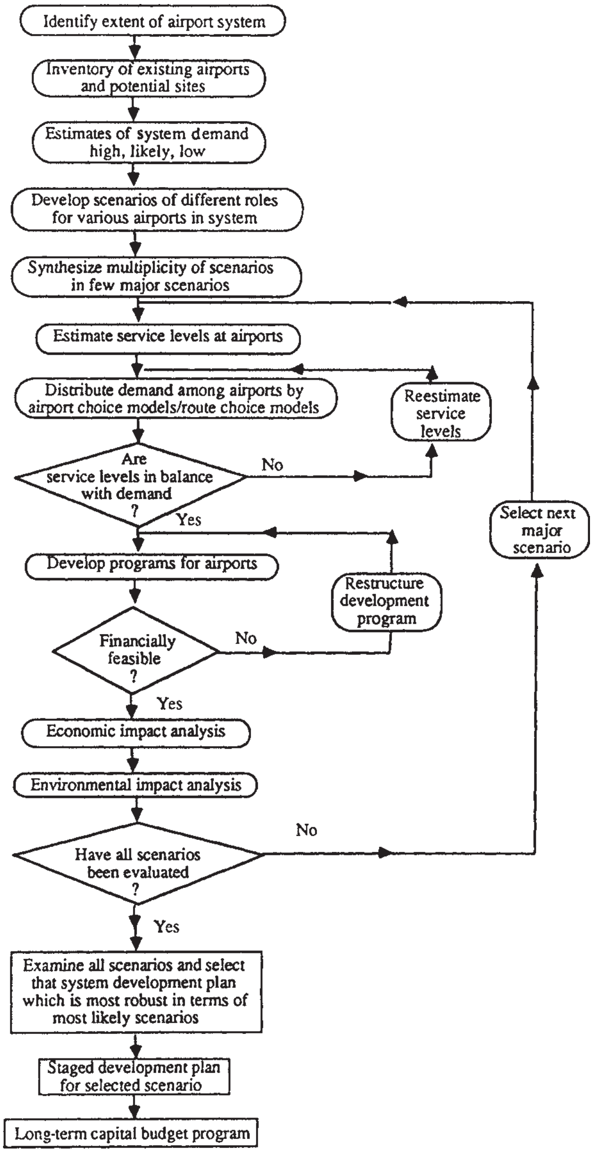


Figure 4.17 "Top-down" comprehensive airport systems planning analysis for secondary airport systems (4).

- Select the most robust scenario.
- Draw up a staged development plan.
- Establish a long-term capital budget program.

Airport System Performance

With the passage in the United States of the Inter-modal Surface Transportation Efficiency Act (ISTEA) of 1991 and the Transportation Equity Act for the 21st Century

(TEA-21) in 1999, the transportation planning community grew more cognizant of decision making of future investments in the transportation system from a multimodal perspective. In other words, there is competition between the modes that will be based on how each modal system fared and performed. Investment decisions on a rational multimodal basis will therefore have to be assessed based on the performance of each mode in a consistent way so that resource allocation across modes would maximize the contribution to the overall performance of the entire transportation system. The California Department of Transportation initiated an effort to identify and assess system performance measures of the state transportation plan that was conducted by the University of California at Berkeley under FAA funding through NEXTOR (19).

The state transportation plan proposed the system performance objectives to include three categories: economic vitality, safety and security, and mobility with system efficiency and cost-effectiveness. It also identified a set of desirable outcomes of two categories: effectiveness and efficiency and responsibility. In its analysis, the study proposed a performance measuring system that includes two main categories:

- *Effectiveness and efficiency*, focusing on mobility and accessibility, reliability, cost-effectiveness, customer satisfaction, and economic well-being
- *Responsibility*, covering sustainability, environmental quality, safety and security, and equity

System performance outcomes and respective measures are indicated in Table 4.2.

In complying with the Government Performance and Results Act of 1993, the FAA started introducing conditions and performance of the airports in the NPIAS plan

Table 4.2 System Performance Outcomes and Respective Measures (19)

Proposed performance measures California transportation plan update	
System performance outcomes	Candidate performance measures
Effectiveness and efficiency	
Mobility/accessibility	Travel time
	Delay (lost time)
	Access to desired locations
	Access to the transportation system
Reliability	Standard deviation of average trip time
Cost-effectiveness	Customer satisfaction index
Customer satisfaction	User opinion survey
Economic well-being	Share of transportation final demand in gross regional or state product
Responsibility	
Sustainability	Household transportation costs
Environmental quality	Conformity/compliance
	Livability
Safety and security	Accidents rates
	Crime rates
Equity	Income group share of mobility benefits

addressing six outcomes: capacity, safety, aircraft noise, pavement condition, accessibility, and financial performance (20). For each of these outcomes the FAA either compiles the data or asks airports to provide the data on a regular basis.

Another study conducted by MITRE assessed the national airspace system (NAS) performance and developed metrics to assist decision-makers in allocating scarce resources to produce most benefits and continue to improve service offered by the FAA air traffic management (ATM) system (21). This study identified eight performance outcomes grouped into two main elements:

- User perspective
  - Increase system capacity.
  - Decrease system delays.
  - Increase system flexibility.
  - Increase system predictability.
  - Increase user access.
- ATM service delivery
  - Increase availability of critical systems and improve service delivery.
  - Increase productivity.
  - Create a model work environment.

Dynamics of Regional Airport System Development

As demand for air travel grows at major airports that are capacity limited, capacity expansion of the airport system at the metropolitan and regional levels becomes critical. Increased use and expansion of secondary airports would be key to meeting future demand in capacity-starved airports of metropolitan areas. A study was conducted at MIT to explore the factors influencing the emergence of secondary airports and investigate the dynamics of multiairport regional systems (22). The study's objectives were to evaluate the dynamics of emergence of successful secondary airports and identify proactive ways to accelerate the emergence of future underutilized regional airports.

The life cycle of airports in metropolitan areas starts with airport construction and the airport proceeds in several steps, as depicted in Figure 4.18. First commercial service commences at the airport, and when a particular carrier enters the airport, growth starts and the airport matures and grows until it becomes capacity constrained. At this stage search is initiated by industry to find a secondary airport to relieve the core airport.

To reflect this discussion on the entire United States, the national airport system was composed of 19,576 airports in 2004; 5280 open to the public mostly concentrated on the two U.S. coasts, correlated with distribution of population. Based on the 2009 NPIAS report (5), there are 19,815 airports; 5190 open to the public, of which 3411 are NPIAS airports—386 of them are primary airports. Due to lack of land availability in metropolitan areas, opposition from local residents to building new airports, and development funding pressures, the number of airports has been reduced. Statistics of US Bureau of Transportation Statistics (23) have shown that certified public airports have been decreasing at a rate of four per year during the last 20 years at an annual

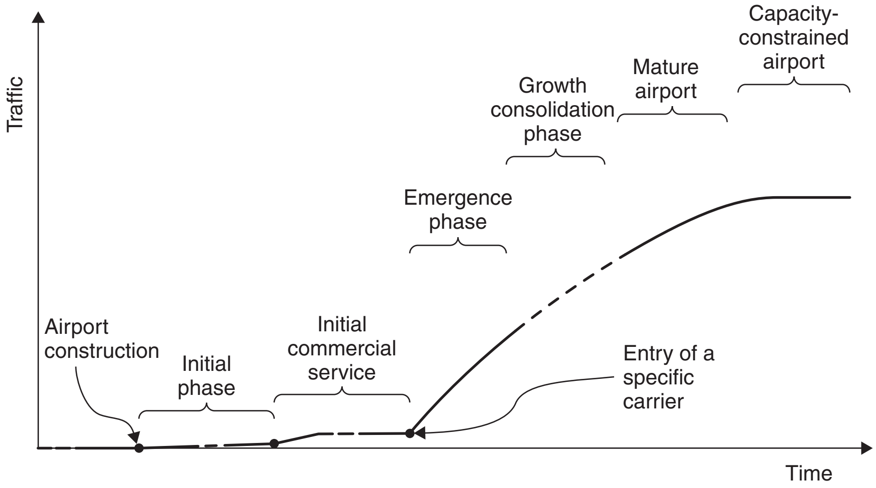


Figure 4.18 Typical life-cycle and stages of airport evolution (22).

rate of –0.6%. For all public airports, there was an average loss of 36 airports per year, which implies that the current set of airports will have to accommodate the growth of air travel demand.

The MIT study (22) provided a systematic methodology to analyze, the emergence of secondary airports and criteria to identify active secondary airports within the U.S. national airport system (NPIAS) (22). The identification and classification of secondary airports and the factors influencing their emergence were evaluated. The study integrated factors identified into the system dynamics model that was used to evaluate regional dynamics of multiairport systems. In order to do that, the top 30 highest volume airports in the United States were selected. Of the 30 airports 26 "regional airport systems" were identified. (A regional airport system is defined as all airports within 50 miles of a reference core airport.) There may be more than one core airport within the same region (e.g., JFK, LGA, and EWR in New York–New Jersey area and IAD, DCA, and BWI in the Washington–Baltimore area). Within the 26 regional airport systems, there were 275 airports identified, but mostly they were small GA airports. Table 4.3 and Figure 4.19 provide passenger enplanements and geographic locations for the 30 airports in the study.

Secondary airports were identified by analyzing traffic shares based on historical records of passenger enplanements as per the equation

$$\mathrm{T.S.}_{\mathrm{RAS}} = \frac{\text{enplanements at airport i}}{\sum_{\mathrm{i} \in \mathrm{A}} \text{enplanements at airport i}}$$

$$\text{with A} = \{\text{airports part of the regional airport system}\}$$

Airports with traffic share greater than 1% were considered to be core airports or secondary airports. Table 4.4 provides the percent share of core and secondary airports of their respective regional airport systems.

Table 4.3 Reference Airports for Case Studies (22)

Airport code	Airport name	Passenger enplanements
ATL	Atlanta	37,224,000
ORD	Chicago	31,483,000
DFW	Dallas/Ft. Worth	27,581,000
LAX	Los Angeles	24,007,000
MSP	Minneapolis/St. Paul	18,944,000
DEN	Denver	17,435,000
DTW	Detroit	16,563,000
SFO	San Francisco	16,431,000
PHX	Phoenix	16,083,000
LAS	Las Vegas	15,311,000
STL	St. Louis	14,923,000
EWR	Newark	14,904,000
IAH	Houston	14,735,000
SEA	Seattle	13,062,000
MIA	Miami	12,721,000
MCO	Orlando	12,529,000
BOS	Boston	11,066,000
LGA	LaGuardia	10,785,000
PHL	Philadelphia	10,346,000
JFK	Kennedy	10,137,000
CLT	Charlotte	9,442,000
SLC	Salt Lake City	8,709,000
PIT	Pittsburgh	8,014,000
BWI	Baltimore-Washington Intl.	8,002,000
CVG	Cincinnati	7,610,000
SAN	San Diego	7,248,000
TPA	Tampa	6,912,000
IAD	Dulles	6,830,000
DCA	Reagan National	6,657,000
MEM	Memphis	4,524,000

From the analysis of the traffic evolution patterns, airports were sorted based on their 2000 traffic and their historical role in the regional airport system.

Four airport categories were established:

- *Core Airports* (*Original*). The initial airport in the region from historical and evolution standpoints.
- *Core Airports* (*Emerged*). Airports that emerged while an original core airport was already in place and grew where traffic now exceeds passenger traffic of the original core airport.
- *Secondary Airports*. Airports with a traffic share between 1% and the traffic share of the core airport.
- *Secondary Airports* (*Reemerged from Original Core Airport*). Airports that met the secondary airport criteria but were the original core airport in the system. At some point they lost traffic, then regained traffic and reemerged.

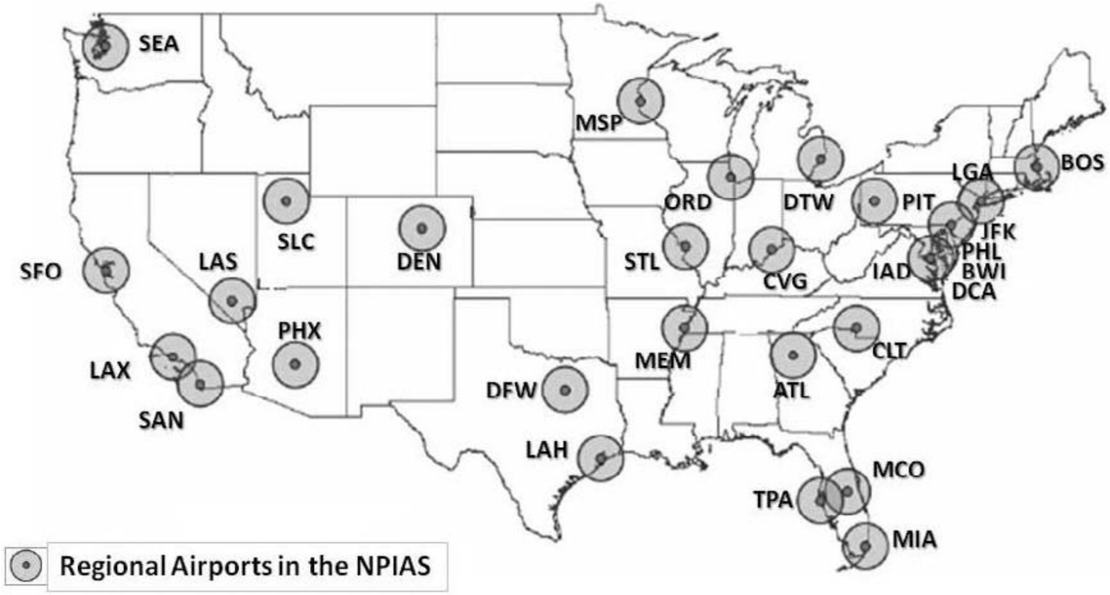


Figure 4.19 Map of the 30 selected U.S. regional airport systems (22).

Table 4.4 Passenger Traffic Share at Core and Secondary Airports (22)

Core airport	Traffic share (based on passenger traffic)	Secondary airport	Traffic share (based on passenger traffic)
Miami (MIA)	69%	Fort Lauderdale (FLL)	31%
Boston (BOS)	76%	Providence (PVD)	15%
		Manchester (MHT)	8%
Orlando (MCO)	95%	Orlando Sanford (SFB)	3%
		Melbourne (MLB)	2%
Tampa (TPA)	88%	St Petersburg (PIE)	4%
		Sarasota (SRQ)	8%
San Francisco (SFO)	64%	Oakland (OAK)	17%
		San Jose (SJC)	20%
Los Angeles (LAX)	77%	Burbank (BUR)	6%
		Ontario (ONT)	8%
		Orange county (SNA)	9%
		Long Beach (LGB)	1%
Washington National (DCA)	27%		
Baltimore (BWI)	36%		
Dulles (IAD)	37%		
La Guardia (LGA)	27%	Islip (ISP)	2%
Newark (EWR)	37%		
JF Kennedy (JFK)	34%		
Chicago O'Hare (ORD)	83%	*Chicago Midway (MDW)*	17%
Dallas Fort Worth (DFW)	89%	*Dallas (DAL)*	11%
Houston International (IAH)	79%	*Houston Hobby (HOU)*	21%

Note: Core airports in bold characters are emerged core airports
Secondary airports in italic characters are secondary airports (re-emerged from an original core airport)

The other types of airports in the system fell into three other categories:

- *General Aviation Reliever Airports*. Airports that are generally located at the periphery of a major metropolitan area but serve as high density GA airports.
- *Other Commercial and General Aviation Airports*. Airports that did not meet the 1% traffic share. They are part of a larger set of surrounding airports that generally have GA activity and/or low volume of commercial traffic.
- *Military Airports*. Airports used for military purposes but characterized as joint civilian/military use airports.

Major factors identified by the study with emergence of successful secondary airports include congestion at the core airport, distribution of population at the regional level, existence and proximity of a secondary basin of population close to the secondary airport, availability of airport ground access and infrastructure, and low level of connecting passengers at the core airport. The level of connecting passengers at the core airports is depicted in Figure 4.20.

Airport delays are an essential component of the level of service observed at the airport. From a customer perspective, poor level of service implies low airport attractiveness to passengers. The study found that there is correspondence between the congestion of the core airport and the existence of secondary airports in the system, and concentration at airports in the system generally correlates with the ranking of delays at airport.

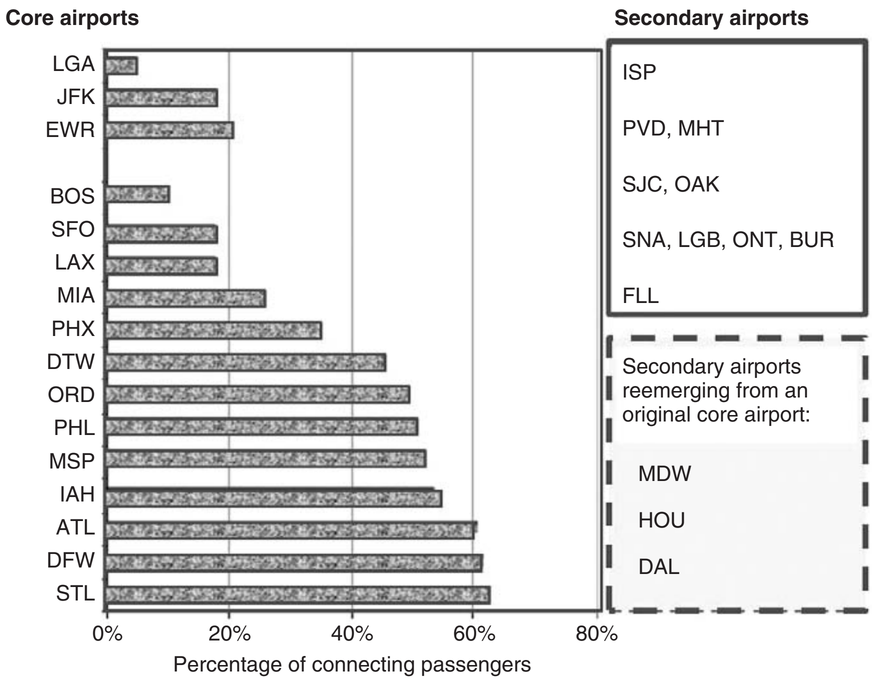


Figure 4.20 Percentage of connecting passengers at core airports (22).

Table 4.5 Low-Cost Carrier Entries into Secondary Airports (22)

Secondary airport	Low-cost carrier	Year of entry
Chicago Midway (MDW)	Midway	1979
	Southwest	1985
Fort Lauderdale (FLL)	Southwest	1996
Providence (PVD)	Southwest	1996
Manchester (MHT)	Southwest	1998
Orlando Sanford (SFB)		
Melbourne (MLB)		
St Petersburg (PIE)		
Sarasota (SRQ)		
Oakland (OAK)	Southwest	1989
San Jose (SJC)	Southwest	
Burbank (BUR)	Southwest	1990
Ontario (ONT)	Southwest	1985
Orange county (SNA)	Southwest	1994
Long Beach (LGB)	jetBlue	2002
Islip (ISP)	Southwest	1999
Baltimore (BWI)	Southwest	1993
Newark (EWR)	People Express	1980
Dallas (DAL)	Southwest	1971
Houston (HOU)	Southwest	1972

A more direct factor and an essential stimulus in the emergence phenomenon is the entry of an air carrier, generally a low-cost carrier (LCC). Entry of an LCC to secondary airports impacts the fares and energizes airport competition, resulting in market stimulation. As a result of LCC entry and the resulting fare competitiveness, these airports will soon experience rapid traffic growth. Table 4.5 lists the LCC entry into the airports selected in this study.

The analysis of what influences emergence of secondary airports indicated that the following factors play an important role in the emergence:

- Level of service at core airport, where congestion results in delays
- Availability of capacity at the regional level
- Distribution of population (density)
- Size of the local basin of population
- Airport infrastructure
- Political factors
- Connecting passengers at the core airport
- Entry of a LCC

The dynamic analysis of the study adopts the basic airport model built around the standard system dynamics approach using stock and flow diagrams and causal loops.

The stock and flow diagram starts with the demand for air transportation and then distributes this demand through the actual passenger enplanements if the demand is materialized. If not, the demand is spilled and flows to substitution modes of transportation (e.g., car, train). If the demand is still not materialized in any of the available modes of transportation, it is simply "spilled," and the potential passenger chooses not to travel.

Factors identified in the analysis of emergence of secondary airports were included in those causal loops. They are basically centered on two main composite variables: the airport attractiveness to airlines and the airport attractiveness to passengers.

In this study, two model subparts (core and secondary) were developed where inputs to both could describe real-world interaction between both subparts. Figure 4.21 schematically represents these two subparts in the system dynamics model:

- The *core airport congestion model* (congestion/capacity inadequacy), where the core airport congestion model is triggered by the lack of supply (capacity) at the core airport. It impacts negatively the attractiveness of the core airport to passengers, which translates into an increase in regional airport attractiveness to passengers. However, this attractiveness will only materialize in actual enplanements and operations if an airline is willing to enter this airport.
- The *local market demand model* (local market/unmet demand) is triggered by the unmet demand at the local level. It directly impacts the attractiveness of the secondary airport to airlines. A carrier that decides to enter this market and serve this unmet demand will trigger both the stimulation and the airport growth loops, resulting in the emergence of the secondary airport.

4.8 DATA STRUCTURE FOR AIRPORT SYSTEM PLANNING

The amount of desirable data for a system plan for even a limited number of airports is very extensive. In many cases, to obtain all such data would be prohibitively expensive in terms of time and cost. Where budgets are constrained, it would be necessary to collect only the most important of those which are not almost immediately available.

It is important to note that the data required for the airport system plan are similar in structure to the data used in a typical master plan, which will be addressed in Chapter 5, but they are different in two ways. The granularity of the data required for the airport system analysis is on the airport macrolevel. Also, the kind of analysis data adopted for the system plan would be different from the master plan analysis for the individual airport, as the former represents networks while the latter represents the nodes in a network.

The structure of a comprehensive database used in airport system plans includes (23):

Traffic Data

- Route and city pair specific data, including origin/destination flows
- Airport specific traffic data
- Traffic by other modes, especially in short-haul situations

The traffic data should be obtained on an annual, monthly, and daily basis, covering airport passengers, cargo, and aircraft operations. For the calibration of demand forecasting models and to determine each airport's traffic patterns, it is necessary to obtain traffic data for at least the seven past years.

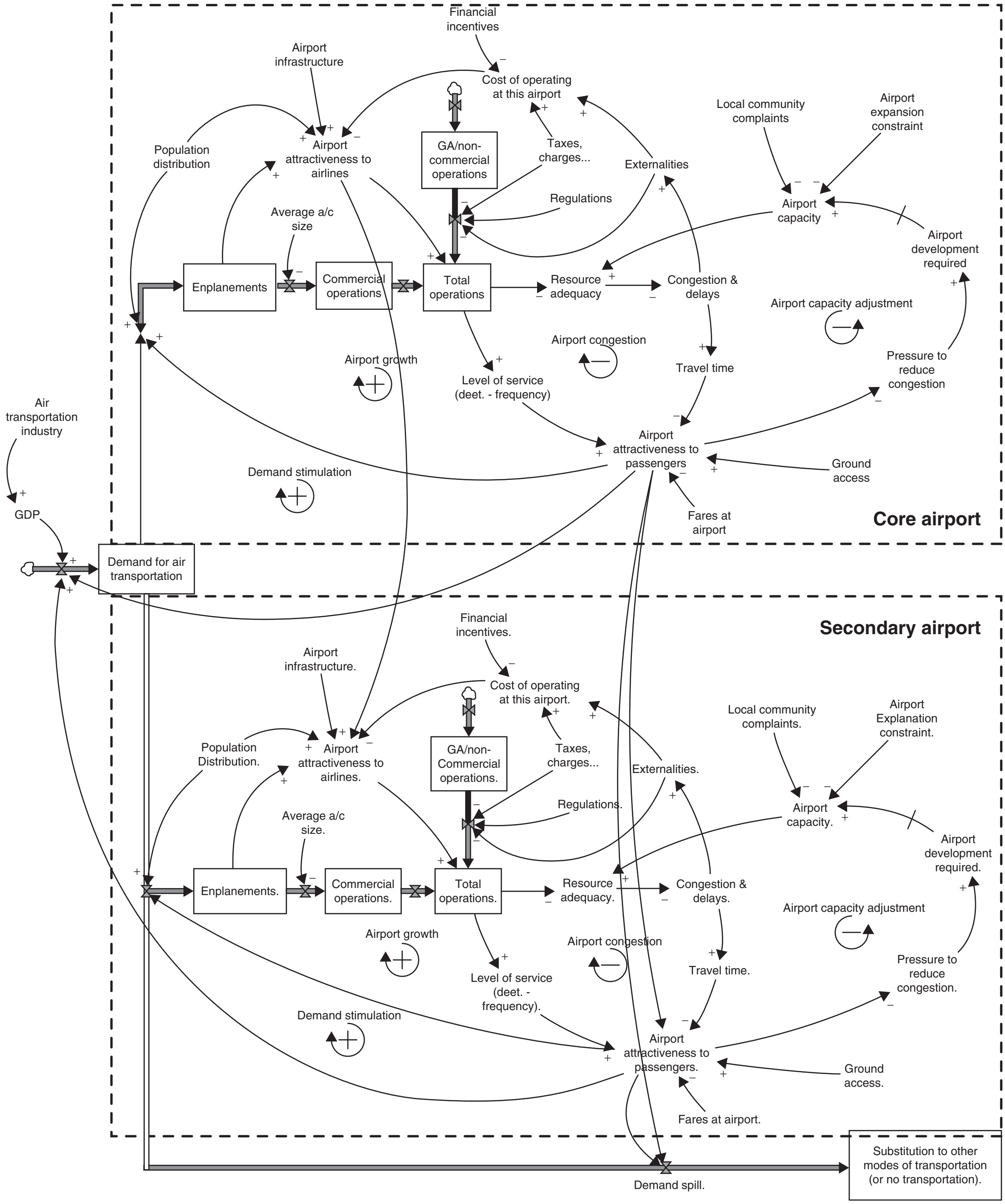


Figure 4.21 System dynamics model of a multiairport system (22).

Demand Characteristics

- Origin destination demand
- Trip purpose distributions for passenger demand
- Commodity classifications for cargo demands
- General aviation activity demand

Airport Data

- Financial results, operating costs, and revenues
- Facility inventories
- Capacity, for both airside and landside facilities
- Temporal traffic patterns, including hourly distributions
- General aviation–based aircraft and fixed-base operators
- Airlines served
- Access traffic conditions and facility inventories
- Safety records
- Weather conditions
- Traffic operating patterns, including delay characteristics

Supply Data

- City pair available capacity
- Schedules and fares for passengers and cargo
- Load factors prevailing
- Airline operating cost data

Socioeconomic Data

- Economic studies for regions and economic plans, if available
- Population and demographic characteristics and forecasts, if available
- Income characteristics and consumption patterns
- Foreign and tourism trade patterns
- Resource costs, including labor, fuel, and other inputs to aviation systems
- Prevailing land use patterns, both locally and regionally

The products of a typical airport system plan include (15, 25):

(a) An *airport system plan report*, which is a document that identifies the system of airports that meets the air transportation needs of a state, metropolitan area, or multistate region. The airport system plan report is the guiding document for assigning a current and future role to each airport and in determining development needs, expressed in estimated costs and implementation schedules, based on priorities and likely funding sources.

(b) *Interim updates* are a critical element of the airport system planning process that involve a reevaluation of the basic airport system plan report in relation to existing conditions in the local airport system. A reevaluation will be necessary when planners identify changes or constraints that affect the validity of the existing plan. Specific examples of areas that may need frequent updates include pavement condition surveys, obstruction analysis, design standards review, and airport capital improvement plans.

(c) *Electronic data systems*:

- GIS database covering planning, environmental, engineering, and financial information and analyses.
- Airport surveying–GIS program to accurately collect and maintain airport information, hence reducing duplication and maintenance of redundant or disparate data.
- Airport Capital Improvement Program (ACIP).
- Electronic ACIP database for the airports in the plan. It should include a three- to five-year list of recommended priority development, describing the proposed project, funding requirements (federal, state, local), and implementation years.
- Airport Layout Plan (ALP) electronic database is prepared in accordance with the criteria included in the FAA airport master planning circular (25), based on an FAA ALP checklist.
- Airport inventory electronic inventory of the airport reporting current and historic aircraft activity, based aircraft, enplanements, design aircraft using the airport (Airport Reference Code), the annual service volume (ASV) for the existing airfield configuration, and environmentally sensitive features.
- Aviation forecasts for 5, 10, and 20 years for based aircraft, passenger enplanements, and aircraft activity and current and expected design aircraft.
- Financial data in electronic format includes the portions of the development costs covered by AIP grants, passenger facility charges, state grants, bonds, and airport revenues as well as the potential for financing capital projects with general funds or debt financing instruments.

(d) *Special studies* that may include air service, air cargo operations, standards reviews, safety area analyses, business jet access, satellite navigation and GPS, environmental or drainage inventories, surface access, economic impact, obstruction analysis, general aviation security, multisite acoustic aircraft counters, and pavement management system.

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5

Airport Master Planning

5.1 AIRPORT MASTER PLAN: DEFINITION AND OBJECTIVES

The planner's idealized concept of the form and structure of the ultimate development of the airport is contained in the airport master plan (1, 2, 3). This plan is not simply the physical form of the ultimate development but a description of the staging of development and both the financial implications and the fiscal strategies involved. Master planning applies to the construction of new airports as well as to the significant expansion of existing facilities.

The FAA states that the goal of a master plan is to provide the framework needed to guide future airport development that will cost-effectively satisfy aviation demand while considering potential environmental and socioeconomic impacts. The FAA strongly encourages that planners consider the possible environmental and socioeconomic costs associated with alternative development concepts and the possible means of avoiding, minimizing, or mitigating impacts to sensitive resources at the appropriate level of detail for facilities planning.

Specific objectives of the master plan include (1):

1. Document the issues that the proposed development will address.
2. Justify the proposed development through the technical, economic, and environmental investigation of concepts and alternatives.
3. Provide an effective graphic presentation of the development of the airport and anticipated land uses in the vicinity of the airport.
4. Establish a realistic schedule for the implementation of the development proposed in the plan, particularly the short-term capital improvement program.
5. Propose an achievable financial plan to support the implementation schedule.
6. Provide sufficient project definition and detail for subsequent environmental evaluations that may be required before the project is approved.
7. Present a plan that adequately addresses the issues and satisfies local, state, and federal regulations.
8. Document policies and future aeronautical demand to support municipal or local deliberations on spending, debt, land use controls, and other policies necessary to preserve the integrity of the airport and its surroundings.
9. Set the stage and establish the framework for a continuing planning process. Such a process should monitor key conditions and permit changes in plan recommendations as required.

5.2 HIERARCHY OF PLANNING (1)

In the United States, airport planning is carried out by a multilevel governmental process, where plans are formulated to meet overall transport demand in coordination with other transportation and comprehensive land use planning. These levels are as follows:

- *The National Plan of Integrated Airport Systems* (*NPIAS*), a 10-year plan continually updated and published biennially by the FAA. It lists public-use airports and describes the development considered to be in the national interest, making them eligible under the Airport and Airway Improvement Act of 1982 for financial assistance for airport planning and development.
- *Statewide integrated airport systems planning,* which is executed by state aviation planning agencies. This level of planning identifies the general location and characteristics of new airports and the expansion needs of existing airports in furthering statewide aviation goals.
- *Regional/metropolitan integrated airport systems planning,* which identifies and plans for large regional or metropolitan areas. Needs are stated in general terms within the context of statewide system plans.
- *Airport master plans* are prepared for individual facilities. The operators usually require the assistance of consultants for such detailed studies of the long-range development plans of the individual airport within the context of statewide plans.

5.3 ELEMENTS OF AIRPORT MASTER PLAN: FAA

The structure and content of the FAA master plan are closely aligned to the FAA's objective to establish a planning process that is uniform across the United States and is suitable for implementing development of U.S. airports within a coordinated federal funding process. As such, it is at variance with the more heterogeneous approaches of countries which plan according to ICAO guidelines. The FAA specifies a number of elements which are generally to be included in any master planning exercise (1):

1. *Preplanning*. The preplanning process includes:

   - Initial needs determination based on observed or potential deficiencies in the existing plan or airport
   - The manner of calling for requests for proposals and subsequent consultant selection
   - Development of study design, showing a scope of work that includes goals and objectives, data availability, forecast horizons, environmental considerations, schedules, and deliverables; organization of a formal structure of review committees for coordination and public involvement program; adjustment of the scope of work to budgetary requirements
   - Negotiation of consultant contract
   - Application for study funding

2. *Public Involvement*. Once the consultant team is under contract and has been issued a notice to proceed, a public involvement program is established and the key issues of various stakeholders are identified and established, ensuring:

- Timing of public involvement that ensures that all major decisions are set before the public at an early stage of the planning process before irreversible decisions are made
- Appropriate public involvement techniques where appropriate: technical advisory and citizens' advisory committees, public information meetings, small-group meetings and briefings, public awareness campaign, and Internet exposure with Web pages
- Stakeholder identification, including potentially users and tenants, groups and individuals within the sponsor's (airport's) organization, FAA personnel, resource agencies and governmental units with regulatory or review authority, and other interested groups
- Identification of key issues, broadening those earlier identified in the preplanning stage to include the stakeholders
- Documentation of the key issues and the operation of the public involvement progam itself

3. *Environmental Considerations*. It is necessary that the airport master plan demonstrate a clear understanding of the environmental requirements needed to move forward with each project in the recommended development program.One of the requirements of the Airport and Airway Development Act of 1970 is that environmental factors must be considered both in the site selection process and in the design of the airport. Furthermore, the National Environmental Policy Act of 1969 established the Council of Environmental Quality to develop guidelines for federal agencies affected by the policy law. These requirements are mandated by subsequent FAA orders. A proposed project must be considered not with respect to individual work items but from a broader program context and will be classified into one of three categories (4):

- Categorical exclusions
- Actions normally requiring an environmental impact assessment
- Actions requiring an environmental impact statement (EIS)

Although relatively few airport actions require an EIS, any federal actions regarding proposals with respect to airport development that significantly affect environmental quality must be accompanied by an EIS which will cover the following areas(4):

- *Purpose and Need for Action*. The problem being addressed, alternatives to resolve the problem, the benefits of federal action, the need for the proposed action, preferences of the applicant and agency, and the parameters for defining a reasonable range of alternatives to be considered.
- *Alternatives Including Proposed Action*. These must be reasonable, feasible, and meet the project's purpose. Reasonable alternatives not within the agency's jurisdiction should be included.

- *Affected Environment*. The existing environmental conditions of the potentially affected geographic area.
- *Environmental Consequences.* Environmental consequences of the alternatives, including the proposed action, adverse environmental impacts which cannot be avoided, relationship between short-term use of the environment and the maintenance and enhancement of long-term productivity, and the irreversible commitment of resources.
- *Mitigation.* The EIS describes mitigation measures considered or planned to mimimize environmental impact.

It is therefore suggested that any airport master plan be evaluated factually in terms of the following potential effects where applicable:

Air quality	Fish, wildlife, and plants	Noise
Coastal resources	Floodplains	Secondary Impacts
Compatible land use	Hazardous materials, pollution prevention, and solid waste	Socioeconomic impacts
Construction impacts	Historical, architectural, archeological, and cultural resources	Water quality
DOT Act	Light emissions and visual impact	Wetlands
Farmlands	Natural resources and energy supply	Wild and scenic rivers

For the full details of the requirements of the EIS for a U.S. airport the reader is referred to Chapter 17 and reference 4.

4. *Existing Conditions*. An inventory of pertinent data for use in subsequent plan elements. The inventory is a large data collection exercise that allows the airport planner to gain complete understanding of the nature and scale of existing facilities. For all potential sites, the planner needs data relating to the following: the physical and environmental characteristics of the site; the presence nearby of any existing airport; the structure of airspace and the status of air traffic management in the area and the availability and location of navigational aids; existing and projected land uses at and in the general affected area of the site; the location of utilities, schools, hospitals, and other public infrastructures; and the legislative constraints related to ordinances, bylaws, zoning, building codes, and so on, which could affect the nature and scope of any projected airport development.

All existing plant at the site is inventoried with respect to condition and remaining useful life. Data will be required on ground access, circulation, and parking. Additionally, historical data on weather conditions need to be gathered because of the weather's effect on airport operations and capacity.

Financial data are necessary for the preparation of a financial plan. Historic and current data should be available from management in the form of aeronautical and nonaeronautical revenues and expenditures as well as the structure of airport indebtedness.

To avoid unnecessary data gathering, existing data, master plans, and regional and local planning studies should be used to provide an information base. The scope of the data-gathering exercise should be carefully examined as to its potential use in order to avoid collecting unnecessary data.

5. *Aviation Forecasts*. There is a need to develop short-, medium-, and long-term forecasts of aeronautical demand to permit well-conceived planning leading to the ultimate development of the airport site. The discussion of forecasting procedures appearing in Chapter 2 is not repeated here. The planner needs forecasts of passenger volumes as well as movement of aircraft and cargo both at the annual and the peak levels. Knowledge of annual movement is necessary for estimating the magnitude of revenues that will accrue to the facility; peak movement levels determine the scale of facility required to assure a balance of capacity to demand.

The aviation demand elements which need to be forecast for airport master planning purposes may be summarized as follows:

Aircraft operations

Itinerant:	Air carrier, air taxi, commuter, general aviation, military
Local:	General aviation, military

Where appropriate, further forecasting of operations should predict domestic/international splits, annual instrument approaches, IFR versus VFR operations, and helicopters.

Passenger volumes

Total enplanements, air carrier, air taxi, and commuter passengers. Where appropriate, the passenger forecasting would also include domestic versus international split, general aviation, and helicopter passengers.

Based aircraft

Aircraft mix

Air cargo and mail

For master planning purposes, forecasts are usually prepared in terms of *levels of annual activity* for 5-, 10-, and 20-year horizons. In addition to this, peak load forecasts are made. It is not generally appropriate to design airport facilities to meet the full requirements of short-lived peaks of demand. Some middle ground between supplying for average and peak demands is sought. A commonly used concept in this regard is the “design hour,” which is an estimate of the peak hour of an average day in the peak month. Additional peaking forecasts may be required for special areas in the airport. For example, peak 20-min forecasts are frequently used for designing baggage facilities.

For forecasting purposes, the FAA recommends using estimates of economic growth and changes in industrial activity, demographic patterns, disposable personal income, geographic factors, alternative technology, sociological and political factors, regulatory changes, and historical air traffic data.

6. *Facility Requirements*. At this stage, having determined the levels of future demand, it is possible to assess the ability of the existing airport, both airside and landside, to support the forecast demand. Furthermore, the planner will identify the demand levels that will trigger the need for facility additions or improvements and will estimate the extent of new facilities that may be required to meet that demand. The requirements for new facilities can be driven by a number of factors:

- Lack of capacity due to increased demand
- Changes in security requirements required by the Transportation Security Administration
- Changes in FAA standards or noncompliance with existing standards
- Changes in the nature of the airport's vision of service provision
- Outdated and unsuitable existing facilities

Future facility requirements can be estimated by simulation of future operations. These should be related to future levels of demand, so that the planner can identify what demand levels trigger the need for expansion or improvement of a particular facility.

Demand–Capacity Analysis

With knowledge of forecast demand for a proposed airport site and with different estimates of staged development beyond existing infrastructure levels, the analyst is able to test a variety of options of development through a demand–capacity analysis. The analysis should be broad and should cover the following areas of operation in sufficient detail to permit preliminary facility sizing. The planner can then compare:

(a) Forecast aircraft operations vis-à-vis airspace capacity (5)
(b) Forecast aircraft operations vis-à-vis air traffic control facilities (6, 7)
(c) Forecast aircraft operations vis-à-vis airfield capacity (8, 9, 11)*
(d) Forecast passenger movements vis-à-vis passenger terminal capacity (10) (see Chapter 10)
(e) Forecast cargo volumes vis-à-vis air cargo terminal capacity (see Chapter 11)
(f) Forecast access traffic vis-à-vis surface access route capacity (12)

The types of new facilities required, their scale, and the staging of their construction are determined as a result of the demand–capacity analysis. These elements are developed according to FAA standards in the United States and according to ICAO or applicable national standards elsewhere. The facilities required and the elements requiring consideration are as follows (1):

(a) *Runways.* Orientation, length, width, clearances, clear zones, approach slopes, orientation, crosswind runway provision, grades, capacity, staged construction, cost implications of delay to aircraft, pavement design strength and cost effectiveness.

*ADSIM, SIMMOD and RDSIM referenced here are FAA simulation models which are available to the public at reasonable cost. Propietary simulation models are also available and many planning organiztions may choose to use models which they find more suitable for their purposes.

(b) *Taxiways.* Width, location, clearances, design and location of exits, grades, effect on runway capacity, staged construction, pavement design strength and cost effectiveness.

(c) *Electronic, Visual, and Satellite Aids to Navigation*. This provision depends on fleet mix, percent of time bad weather is present, and cost to users.

(d) *Airspace Requirements*. This may require a detailed examination, often using simulation techniques. Major airfield reconfigurations can require significant airspace changes or redesign.

(e) *Passenger Terminal Complex* (12–17).

Gates and apron frontage: Clearances, grades, aircraft mix, number of aircraft gate positions by aircraft class, aircraft parking clearances, ground servicing equipment space requirements.

Passenger terminal building: Public areas required for major functions such as baggage claim, check-in, government controls etc;airline and administration offices, maintenance and mechanical services; commercial space for shops and services.

Curbfronts: These are a function of the modal splits used by arriving and departing passengers and the needs of service vehicles

(f) *General Aviation Requirements*. These include a wide variety of users: business aircraft, light cargo, recreation, law enforcement, flight training, agriculture, and fixed base operators. They require aircraft storage areas and buildings for the based aircraft, transient aircraft parking areas, and terminal facilities. The terminal facilities can range from simple one-room structures to extensive terminals with many amenities for the business traveler.

(g) *Air Cargo*. For commercial service airports and large general aviation airports, cargo operations can be very diverse. They include the following:

Belly freight carriers: passenger aircraft, using some of the belly space for containerized freight

Combination carriers: passenger aircraft with a reconfigured cabin, using some of the main deck for containerized freight

All cargo carriers: sell space to freight forwarders or companies and carry freight between airports

Integrated carriers: door-to-door services using their own aircraft and trucks, often requiring their own freight terminal

Freight forwarders: arrangers of transport which includes ground transport at either end of the flight and customs clearance where necessary. The air transport leg is arranged but not carried by the forwarder.

(h) *Support Facilities*. The future requirements of the following support facilities should be examined: aircraft rescue and firefighting, airport maintenance, fuel storage, aircraft maintenance and deicing.

(i) *Ground Access*

Regional transportation network: Only at the largest airports, the demand on the regional network must be examined and the impact of increased air transport demand evaluated.

On-airport circulation roadways: The added demand from passengers and their meters and senders, employees, delivery vehicles, and others will be diverse in destinations and timing of peaks.

Users of the roadway facilities requiring consideration are passengers, passenger meeters and senders, taxis, limousines, courtesy vans and buses, local buses, regional buses and coaches, rental cars, and charter bus operations.

Parking must be supplied for passengers, meeters and senders, employees, visitors, and delivery vehicles.

(j) *Utilities*. The master plan will address the future requirements for water, sanitary sewage, stormwater drainage, deicing run-off, industrial waste, communications, natural gas, and electric power supply.

(k) *Other Requirements*. At many airports there are extensive areas and some developments that are nonaeronautical in character. Some are considered temporary until the land is needed for aeronautical purposes; others have been developed along with the airport. Agricultural land is an example of the first type; the newly developing airport cities covered in Chapter 16 are examples of the second. At this stage the planner needs to review the future spatial and infrastructure needs of these areas.

7. *Alternative Development and Evaluation*. Options are identified to meet projected facility requirements and to provide alternative configurations for each major component. In an elaborate three-stage process recommended by the FAA, the expected performance of each alternative is assessed against a wide range of evaluation criteria, including its operational, environmental, and financial impacts, plus consideration of best planning practice. Qualitative and quantitative measures are used. The recommended development alternative which emerges from this process is developed in the airport layout plan. The FAA-recommended procedure for alternative development and evaluation is too detailed for reproduction here but is fully documented in reference 1.

8. *Airport Layout Plan Drawing Set*. One of the key products of a master plan is a set of drawings that provides a graphic representation of the long-term development plan for an airport. The primary drawing in this set is the airport layout plan. Other drawings may also be included, depending on the size and complexity of the individual airport.

The full set of recommended drawings comprises:

Cover sheet
Airport layout plan
Data sheet
Facilities layout plan
Terminal area plan
Airport airspace drawing
Inner portion of approach space drawing
On-airport land use drawing
Off-airport land use drawing
Airport property map
Runway departure surface drawing

Utility drawing
Airport access plan
Other necessary plans that are specific to the airport

9. *Facilities Implementation Plan*. This section of the master plan provides a summary description of the recommended improvements and associated costs. The actual timing of improvements depends, in large part, on the levels of demand that trigger the need for expansion of existing facilities. However, based on the output of the demand/capacity analysis, a capital improvement program can be produced that identifies expenditure and the most likely time that these will be incurred. Table 5.1 shows an example of a simple capital improvement program for the three-stage expansion of an existing facility. The scheduling of the various elements of facilities implementation is usually in the form of a time- and activity-based Gantt chart.
10. *Financial Feasibility Analysis*. The financial plan for the airport describes how the sponsor will finance the projects recommended in the master plan and demonstrates the financial feasibility of the program.

Financial Feasibility. A financial analysis must be made of the forms of capital available for carrying out the development. In the United States, these include general obligation bonds, revenue bonds, private finance, financing from specially formed nonprofit corporations, industrial development authority bonds, federal grants, state and municipal grants, and retained revenues:

General obligation bonds, backed by the full faith and credit of the municipality, have been the most common funding mechanism. They bear relatively low interest rates.

Revenue bonds are backed by the revenues generated by the facility being financed. Generally, they have interest rates 1–1.5% higher than general obligation bonds. They can be used only where facilities generate a sufficient operating surplus.

Special facility revenue bonds are normally issued by the airport for the construction of a facility for a third party, backed by the revenues generated by the facility.

Industrial development bonds can be issued by states, local governments, or airports to fund construction of a facility to increase nonaeronautical revenues.

Third-party or Private financing can be arranged for facilities such as hangars, hotels, and fuel distribution systems. The availability of such financing depends on developing sufficient revenue to pay off the indebtedness. Usually available from banks, private financing is a typical arrangement for constructing facilities on land leased from the airport by a third party. The airport is, in this way, relieved of the responsibility of raising the necessary capital.

Nonprofit corporation bonds are backed by special-use taxes. In some instances, nonprofit corportions have been formed to finance improvements, with these improvements reverting to the municipality on the retirement of the bonds. Interest rates are usually lower than for revenue bonds. The method has been used for financing maintenance hangars and air cargo facilities.

Table 5.1 Outline of ICAO Master Planning Process

Planning Step	Description
Preplanning considerations	Coordination, planning procedure, planning organization, goals, and policy objectives
Forecasting for planning purposes	Requirements, forecasts required, accuracy, methods and principles of forecasting, factors, presentation of forecasts
Financial arrangements and controls	Capital costs: currency requirements, source of funds, domestic and foreign financing; operational costs: sources of income; financial control and accounting
Site evaluation and selection	Land required, location of potential sites, factors affecting airport location, preliminary study of possible sites, site inspection; operational, social, and cost considerations; environmental study; review of potential sites; outline plans and estimates of costs and revenues; final evaluation
Runways and taxiways	Dimensions, strength; aircraft characteristics, performance, and runway length; configuration; airfield capacity
Aprons	Layout of aprons, size of stands, parking, service, and hangar aprons, holding bays, security, apron accommodations
Air and ground navigational and traffic control aids	Visual aids, radio navigation aids and their buildings, demarcation of critical areas, air traffic services, search and rescue services, apron control, communications
Passenger building	Planning principles, airport traffic and service characteristics, factors affecting scale of services to be supplied, capacity and demand
	Connection of passenger building to access system, passenger and baggage processing, waiting areas, governmental frontier controls, airside linkages, apron passenger vehicles, transit and transfer passengers, passenger amenities and other passenger building services
Cargo facilities	Siting, building function and type, apron, facility requirements, access, parking, inspection, and control
Ground transport and internal airport vehicle circulation and parking	Private and public transport modes, traffic data, internal roadway circulation, curbside, vehicle parking
Airport operations and support facilities	Administration and maintenance, medical center, ground vehicle fuel stations, generating stations, water supply and sanitation, flight catering, kitchens, meteorological services, aircrew briefing and reporting, aircraft maintenance, rescue and firefighting, general aviation facilities, police, hotels
Aircraft fuel facilities	Safety, implications for gate occupancy times,movements of large and heavy vehicles, storage capacity, fuel storage location, aircraft fueling systems
Security	Airside security: roads, fencing, isolated parking position, security parking area, emergency explosive holding area
	Landside security: passenger buildings, public storage lockers

Federal grants are available to public-use airports included in the NPIAS. Such grants are partially awarded on a traffic share basis and partly at the discretion of the FAA. The funds are limited to specific types of improvements. Not all forms of improvements are eligible for federal grants.

State grants are awarded on a discretionary basis, usually through the state Department of Transportation.

Retained revenues—Some of the financing for improvements comes directly form the airport's own retained earnings from revenue-generating activities such as:

- *Passenger facility charges* paid by the passengers through the airlines. There are strict FAA limitations on what can be funded from these charges: safety, security, congestion reduction, noise mitigation air quality improvement enhanced competition, and so on.
- *Customer facility charges* are fees paid by airport customers for facilities that provide nonaeronautical services on the airport.

For further discussion of the financing of airports both within the U.S. system and in developed and developing nations, the reader is referred to reference 17.

Economic Feasibility. The FAA requires that, when possible, airports should carry out benefit–cost analyses (BCAs) as part of the master planning process. A formal BCA should be written for projects that enhance the capacity of the airport and exceed $5 million in AIP funds. Guidelines for such an analysis according to FAA requirements are contained in reference 18.

An FAA-approved Airport Layout Plan Update (ALU) may be considered satisfactory for airport development purposes, where a full master plan incorporating steps 1–10 above is considered more than is necessary. The ALU must be considered as a substitute for a master plan only for small changes in airport planning.

Figure 5.1 shows a typical structure for the preparation of the master plan in diagrammatic form.

5.4 ICAO GUIDELINES FOR STRUCTURE OF MASTER PLAN

A planner operating outside the United States is likely to use the ICAO manual procedures or national procedures based on the ICAO manual (10, 11). In general terms, the ICAO procedure is very similar to that recommended by the FAA.*

However, since member countries of the organization range from highly industrialized states to quite undeveloped nations, the procedures outlined are less specific with respect to the form of the master plan, the methods of analyzing problems of environmental impact, and the manner in which economic analysis is to be carried out.

The ICAO manual states that the airport master plan is a guide for:

- Development of physical facilities of the airport
- Development of land uses for areas surrounding the airport
- Determination of environmental effects of aerodrome construction and operation
- Establishment of airport access requirements

In addition, the plan can be used to provide guidance on policy and decisions in both the long and short term, to identify potential problems and opportunities, to assist in securing financial aid, to serve as a basis for negotiations between the airport authority and its tenants, and to generate local interest and support. The manual identifies a

*It is interesting to note that the preface to the ICAO manual states that the material contained in the document does not necessarily reflect the views of the ICAO.

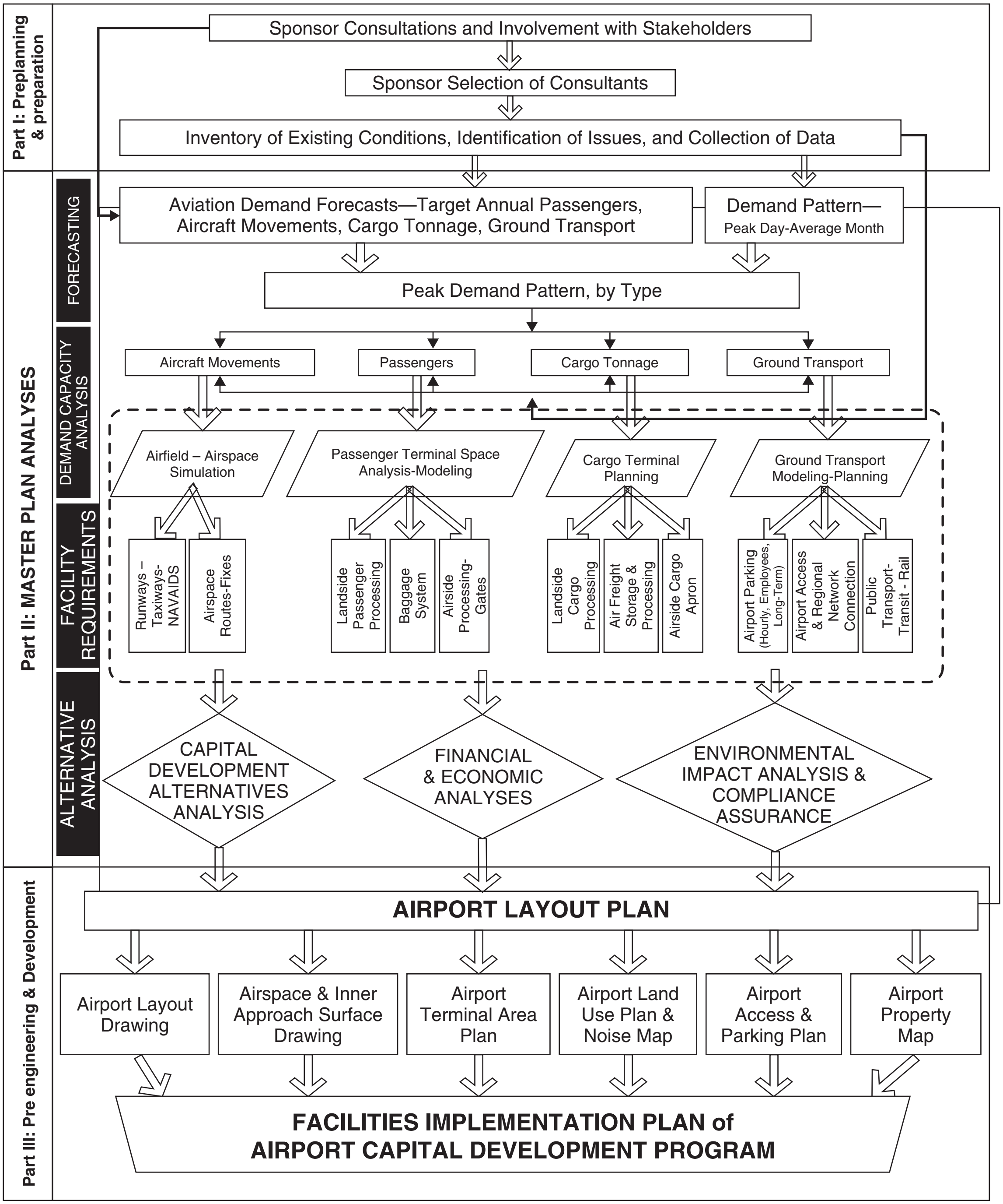


Figure 5.1 Master plan preparation process.

number of areas that will be included in any master planning activity. These are policy and coordinative planning, economic planning, physical planning, environmental planning, and financial planning. The master planning process itself is made up a number of defined steps:

1. Prepare a master work plan.
2. Inventory and document existing conditions.
3. Forecast future air traffic demand.
4. Determine scale and time phasing of facilities.
5. Evaluate existing and potential constraints.
6. Determine the relative importance of constraints and other considerations.
7. Develop a number of master plan options.
8. Evaluate and screen all plan options.
9. Select the most acceptable and appropriate option, refining and modifying it in response to the evaluation process.
10. Prepare master plan documents in final form.

The ICAO manual states that the master plan is no more than a guideline that must later be developed into a more detailed implementation program. Table 5.1 outlines the ICAO master planning process.

5.5 AIRPORT LAYOUT DESIGN

There are no firm rules which can be stated for determining airport layout. The procedure is a design exerecise in which compromises in one area must be weighed against advantages gained in others. The design for each airport layout is site specific, and whereas general concepts can be moved between sites, the individual aspects of each site will almost certainly result in slightly different layouts. The layout of an airport is dependent upon a number of factors, of which the most important are:

1. Number and orientation of runways
2. Number of taxiways
3. Size and shape of aprons
4. Area and shape of available land
5. Topography and site soil conditions
6. Obstacles to air navigation
7. Required proximity of land uses within the airport boundary
8. Surrounding land uses
9. Timing and scale of phased development of the airport
10. Meteorology
11. Size and scale of airport facilities being planned

In preparing a layout plan, it is normal to examine a number of potential layouts and to select the best option from competitive solutions. This best solution is further refined by developing and selecting from suboptions.

The principal facilities to be considered in an airport plan include:

Runways
Taxiways
Passenger terminals and aprons
Cargo terminals and aprons
Rescue and firefighting services
Air traffic control tower
Aircraft maintenance
Long-term and short-term parking
Access roads
Rail and public transport access
Airport maintenance, snow clearance, engineering base
Navaids
Lighting
Flight kitchens
Fuel farm
General aviation terminal and apron
Sewage treatment and pumping stations
Electrical substations
Security fences and control gates
Hotels
Industrial uses

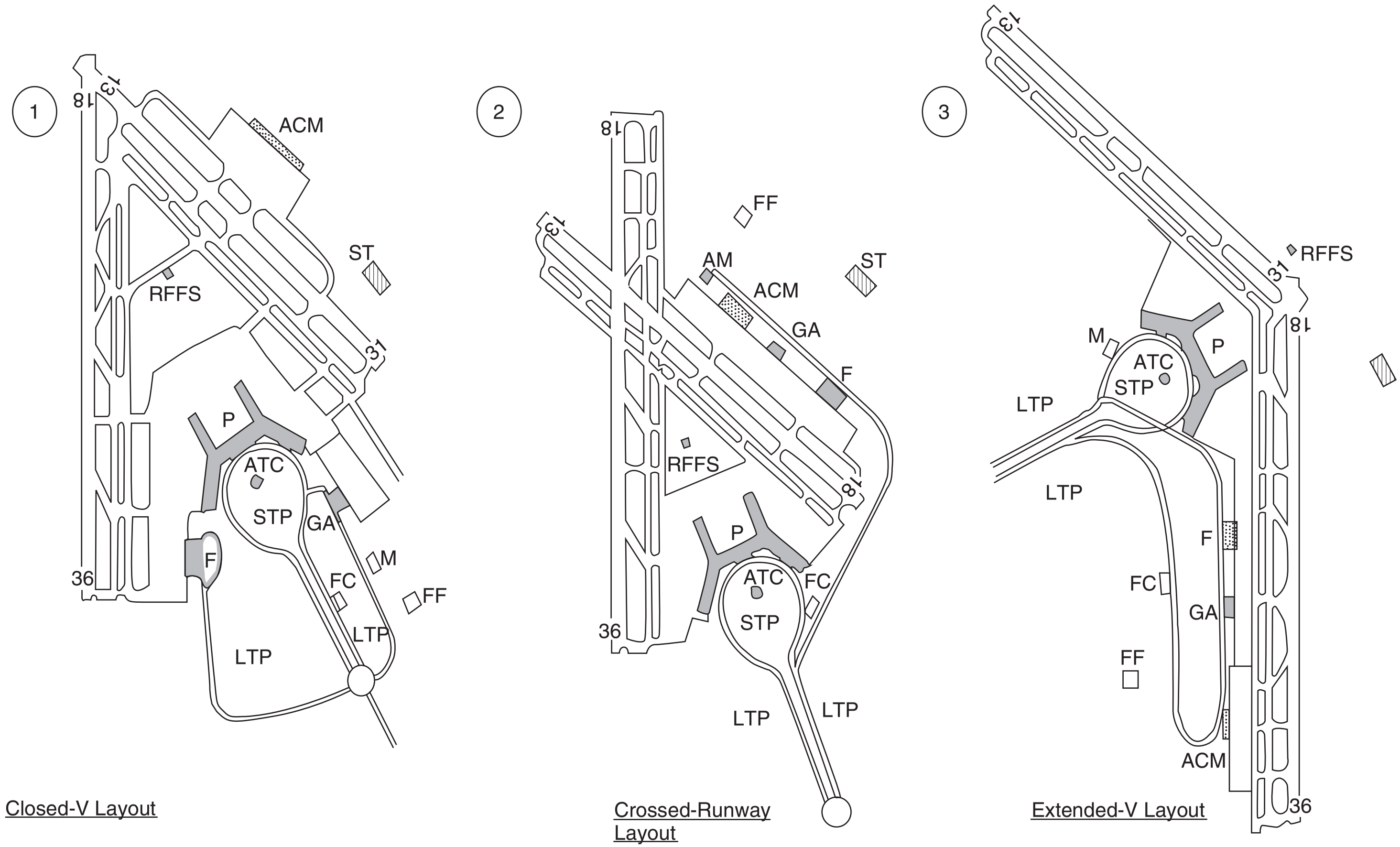
For a more detailed description of the content of the airport layout plan, the reader is referred to Appendix F of reference 1.

Figure 5.2 shows three schematic layouts of an airport with two runways of orientation 18-36 and 13-31. The *closed-V* layout is reasonably compact in its overall space requirements, has reasonable taxiing distances, and provides reasonable space for expansion of the terminal area between the two runways. On the other hand, the *crossed-runway* layout, while providing short taxiing distances and a compact overall site, squeezes the terminal into a site which offers little opportunity for expansion. The *extended-V* layout provides ample flexibility in the design of the terminal area but at the expense of a large overall land requirement and poor operational efficiency on the airside.

At large airports which are used by large transport aircraft, there is a need for parallel runways to accommodate the high volumes of air transport movements. As indicated in Chapter 3, the spatial needs of the extensive passenger terminals and the associated aprons require much greater runway separation than the minima required for IFR parallel approaches.

5.6 DATA REQUIREMENTS FOR MASTER PLANNING

Notwithstanding the method used, all master plans must be founded on assumptions and forecasts built from an extensive and valid database. The collection and validation of data are therefore important and time-consuming elements of the master



Key

RFFS	Rescue & fire fighting systems
P	Passenger terminal
ATC	Air traffic control tower
F	Freight terminal
FC	Flight kitchens
M	Airport maintenance, engineering, motor transport
ACM	Aircraft maintenance
ST	Sewage treatment
LTP	Long-term parking
STP	Short term parking
FF	Fuel farm

Figure 5.2 Layout options for given runway lengths and orientation.

planning process. In a master planning exercise, the following data requirements could be expected:

Demand and Traffic

Passengers

Annual passenger movements over the last 10 years

Monthly passenger movements over the last 5 years

Hourly passenger movements for 10 peak days during the last 5 years

Aircraft

Annual movements over the last 10 years

Monthly movements over the last 5 years

Hourly movements for 10 peak days during the last 5 years

Airline and ICAO estimates of regional passenger growth, both domestic and international

Current and future aircraft fleet mix over the next 15 years

Historic patterns of military movements and estimates of growth of these movements if the airport is a shared facility

Scheduled patterns of operating airlines

General socioeconomic data based on the size and projected growth rates in the locality and region of airport, including data on population, employment, income, tourism, building activity, retail sales, industrial output, and so on; current income distribution within city, region, and nation, with projected changes in distribution pattern

Cost and service levels of competing land (and, if applicable, sea) transport modes

Environmental Data

Local planning regulations

Local development plans, both detailed and structural, indicating plans for metropolitan and regional developmen.

Existing land uses and status of development in the airport surroundings

Local transportation plans

Relationship between local transportation plans and national transportation plans and investment strategies at various governmental levels

Local and national noise regulations, both current and planned

Physical Data

Description and modal share of existing access modes

Meteorological data—wind records, rainfall, snow, periods of low visibility

Topographical details to approximately 30 km (18 mi) around each airport with contours to 10 m at a scale of 1:50,000

More detailed topography to a limit of 3–5 km (2–3 mi) outside airport boundary to a contour of approximately 1 m at a scale of 1:2000

As-built plans of existing facilities with details of ownership

Detailed breakdown of square footage of existing building space allotted to various functions

Architectural detail plans of any existing terminal, designating usage to various facilities: for example, immigration, customs, departure lounge, check-in, baggage claim, administration, concessions

Structural details of construction of aprons, taxiways, runways, and major buildings; evaluation of the strength and surface condition of these structural elements

Appraisal of the structural soundness of existing buildings, plus an indication of structure type (permanent, light construction, or temporary)

Condition and extent of existing drainage and sewerage

Condition and extent of existing lighting on runways, taxiways, aprons, and approaches

Condition and extent of existing markings

Condition, type, and capability of existing navigation and telecommunication aids

Data on hazards to aircraft penetrating protected surfaces

Details of existing services/firefighting/apron services, and so on

Other necessary physical data, including environmental data on flora and fauna

General

Other transportation and major development plans in the environs of the airport site

Commercial, tourist, industrial, and governmental development plans

Aeronautical

Holding stacks, approaches, missed approaches, takeoff, and climbout procedures

Airways

Financial

Revenue/expense account

Debt structure

Capital expenditure

Assets/liabilities

Breakdown of revenues by source

Legal limitations on debt structure and financing

Construction

Detail costs of unit prices of construction materials: for example, earth, steel, concrete, and masonry prices

Finish costs

Equipment costs

5.7 STRUCTURE OF MASTER PLAN REPORT

The presentation of the master plan is in the form of a report which describes the following:

Introduction and purpose of the master plan

Inventory of the existing conditions and facilities

Demand analysis: forecasts of passenger traffic , cargo traffic, air transport movements, general aviation and military movements, ground access traffic movements by public and private modes

Demand/capacity analysis: comparison of the existing capacity vis-à-vis the forecast demand—approaches, runways, taxiways, aprons, terminals, support facilities, access, and parking

Sequenced facility provision: sequenced and staged provision of capacity in accordance with the development of demand. Where necessary, capacity enhancement will be computed for:

Airside: Runways, taxiways, apron, holding areas, support facilities

Terminals: Passenger and cargo

Landside: Access modes and parking, support facilities

Passenger terminal layout with preliminary sketches

Cargo terminal

Schedule of improvements: usuallyin the form of a Gantt chart showing major improvement items and timing

Cost estimates: runways, taxiways, aprons, and holding areas; cargo and passenger terminals; navaids, control tower

Utilities and support facilities (meteorological, fire, fuel, catering, security, etc.); roads, parking, and other access facilities; military areas; general aviation facilities; aircraft maintenance areas, airport maintenance areas

Capital improvement program: usually supplied in spreadsheet format, for example, as in Table 5.2

For FAA purposes, Appendix F in reference 1 sets out the normal requirements for an FAA layout plan set. For other purposes, the following drawings will form part of the master plan report:

A. Airport Layout Plan

1. Location map (1:500,000)
2. Vicinity map (1:25,000) approximately
3. Airport layout map, which includes:

   (a) Prominent airport facilities, such as runways, taxiways, aprons, blast pads, stabilized shoulders, runway end safety areas, buildings, navaids, parking areas, roads, lighting, runway marking, pipelines, fences, drainage, segmented circle, wind indicators, and beacon

   (b) Natural and man-made features: trees, streams, ponds, rock outcrops, ditches, railroads, power lines, towns

Table 5.2 Example of a Master Plan Cost Estimate for a Typical Project with Three-Stage Expansion of Existing Facility

	Stage 1	Stage 2	Stage 3
Type of expenditure	2013–2017	2018–2022	2023–2032
Paving			
Airfield (includes lights)			
Runways	9,440,550	2,161,890	25,590,330
Taxiways	16,952,640	9,475,590	24,157,350
Aprons	4,116,660	3,700,155	20,776,500
Roads	—	—	—
Terminal and services	3,985,200	3,645,000	16,912,800
Parking lots	1,093,500	—	3,523,500
Buildings			
Expansion of existing terminal	27,216,000	9,225,000	—
New terminal	—	—	153,090,000
Fire fighting and rescue equipment	—	—	2,430,000
Airport maintenance	—	—	4,009,500
Relocation			
Fixed base operator	4,860,000	—	—
Military	972,000	2,430,000	—
Airport maintenance	850,500	—	—
Miscellaneous			
Electrical	3,280,500	534,600	2,041,200
Utilities	1,093,500	—	4,860,000
Drainage	730,500	364,500	4,252,500
Landscaping	—	—	3,645,000
Fencing	243,000	—	972,000
Site preparation	5,491,800	3,256,200	14,337,000
Total estimate for construction	80,326,350	34,792,935	280,597,680
Legal, administrative, and engineering costs	17,215,545	7,645,725	61,731,495
Total project	97,541,895	42,438,660	342,329,175
Land acquisition	39,183,750	0	0
Total estimated cost	136,725,645	42,438,660	342,329,175

(c) Revenue-producing, nonaviation-related property
(d) Areas reserved for future aviation and services development
(e) Areas reserved for nonaviation uses: industrial areas, hotels, etc.
(f) Existing ground contours (3 m or 10 ft)
(g) Fueling facilities, tie-down areas
(h) Facilities to be phased out
(i) Airport boundaries
(j) Runway clear zones and associated approach surfaces, including location and height of controlling objects
(k) Airport reference point
(l) Coordinates and elevation of existing and ultimate runway ends and thresholds

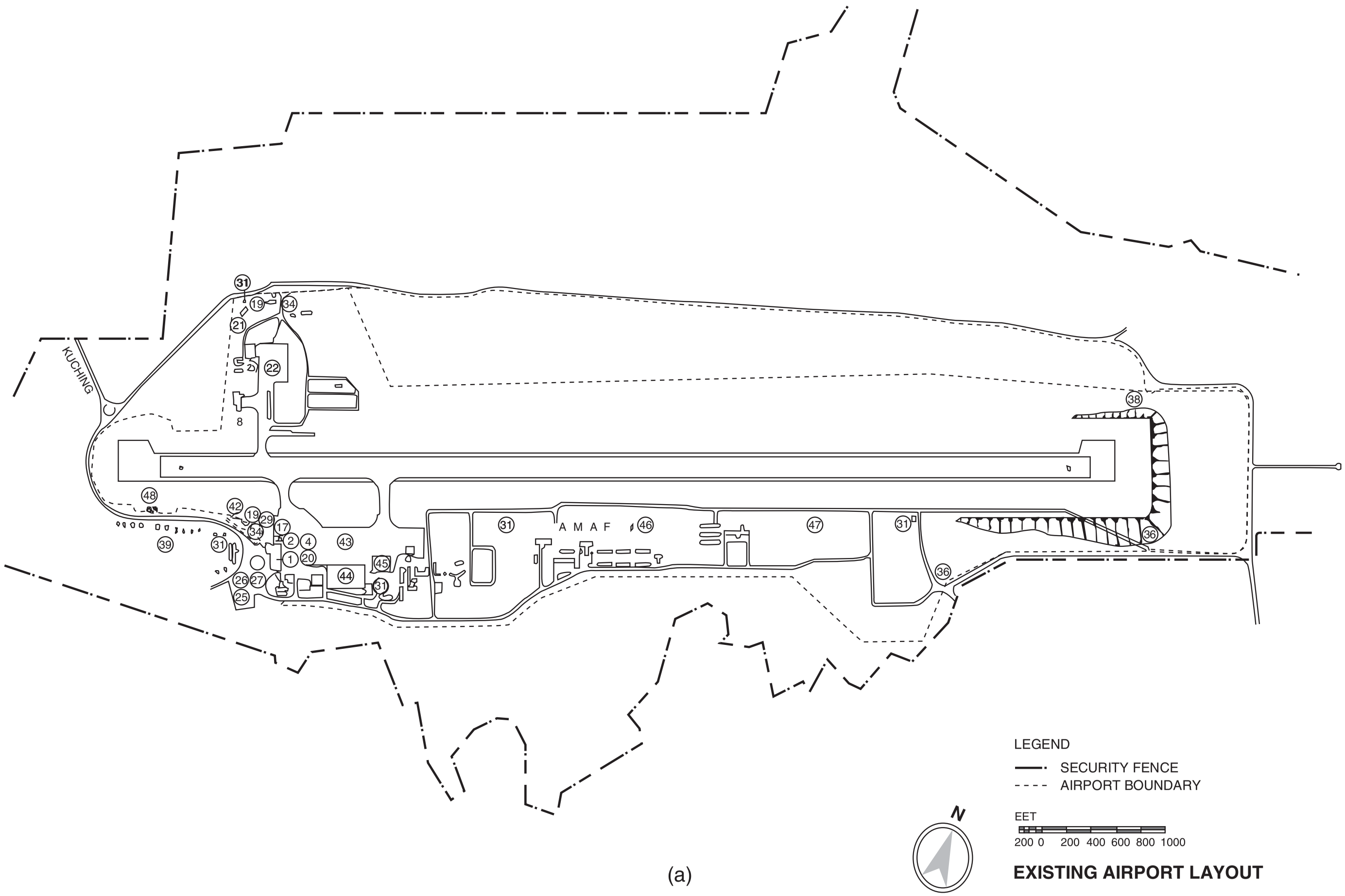
(m) True azimuth or runway
(n) North point-true and magnetic, with magnetic declination (variation) and epoch year
(o) Pertinent dimensional data: runway and taxiway widths, runway length, taxiway widths, taxiway–runway–apron clearances, apron dimensions, building clearance lines, runway clear zones and parallel runway separation. Deviations from FAA standards should be noted.
(p) Map scale 1:2500–1:7500 should be used depending on size of airport.

4. Basic data table showing:

(a) Airport elevation
(b) Airport reference point and coordinates
(c) Airport magnetic variation
(d) Mean maximum daily temperature in hottest month
(e) Airport and terminal navaids
(f) Runway identifications in magnetic numerals, for example, 13/31, 4/22
(g) Percent effective runway gradients on each existing and proposed runway
(h) Percent wind coverage by runways
(i) Designated instrument runway
(j) Pavement type (grass, asphalt, p.c. concrete)
(k) Pavement strength designation of each runway
(l) Approach surfaces for each runway
(m) Runway lighting
(n) Runway marking
(o) Electronic and visual approach aids and weather facilities

5. Wind information—wind rose with runway orientation superimposed
6. Designated instrument runway or runways for precision instrument approach procedures
7. ICAO Type A (operating limitations) and Type B (protected surfaces) drawings
8. Property map, with ownership type size and routing of utilities
9. Master utility drawing showing type size and routing of utilities
10. Phased airport layout plans, where applicable.

To illustrate the ALP diversity and extensive content for a range of airports, three types of airports are presented: (1) medium- International, (2) small- US, and, (3) large US/international. Figure 5.3 depicts the airport layout plan for an international airport in a developing country (Kuching, Malaysia), where (a) depicts the existing airport layout plan and facilities, and (b) the ultimate development of the airport. Figure 5.4 depicts the airport layout plan for the ultimate development of a small US airport (Palm Beach, Florida). Figures 5.5 (a) to (d) provide representative airport layout plan for a large international



(a)

Figure 5.3(a) Kuching, Malaysia airport layout plan—current facilities. (*Source*: Malaysian Associate Architects and Sir Frederick Snow and Partners. By permission of Department of Public Works, East Malaysia.)

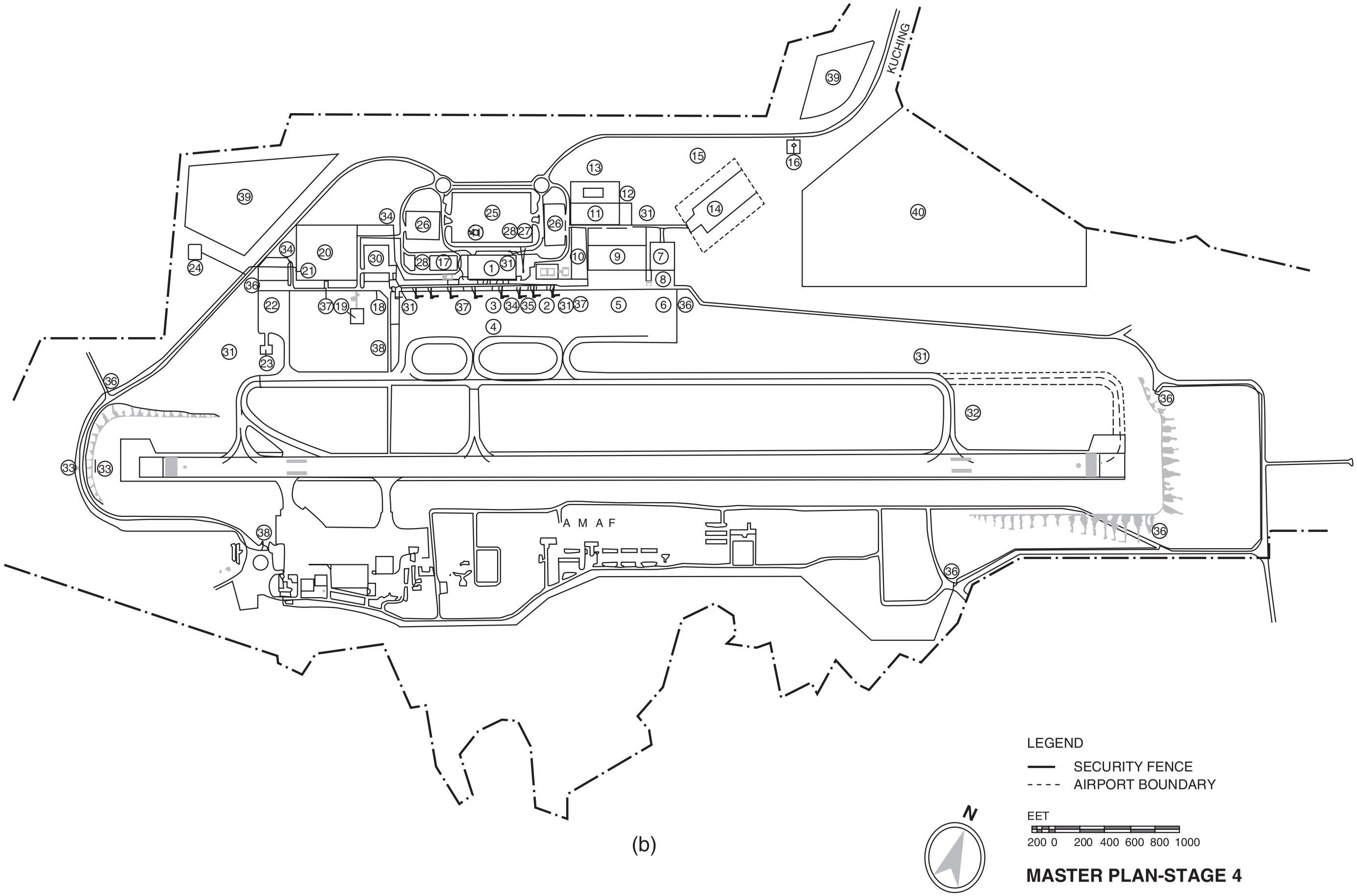


Figure 5.3(b) Kuching, Malaysia airport layout plan—ultimate development. (*Source*: Malaysian Associate Architects and Sir Frederick Snow and Partners. By permission of Department of Public Works, East Malaysia.).

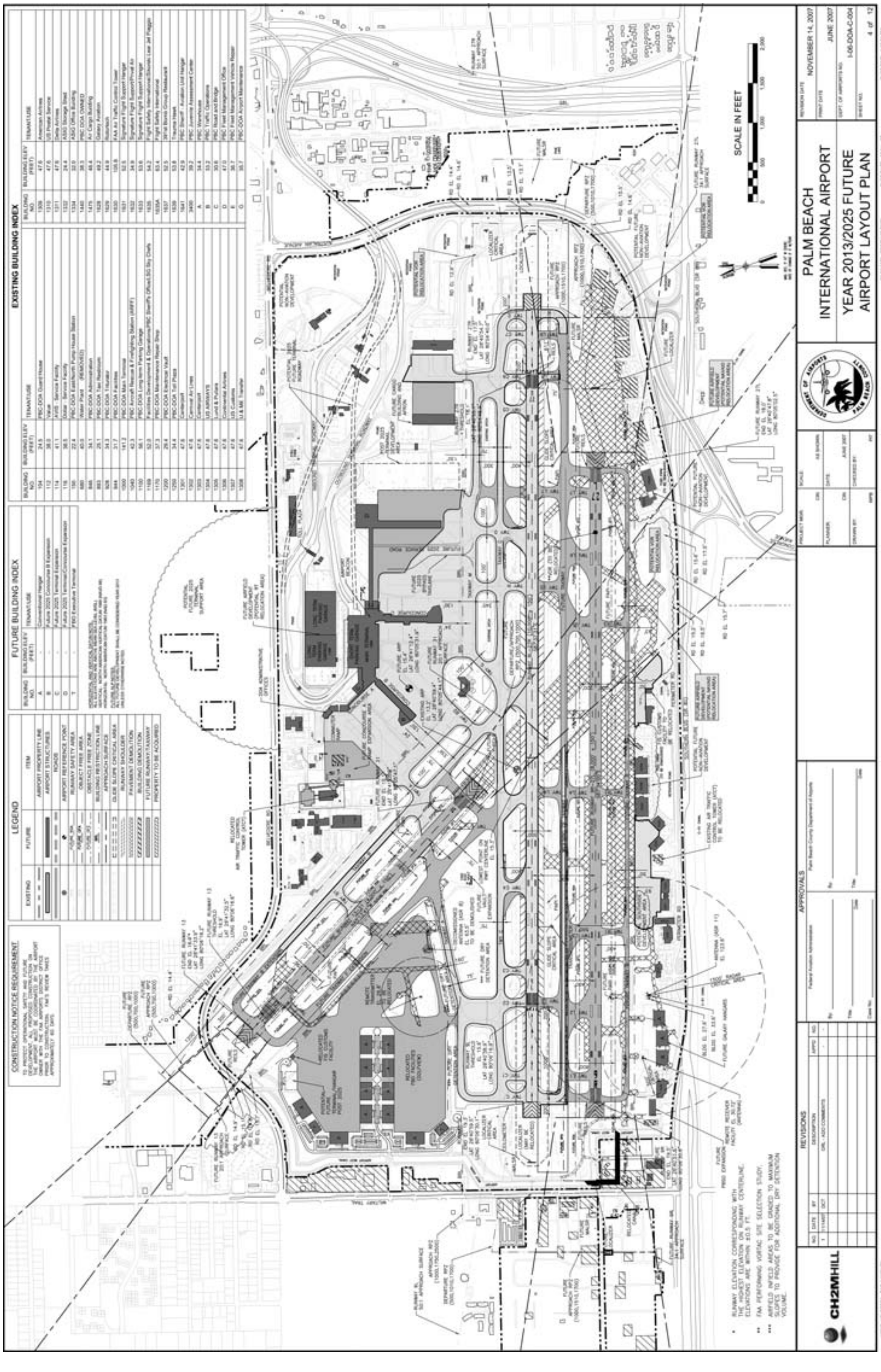
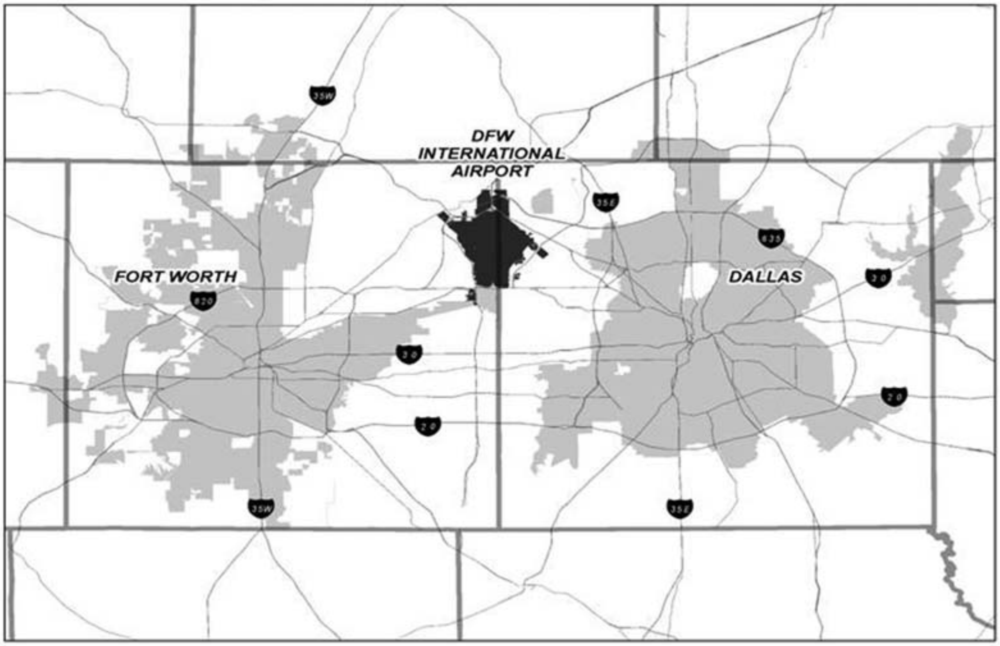


Figure 5.4 Palm Beach airport layout plan—ultimate development. (*Source*: Palm Beach County Department of Airports, prepared by CH2M Hill and Ricondo & Associates).

Airport Location and Data Table



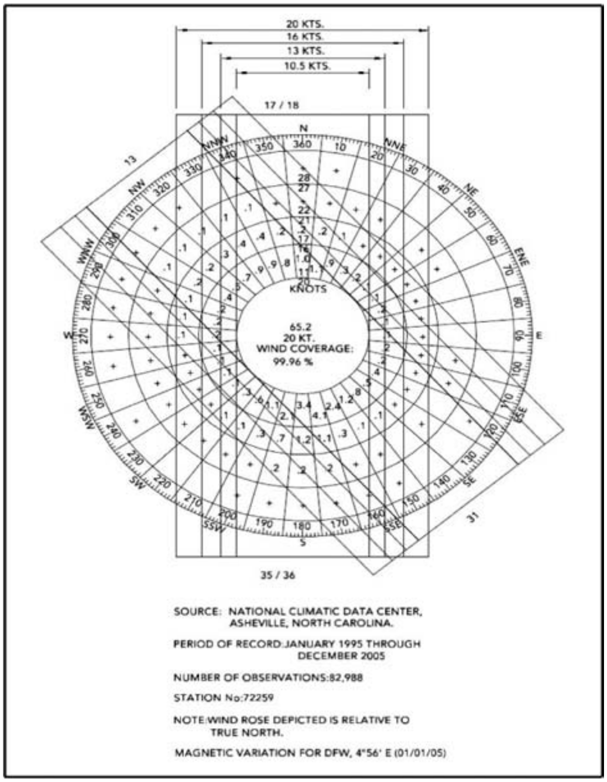
DESCRIPTION	EXISTING	ULTIMATE
AIRPORT ELEVATION (MSL_NAVD 88)	606.7'	637.5'
AIRPORT SERVICE LEVEL	COMMERCIAL SERVICE-PRIMARY	SAME
AIRPORT ROLE	LARGE HUB	SAME
- MEAN TEMPERATURE (F*)- HOTTEST MONTH	95°	95°
- TOTAL AIRPORT ACREAGE (2005)	18,092 AC.	18,201 AC.
AIRPORT REFERENCE CODE	D / E-VI	D / E-VI
AIRPLANE APPROACH CATEGORY	D / E	D / E
AIRPLANE DESIGN GROUP	VI	VI
AIRPORT NAVIGATION AIDS	DVOR / DME	DVOR / DME
AIRPORT VISUAL AIDS	ROTATING BEACON	ROTATING BEACON
AIRPORT REFERENCE POINT (ARP):		
- LATITUDE	N 32° 53' 50.4511"	N 32° 53' 47.69807"
- LONGITUDE	W 097° 02' 15.68587"	W 097° 02' 21.64290"
- NORTHING (STATE PLANE NAD-83-HARN)	7,012,483.40248	7,012,239.16782
- NORTHING (STATE PLANE NAD-83-HARN)	2,417,298.15362	2,416,793.62764

(a)

Figure 5.5(a) Dallas Fort Worth International Airport—airport location map and airport data table. (*Source*: Planning Department, DFW International Airport.)

ALL WEATHER WIND COVERAGE					
DALLAS / FORT WORTH INTERNATIONAL AIRPORT					
		RUNWAY CROSSWIND COMPONENT			
		10.5 KTS	13 KTS	16 KTS	20 KTS
COMBINED	13 - 35, 18 - 36, 13 - 31	98.53%	99.40%	99.84%	99.96%
BI-DIRECTIONAL	17 - 35, 18 - 36	95.12%	97.59%	99.23%	99.78%
	13 - 31	89.21%	95.04%	98.61%	99.74%
UNI-DIRECTIONAL	17 / 18	63.54%	64.66%	65.31%	65.47%
	35 / 36	36.31%	37.67%	38.66%	39.06%
	13	60.80%	64.70%	67.10%	67.90%
	31	33.14%	35.07%	36.26%	36.58%

NOTE: RUNWAYS 17-35 ARE PARALLEL TO 18-36.



(b)

Figure 5.5(b) Dallas Fort Worth International Airport—all-weather wind coverage table and wind rose. (*Source*: Planning Department, DFW International Airport.)

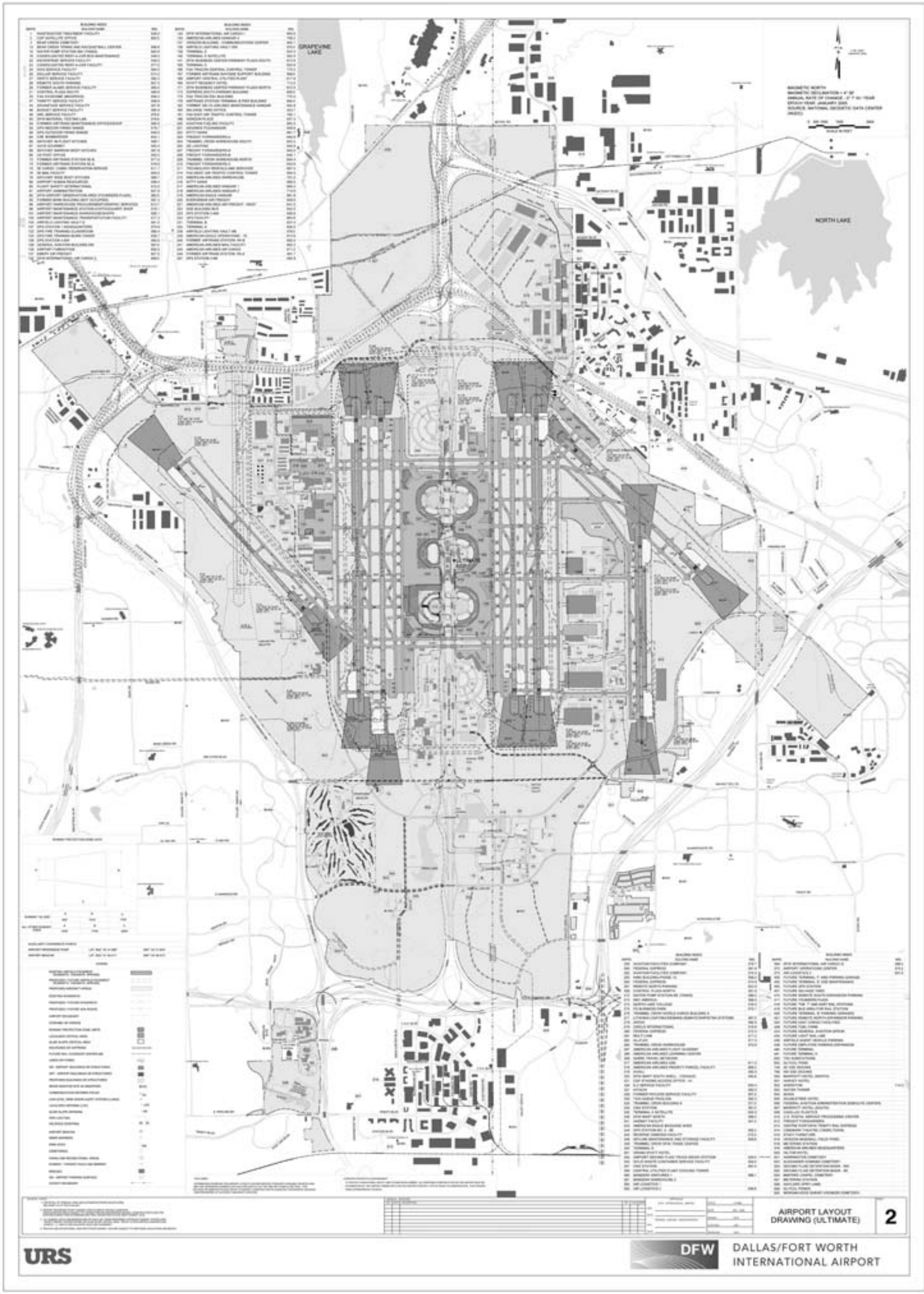
DFW Runway Data Table *

RUNWAY DATA ITEM	17C	35C	18L (Future 18C)	36R (Future 36C)	13R	31L
* Airport Reference Code	D / E-V		D / E-VI		D / E-VI	
* Critical Gear Configuration	Double Dual Tandem		Double Dual Tandem		Double Dual Tandem	
* Runway Ends Coordinates						
- Latitude (NAD 83)	N 32° 54' 56.548"	N 32° 52' 43.962"	N 32° 54' 56.877"	N 32° 52' 44.298"	N 32° 54' 34.472"	N 32° 53' 24.970"
- Longitude (NAD 83)	W 97° 01' 33.494"	W 97° 01' 34.218"	W 97° 03' 02.648"	W 97° 03' 03.344"	W 97° 04' 59.278"	W 97° 03' 47.794"
* Runway Orientation:						
- True Azimuth	180° 15' 29.113"		180° 14' 58.435"		139° 03' 10.515"	
- Grid Azimuth	179° 27' 15.177"		179° 27' 33.132"		138° 16' 29.116"	
* Runway Length & Width (Feet)	13,400' x 150'		15,200' x 200'		9,301' x 150'	
* Runway Declared Distances:						
- Takeoff Run Available (TORA)	13,400'	13,400'	15,200'	15,200'	9,301'	9,301'
- Takeoff Distance Available (TODA)	13,400'	13,400'	15,200'	15,200'	9,301'	9,301'
- Accelerate - Stop Distance Available (ASDA)	13,400'	13,400'	15,200'	15,200'	9,301'	9,301'
- Landing Distance Available	13,400'	13,400'	15,200'	15,200'	9,301'	9,301'
* Runway Pavement Type	CONCRETE		CONCRETE		CONCRETE	
* Runway Pavement Strength	1,000,000 lbs. (PCN82-RBXT)		1,000,000 lbs. (PCN82-RBXT)		1,000,000 lbs. (PCN82-RBXT)	
* Runway Lighting	HIRL, RCL		HIRL, RCL		HIRL, RCL	
* Runway Marking	PRECISION		PRECISION		PRECISION	
* Runway Approach Data						
- Visibility Minima	Category III	Category III	Category I	Category I	Category I	Category I-LPV
- Approach Lighting	ALSF2, TDZ, PAPI 4	ALSF2, TDZ, PAPI 4	MALSR, TDZ, PAPI 4	MALSR, TDZ, PAPI 4	MALSR, TDZ, PAPI 4	MALSR, TDZ, PAPI 4
- Approach NAVAIDS	LOC, GS, RVR	LOC, GS, RVR	LOC, GS, RVR	LOC, GS, RVR	LOC, GS, RVR	LOC, GS, RVR
* Runway Effective Gradient (%)	0.0%	0.0%	-0.2%	0.2%	-0.15%	0.15%
* Runway Elevation Data (AMSL/NAVD 88)						
- Runway End	561.91	562.20	601.75'	572.34'	590.90'	577.10'
- Touchdown Zone	562.02	562.20	601.75'	588.63'	590.90'	581.62'
* Runway Blast Pad (Length x Width)	400' x 220'	300' x 150'	400' x 280'	400' x 280'	400' x 220'	400' x 220'
* Runway Shoulder	36' (Asphalt)		25' (Asphalt)		35' (Asphalt)	
* Runway Object Free Area (OFA)						
- Length Beyond Stop End	1,000'	1,000'	1,000'	1,000'	1,000'	1,000'
- Width	800'		800'		800'	
* Runway Safety Area (RSA)						
- Length Beyond Stop End	1,000'	1,000'	1,000'	1,000'	1,000'	1,000'
- Width	500'		500'		500'	
* Runway Obstacle Free Zone (OFZ)						
- Length Beyond Stop End	200'	200'	200'	200'	200'	200'
- Width	400'		400'		400'	
* Precision Obstacle Free Zone (POFZ)	200' L x 800' W-CLEAR	200' L x 800' W-CLEAR	200' L x 800' W-CLEAR	200' L x 800' W-CLEAR	200' L x 800' W-CLEAR	200' L x 800' W-CLEAR
* Hold Position Sign/Markings from CL	287'		280'		280'	
* Dispalced Runway Threshold Details	N / A	N / A	N / A	N / A	N / A	N / A
* Runway Protection Zone (RPZ)						
- Inner Width	1,000'	1,000'	1,000'	1,000'	1,000'	1,000'
- Outer Width	1,750'	1,750'	1,750'	1,750'	1,750'	1,750'
- Length	2,500'	2,500'	2,500'	2,500'	2,500'	2,500'

* *Representative existing runway orientations, excluding future runway orientations*

(c)

Figure 5.5(c) Dallas Fort Worth International Airport—airport runway tables. (*Source*: Planning Department, DFW International Airport.)



(d)

Figure 5.5(d) Dallas Fort Worth International Airport—ultimate airport layout plan. (*Source*: Planning Department, DFW International Airport.)

airport in the United States with a high-design capacity (Dallas Fort Worth International Airport, Texas). A large set of drawings and tables is typically required to represent the extensive ALP information for such large airport, and Figures 5.5 provide only a partial list of the entire ALP drawings set: Figure 5.5 (a) presents the airport location map and airport data table; Figure 5.5 (b) provides all-weather wind coverage table and the wind rose; Figure 5.5 (c): presents details contained in the airport runway tables; and Figure 5.5 (d): depicts the airport ultimate layout plan.

B. Terminal area plan (1:5000–1:10,000) (staged where applicable)

   1. Conceptual drawings of passenger and cargo terminals
   2. Schematic drawings delineating basic flows of passengers, baggage, cargo, and vehicles
   3. Car parking and curb space

C. Airport access plans (staged where applicable)
D. Noise compatibility plans showing noise exposure contours with respect to developed and developing areas. These should be staged where applicable.
E. Land use plan within airport boundary
F. Land use plan in the airport vicinity

5.8 AIRPORT SITE SELECTION

Before World War II, when air travel was still a relative rarity, aircraft were small and lightly powered, and even metropolitan airports had few daily flights. Airports then were not considered by the community to be undesirable neighbors. Indeed, aviation was still new enough to exert attraction among its close neighbors. Site selection under these conditions was relatively simple and depended principally on aviation and civil engineering requirements. Because of the dramatic increase in air travel, accompanied and engendered by larger and more powerful aircraft, since the widespread introduction of noisy jet aircraft in the 1960s, airports have come to be identified as land users that cause severe environmental deterioration to their neighbors.They are now recognized as generating high volumes of surface traffic and bring economic and community development that may not be in accord with the desires of the surrounding land users. Thus, site selection has become more difficult.

Since the late 1960s, prolonged planning battles have been fought over the proposed locations for new airports in such varied locations as New York, London, Atlanta, Tokyo, Sydney, and Miami, to name only a few. In countries such as Dubai, China, Malaysia, Thailand, and South Korea, very large new airports have been planned and built with little public dissent. The problems of site selection therefore are seen to be related to the political context of where the new airport is to be built. Whatever the political context, a minimum site selection analysis should include consideration of the following factors:

Operational Capability. Airspace considerations, obstructions, weather.

Capacity Potential. Weather, extent of available land, suitability for construction.

Ground Access. Distance from demand for aviation services, regional highway infrastructure, public transportation modes, parking availability.

Development Costs. Terrain, land costs, nature of soil and rock conditions, weather, land values, availability of utilities.

Environmental Consequences. Aircraft noise, impact on flora and fauna, air quality, ground run-off impacts, changes in local land use, existence of endangered species or cultural artifacts.

Socioeconomic Factors. Relocation of families and businesses, changes in employment patterns, changes in the tax base, requirement for new public services.

Consistency with Areawide Planning. Impact on land use, effect on comprehensive land use and transportation plans at local and regional level.

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6

CNS/ATM

The communication, navigation, and surveillance systems in the national airspace system are what make safe, efficient, and cost-effective operations at airports possible. The expression CNS/ATM refers to the communication, navigation, and surveillance and air traffic management system that controls aircraft approaching and departing the airport and those moving on the airfield as well as manages all air traffic in the airspace. Planning and design of airports must integrate this element's role, function, and interaction into the entire system. Major elements in the design of airports are directly linked to the standards and operational performance of these systems. Therefore, airport planning and engineering would not be complete without fully integrating both CNS and ATM.

6.1 EVOLUTION OF THE SYSTEM

Historical Background

In the early days of aviation, at the turn of the twentieth century, few adventurous aviators were taking off in flying machines from dirt strips in fields and flying around primarily for fun and entertainment and landing back onto them ad hoc. The First World War enhanced the technological standards of planes that were manufactured in large numbers for the war effort. The U.S. Post Office began to introduce regular "Airmail Service" in 1918 flown by U.S. Army pilots and planes, and the U.S. Department of Agriculture initiated in 1919 the commercial use of those early planes for the application of pesticides. The end of that year saw the first uses of radio for navigation. By 1925, the U.S. Congress passed the Airmail Act, airmail service was expanded to most major cities of the United States, and full transcontinental service was achieved.

Mail was flown only during daylight hours, weather permitting, since safe, reliable, and consistent nighttime operation was not possible as night navigation was not yet known. The success of airmail service operation in the United States drove the move to night flight navigation. The first experience using bonfires along the stretches of daytime navigation routes was conducted in 1923, when the first successful night flight navigation was flown with electric and gas arc lights as navigation aids along a 72-mi stretch of airway in Ohio.

With this industry maturing, as air routes were flown day and night between U.S. cities and airports became permanent fixtures of the system, pressure was on government to regulate and promote the orderly expansion and modernization of the system. These were the primary objectives of the Air Commerce Act that was passed in 1925.

Under this act, the Department of Commerce—Aeronautics Branch was responsible for licensing pilots and aircraft mechanics and regulating use of airways between airports. Most importantly, communicating between pilots and ground and navigating the aircraft to take off and land safely at airports had not yet evolved. In those days (1):

> Because all aircraft eventually had to land at an airport, it was inevitable that the airspace within the immediate vicinity of busy airports became congested, and some form of local air traffic control would soon be needed. An airport in the 1930s rarely had designated runways, and it usually consisted of a large rectangular plot of land covered with sod and cinder.
>
> After flying over the airport to observe the wind direction, local traffic, and runway conditions, pilots themselves would decide in which direction they wished to land. During the approach and landing of planes, the pilots were kept busy trying to spot other aircraft, decide who had priority, and maneuver their planes behind the others, allotting sufficient time for a previous plane to land, brake to a stop, and taxi clear of the "runway" prior to other arrivals. In addition, pilots needed to constantly scan the airport surface area to detect aircraft taxiing for takeoff. To decrease ground-roll distance, pilots usually maneuvered their aircraft to land or take off into the wind. On windy days this forced most pilots to land and take off in the same direction. But on calm days, aircraft could be seen landing and taking off in every direction!
>
> It was immediately apparent that some form of control system would have to be initiated around airports to establish a consistent safety regime, or accidents would begin to occur at an increasing rate.

With this background, by 1935 major airports had become increasingly crowded, and both the flying public and people living around airports felt the risks associated with major aircraft accidents. But the aviation industry feared this pressure would restrict or ban operation in certain areas. Public and industry pressures were exerted on government to provide a solution. In 1938, the Civil Aeronautics Act established the Civil Aviation Authority (CAA) responsible for managing and controlling air traffic on airways, certifying pilots and controllers, ensuring safety, and investigating accidents.

The beginning of World War II brought about lasting and important changes: institutionally to the structure of the CAA, technologically to the aviation industry as a whole. The aviation industry, with all its sectors, became the largest industry in the world immediately after the war. The technological advances during the war in terms of aircraft and CNS technologies were immediately shifted to civilian use and adapted to the air transport industry that grew by leaps and bounds after the war, making use of war surplus planes, military pilots, and more advanced CNS system. However, this explosion of the air transport industry was not all positive—several midair accidents occurred throughout the United States in close succession. Government was forced to take immediate action.

The CAA announced a plan to form an independent Airways Modernization Board (AMB) in 1957 to coordinate civilian–military aviation technology research and development and establish a modern U.S. aviation system. In 1958, the FAA was formed. Today, the FAA is the sole federal agency responsible for operating and managing the U.S. air traffic system, setting technical standards to design airports and certifying them for operation and providing federal funding to maintain their development and safe operation. The FAA is responsible for the basic air traffic control system on and around airports, establishing airside design principles for airports, and ensuring that the airspace and airfield of airports both operate in unison and harmony and are integrally and optimally connected.

Technology Background

As stated earlier, the technological development for airport CNS has gone through three major development phases of navigation from inception, as discussed below.

Visual Navigation. Airport navigation started with an entirely visual system whereby the pilot was the sole member in the system working under the concept of "see and be seen" with other pilots. This was later translated into *visual flight rules* (VFRs), and this is still recognized today. Later, an airport controller on the ground or in an elevated platform (tower) conveyed to the pilot basic control instructions visually, first through colored flags, then using colored "light guns" to instruct the pilot of certain actions to take at certain gun colors emitted—steady green for *cleared for takeoff*; flashing green for *cleared to taxi*; steady red for *stop*; and alternating red and green for *exercise extreme caution*. With the advent of radio communication, the ground controller at the airport tower would relay information and instruction to the pilot through the radio. Airport radio navigation was born in the 1930s in Cleveland, Ohio, with a 15-W transmitter–receiver radio with a 15-mile range.

Today, airport visual navigational aids include all airfield signs and markings, runway and taxiway centerline and edge lighting, runway light landing aids, and aircraft gate docking systems. These will be described individually later.

Radio Navigation and Communication and Radar Surveillance. Radio was first used in the early days of aviation for airport navigation strictly through communicating between ground controllers and pilots to provide direction for them to navigate their approach and landing. In the era between the two great wars, extensive research was conducted on using radio waves to detect objects, which culminated in the discovery of the RAdio Detection And Ranging technology, or radar. Radar and other radio-based navigation technologies were developed, perfected, and used during the war effort. By the end of World War II, air navigation and surveillance technologies were mature and were immediately utilized for civilian commercial use in airways and airports in the United States and around the world.

Radio-based navigation includes such technologies as marker and nondirectional beacons, VOR, DME, TACAN, VORTAC, LORAN, instrument runway approach and landing systems (ILSs), and microwave landing systems (MLSs).

Radio communication is still the backbone of the communication system between pilots, controllers on the ground, and an array of radio-based ground navigation equipment. To avoid interference between all radio frequencies, *duplex* communication was adopted that isolates voice communication from navigation-based transmitter–receiver frequencies. Today, modern cockpit communication relies on the *simplex* transmission principles with elaborate frequency assignment of blocks of VHF bands for various uses.

In terms of surveillance, an array of radar types and technologies are in use today, ranging from primary and secondary radars that include ASR, ARSR, and PAR; automated ARTS series radars; and airport surface detection equipment (ASDE) radars. These technologies and equipment are also described.

Satellite-Based Navigation, Communication, and Surveillance. As air traffic continued to grow, system inefficiencies and associated costs were compounded by constraints on the air traffic control (ATC) system. Technologies implemented in the ground-based ATC system have reached their technological limits and there was no envelope to push further to achieve more efficient, cost-effective, and safe systems. The capacity of the NAS was constrained by rules, procedures, and technologies that require pilots and air traffic controllers to conduct operations within narrow, often inefficient guidelines, and system inefficiencies and associated costs are compounded by the significant increase in traffic as a result of deregulation, new airlines entering the industry, and the building of new airports and expansion of existing ones. As a result, the 1980s witnessed major technological modernization that eventually got the FAA to collaborate with the industry on major paradigm-shift initiatives. This new paradigm focused on two major fronts: (a) moving into satellite-based CNS systems instead of ground-based ones and (b) adopting a more collaborative concept of ATC modernization where the controllers, managers, and pilots collaborate in using the new systems utilizing more advanced ATM. This new system adopts collaborative decision-making (CDM) concepts and advanced conflict resolution techniques with satellite-based technologies and advanced aircraft flight management systems (FMS). The FAA has recently embarked on NEXTGEN (2)—an advanced modernization program to bring about the next-generation air transportation system, with a next-generation CNS/ATM system for the twenty-first century. The FAA effort is in parallel to similar efforts across the Atlantic, where EUROCONTROL is involved in SESAR (3)—Single European Skies Airspace. Satellite-based technologies for CNS/ATM, such as local-area augmentation system (LAAS), wide-area augmentation system (WAAS), and automatic dependent surveillance-broadcast (ADS-B), are described. The FAA, EUROCONTROL, and ICAO are cooperating closely on these two modernization programs.

Visual Flight Rules and Instrument Flight Rules

As the system evolved from its humble roots and started to integrate the radio-based technologies, and more recently satellite-based navigation, a two-rule system emerged: both catered for and implemented in the CNS/ATM system—visual flight rules (VFRs) and instrument flight rules (IFRs). The use of these “rules,” which are essentially systems and procedures, depends on aircraft equipage, weather conditions, and the location and altitude of the flight paths.

In general, VFR operations prevail when weather, or meteorological conditions, is good enough for the aircraft to be operated by visual reference to the ground and to other aircraft based on the rule of “see and be seen” and when traffic densities are sufficiently low to permit the pilot to depend on vision rather than on instrument readings. IFR conditions exist when the visibility or the ceiling (height of clouds above ground level) falls below that prescribed for VFR flight or when air traffic densities require IFR-controlled conditions.

In VFR conditions, there is essentially no en route air traffic control except where prescribed; aircraft fly according to “rules of the road,” using designated altitudes for certain headings, and pilots are responsible for maintaining safe distances between their respective aircraft. Positive traffic control is always exercised in IFR conditions and in designated control areas. Responsibility for maintaining safe aircraft separation passes to the air traffic controller. Essentially, the controller follows the IFR procedures, which call for the controlled assignment of specific altitudes and routes and minimum separation of aircraft flying in the same direction at common altitudes.

6.2 U.S. NATIONAL AIRSPACE SYSTEM (NAS)

What Is the NAS?

> NAS is the common network of U.S. airspace; air navigation facilities, equipment and service; airports; aeronautical charts, information and services; rules, regulations and procedure; and technical information, manpower and material. Included are system components shared jointly with the military. (4)

Formal federal involvement in air traffic began with the Air Commerce Act of 1926, which provided for the establishment, maintenance, and operation of lighted civil airways. Federal rather than state authority governs, operates, and manages the U.S. national airspace system, because the implications of air travel are interstate by nature and have no general relation to or respect for state boundaries.

In the United States, the FAA is the governmental authority responsible for providing control and navigation assistance for the movement of air traffic. One of the major functions of the 1982 Airway and Airport Improvement Act was to provide the FAA with a financial structure that would permit an extensive modernization program for and control over the CNS/ATM system of the United States.

Under this mandate the FAA has been working collaboratively with other stakeholders, mainly the airline industry, to achieve the development of a modern and efficient system. Major factors underlying the need for ATC and ATM are safety, efficiency, and cost-effectiveness. Users of the system must work with efficient airspace structure that avoids any risk of near misses or collisions and to maintain sufficient capacity of movement in heavily trafficked areas. Efficiency necessitates that using the airspace should always put safety as paramount that is never compromised. Furthermore, any airspace system must also consider and balance the needs of all users of airspace. For all the national airspace users, an ATM system must be in place to optimize the utilization of this precious asset, provide increased safety, and avoid congestions and bottlenecks, particularly around busy airports and the congested airspace around them.

With these objectives in mind, the FAA went forward with its modernization plans. Air traffic control measures were instituted and procedures established when it became apparent that there was a necessity for control under traffic conditions having a high probability of human failure. As air traffic activity grows, increasing traffic density and its concomitant problems will undoubtedly necessitate further air traffic regulations and the development of a more sophisticated and extensive system to provide for the safe and efficient movement of all aircraft. The increasing range of aircraft technology will certainly mean that more attention must be given to the allotment of airspace and the compatibility of equipment between different types of traffic and users of airspace: commercial air carrier (both jet and turbo prop), general aviation aircraft, and military. As the number of general aviation aircraft continues to grow, the range of air carrier technology embraces a great variety of aircraft types with various levels of equipage. The air traffic control system, which must accommodate the wide variety of airspace needs, must therefore be responsive in its development to the underlying factors of safety, efficiency, advanced technology, regulation, and cost-effectiveness.

The blueprint of the FAA NAS modernization program is the NAS architecture. It constitutes a framework that contains processes and their products defining the evolution of NAS over time (4):

> The FAA with the aviation community developed the NAS architecture. The NAS architecture is a 15-year strategic plan that reflects the fundamental organization of the NAS. It includes existing and planned capital investments, their relationships to each other and the environment, and the principles governing their design and evolution. The NAS architecture includes the replacement of aging equipment and the introduction of new systems, capabilities, and procedures.

The NAS architecture is a “living” representation of an integrated and evolutionary approach to modernization that:

- Promotes FAA and industry collaboration
- Supports the FAA acquisition and budget processes
- Provides decision makers with the NAS interdependency data necessary to make mission need, investment, and budget decisions
- Provides the framework to develop NAS and lower level system requirements

The major objectives of developing the NAS architecture and its phased implementation include:

- Accommodating aviation’s growth and replacing aging equipment/infrastructure in collaboration with the aviation community
- Providing an advanced, integrated, and safe aviation system with improved quality and reliability through integrated digital communications
- Using satellite-based services for exceptional accuracy, increased operational safety, and expanded airport coverage
- Timely and accurate weather data for controllers and pilots
- Deploying advanced automation capabilities to accelerate user benefits and assess modernization risks
- Sharing information to more effectively manage flight planning with a common view of traffic flow and optimize aircraft sequence with improved controller tools
- Building upon newly developed advanced capabilities with seamless integration and transition into the NAS

The NAS is a highly technical, highly integrated, and extremely complex system which is the largest of all civil aviation infrastructure systems. It is composed of 45,000 pieces of equipment distributed among 5000 air traffic control tower (ATCT)s, 180 terminal radar approach control (TRACON)s, 22 air route traffic control center (ARTCC)s controlling 800 sectors, 60 flight service stations, and all equipment along its airways.

The NAS is currently handling about 2 million passengers traveling on 60,000 flights daily, amounting to over 600 million passengers per year, and is projected to reach 900 million in few years. The NAS conducts over 26 million operations per year that will soon reach over 33 million.

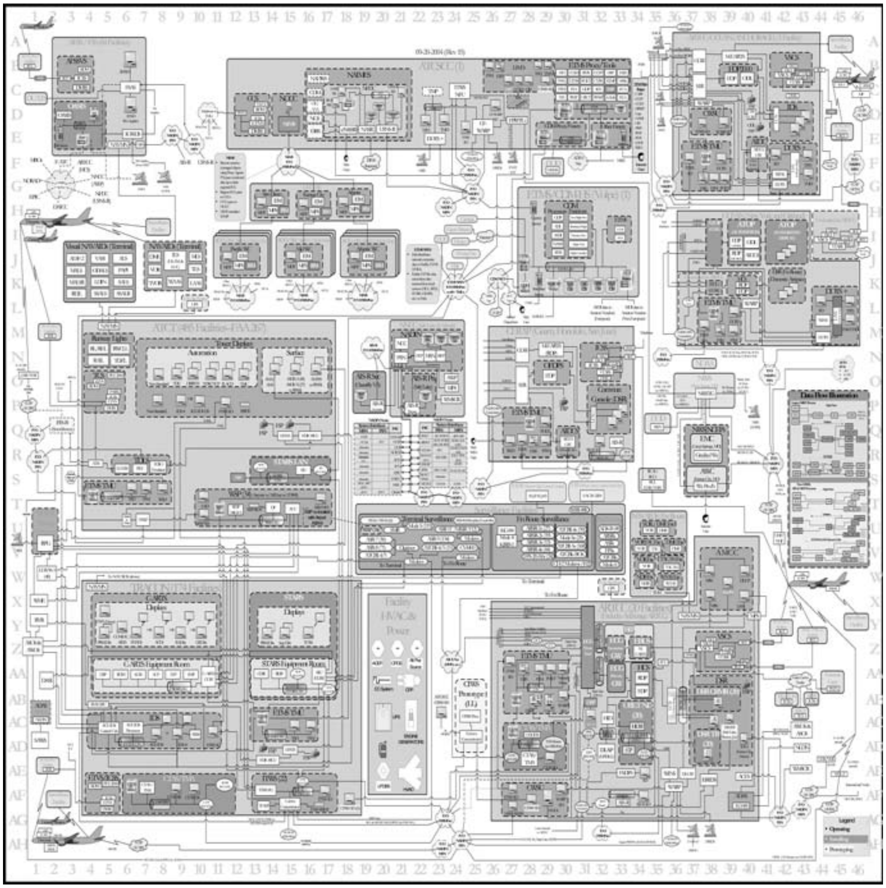

Figure 6.1 The NAS architecture, 2004. (*Source*: FAA (4).)

Airports in the NAS include 546 commercial service airports, 422 of which are primary airports—31 large-hub airports account for 70% of all passengers in the system, 37 medium-hub airports account for 19%, and 74 small-hub airports account for 8%.

Figure 6.1 depicts the graphical representation of the NAS architecture for the U.S. CNS/ATM system. It also includes the airports' ground components of the system.

NAS Structure

The NAS includes the airspace structure [i.e., the airways (routes), fixes (nodes), and parcels of airspace types] and the system that controls movement of aircraft within it and manages its utilization (i.e., CNS/ATM). A fix is a geographical position determined by visual reference to the surface, by reference to one or more radio navigational aids, by celestial plotting, or by another navigational device (5).

Flights from one part of the NAS to another are normally channeled along navigational routes that are as well identified similar to the surface road system. Three separate route systems are identified: (a) VOR (very high frequency omni-directional range) and L/MF (low/medium frequency) airways, (b) the jet route system, and (c) the GPS-based RNAV (area navigation) routes. Airways are defined (in CFR14-Part 71) as "Class E airspace area established in the form of a corridor, the centerline of which is defined by certain types of radio navigational aids" (6). Airspace, airway routes and reporting points as designated in the NAS are defined and described in FAA Order 7400.9U (7)

VOR Airways. VOR airways are a low-altitude system consisting of airways from 1200 ft above the surface up to, but not including, 18,000 ft above mean sea level (MSL). The extent of the system is indicated in the En Route Low Altitude Charts (8).

Known as the Victor airways, the VOR airway uses an alphanumeric code, with V followed by a number (e.g., V21). These airways use only VOR/VORTAC navigational aids (see below). VOR navigation is free from radio static and is easily picked up by the receiver on a line-of-sight basis; therefore, the range of the ground facility is dependent on aircraft altitude. Victor airways are a minimum of 8 nautical mi wide; where the distance between VOR stations is greater than 120 mi, the airway width increases to the envelope encompassed by planes at an angle of $4\frac{1}{2}^{\circ}$ about the centerline joining the two ground stations. The numbering system for Victor airways is even numbers for East and West and odd numbers for North and South.

Jet Airways. The jet route system is comprised of airways from 18,000 ft above MSL to 45,000 ft (flight level* FL450), designed for aircraft that customarily operate at these altitudes. These routes also operate using VOR ground navigation stations, but the system requires significantly fewer stations, since line-of-sight operation gives the VORs substantially greater range when dealing with aircraft at high altitudes. The width of the airways of the jet route system is unspecified. Figure 6.2(a) depicts a portion of a typical Victor airways chart; a jet route chart in the same area appears in Figure 6.2(b).

Area Navigation (RNAV) Routes. The concept of area navigation was developed to permit pilots to navigate directly to the destination airport bypassing the Victor or jet airways. This concept relies not on any ground-based navigational systems but on the aircraft on-board FMS that is part of the aircraft surveillance and navigational equipment. Therefore, the aircraft has to be properly equipped to be able to navigate RNAV routes (1). On-board equipment that is required for RNAV navigation includes the aircraft Doppler radar, the FMS course-line computer (CLS), and more recently the GPS-based systems. Since RNAV as a navigation concept relies on modern satellite-based on-board FMS systems, it is described in detail later in the satellite-based navigation section.

Airspace Categories

The NAS airspace classification provides for three airspace categories:

Uncontrolled Airspace. In this airspace, ATC separation services are not provided by the FAA, and all aircraft are obligated to provide their own separation, regardless of weather conditions.

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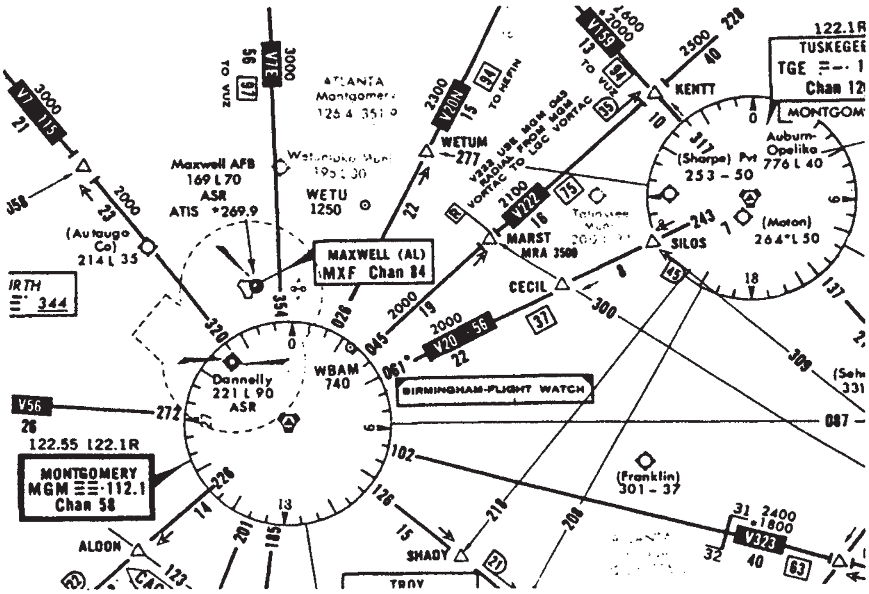
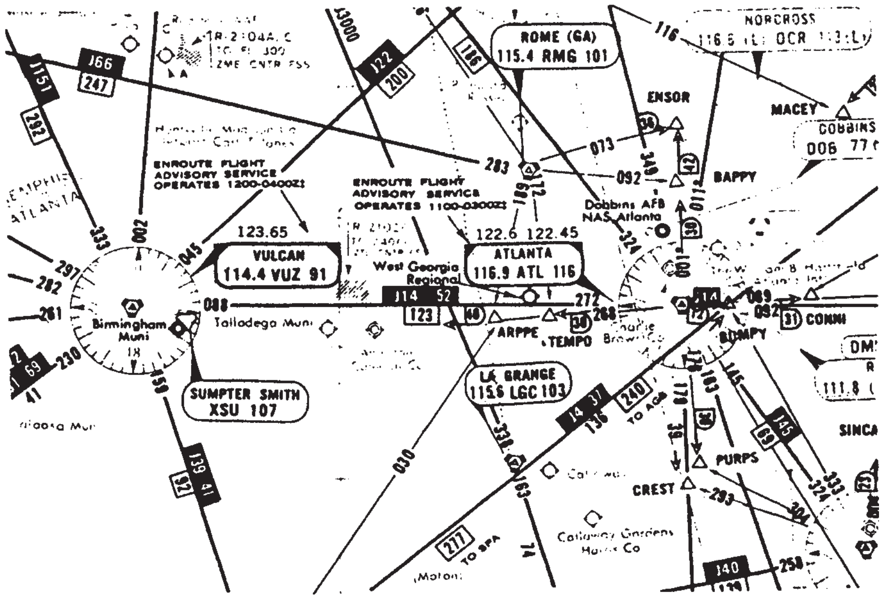
*Flight level = altitude above mean sea level × 100 (in feet).



(a)



(b)

Figure 6.2 (a) Portion of a Victor airways chart. (b) Portion of a jet route chart. (*Source*: FAA (8)).

Special-Use Airspace. Includes prohibited, restricted, warning areas, and military operation areas (MOAs). Restricted airspace is designated by FAR 71, within which flight of aircraft is not wholly prohibited but is subject to certain operating restrictions. In prohibited airspace (which includes MOAs) flights are absolutely prohibited.

Controlled Airspace. ATC separates IFR aircraft, and weather permitting, VFR pilots would provide their own separation. In *positive controlled airspace* (PCA), ATC separates all IFR and VFR traffic but handles each separately. Flight is conducted in accordance with promulgated altitude and heading combinations (Figure 6.3). Controlled airspace extending upward from 1200 ft above ground level (AGL) and in a few areas from 700 ft AGL exists in almost all areas of the contiguous United States where control areas and transition areas have been designated. In addition, controlled airspace extends upward from the ground in areas immediately surrounding an airport in control zones. The nature and variety of demand to use the system necessitate the need for shared airspace. As computers are linked and communication gets markedly improved in the automated air traffic control system, shared utilization of a

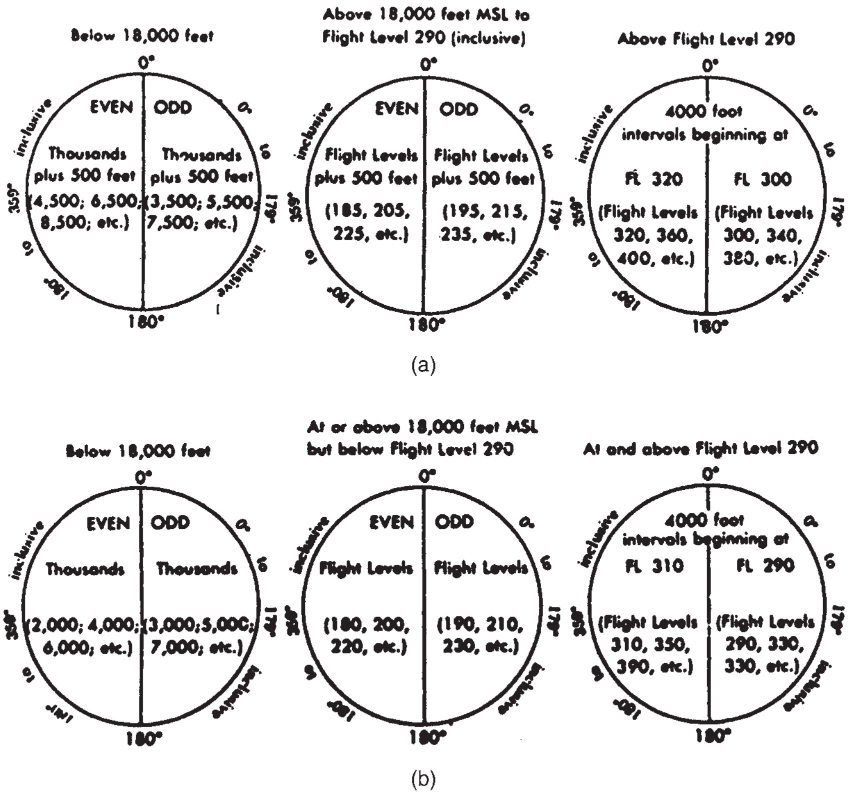


Figure 6.3 IFR and VFR altitudes and flight levels: (a) under VFR at 3000 ft or more above surface, controlled and uncontrolled airspace; (b) under IFR, outside controlled airspace. (*Source*: Reference (5).)

system will become more important. To achieve greater airspace utilization and safety, an area above 14,500 ft MSL has been designated as a *continental control area.* Aircraft flying above this altitude usually have higher performance, have more modern on-board systems, and are jet powered. In positive control areas above 18,000 ft MSL, all aircraft are controlled by continuous surveillance and are required to have certain FMS equipment to permit the higher aircraft densities of the higher performance aircraft.

Airspace Classification

All airspace of the NAS has been designated by the Federal Aviation Regulations into one of six distinct classes. In each of these areas both VFR and IFR traffic must comply with the regulations designated for each by the Federal Aviation Regulations, Part 71(6). These classes are described below, depicted in Figure 6.4., and summarized in Table 6.1.

Class A. Airspace extending from FL 18 MSL up to and including FL 600, including airspace overlying U.S. coastal areas within 12 nautical mi of the coasts of the 48 contiguous United States. Every aircraft within this airspace must be equipped per Federal Aviation Regulations Part 91, General Operating and Flight Rules (FAR 91.215), requirements; pilots must have certain qualifications and operate under instrument flight rules and receive clearance from ATC.

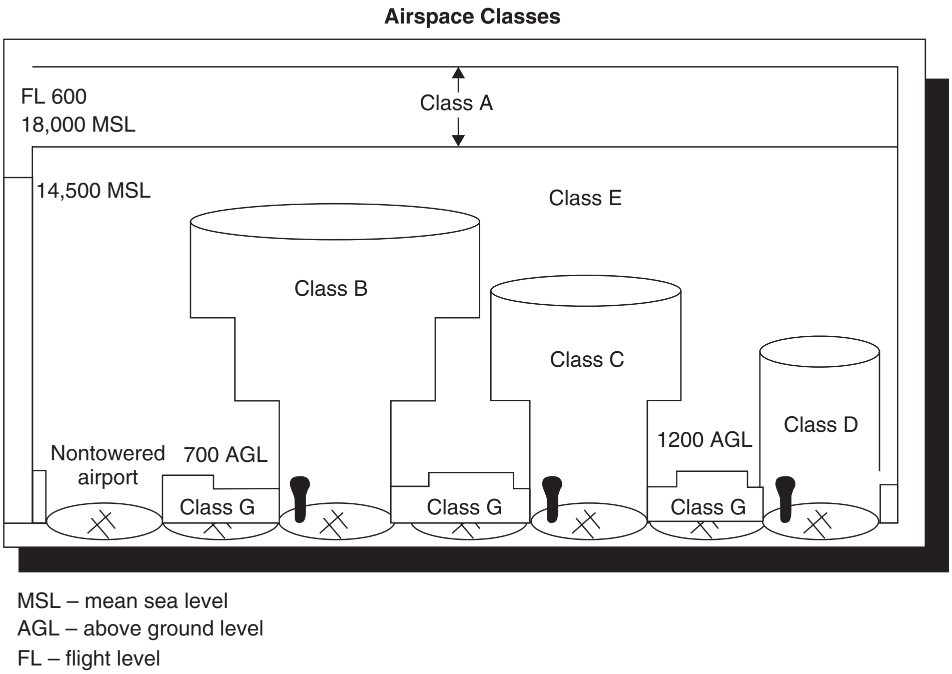


Figure 6.4 Airspace classification (1).

Table 6.1 Airspace Classification: Features and Characteristics

Airspace Features	Class A	Class B	Class C	Class D	Class E	Class G
Former Airspace Equivalent	Positive Control Area (POA)	Terminal Control Area (TCA)	Airport Radar Service Area (ARSA)	Airport Traffic Area (ATA) and Control Zone (OZ)	General Controlled Airspace	Uncontrolled Airspace
Operations Permitted	IFR	IFR and VFR	IFR and VFR	IFR and VFR	IFR and VFR	IFR and VFR
Entry Requirements	ATC clearance	ATC clearance	ATC clearance for IFR. All require radio contact.	ATC clearance for IFR. All require radio contact.	ATC clearance for IFR All IFR require radio contact.	None
Minimum Pilot Qualifications	Instrument Rating	Private or student certificate	Sudent certificate	Sudent certificate	Sudent certificate	Sudent certificate
Two-way Radio Communications	Yes	Yes	Yes	Yes	Yes for IFR	No
VFR Minimum Visibility	N/A	3 statute miles	3 statute miles	3 statute miles	3 statute miles	[2]1 statute miles
VFR Minimum Distance from Clouds	N/A	Clear of clouds	500 below, 1,000 above, and 2,000 horizontal	500 below, 1,000 above, and 2,000 horizontal	500 below, 1,000 above, and 2,000 horizontal	Clear of clouds
Aircraft Separation	All	All	IFR, SVFR, and runway operations	IFR, SVFR, and runway operations	IFR and SVFR	None
Traffic Advisories	N/A	N/A	Yes	Workload permitting	Workload permitting	Workload permitting
Safety Alerts	Yes	Yes	Yes	Yes	Yes	Yes

Source: Ref. 1.

Class B. Airspace extending from ground surface up to FL 10, surrounding the busiest airports in terms of IFR operations or passenger enplanements. Class B airspace is uniquely configured and individually tailored for the particular airport airspace. It consists of a surface area and two or more layers designed to contain all published instrument procedures once aircraft enter the airspace and receive separation services. Class B airspace was called the terminal control area (TCA), which is designated around major aviation hubs, and they include at least one primary airport around which the TCA is located. Successive layers of Class B airspace extend out of from the center of the airport and are designed to provide ATC with sufficient airspace to vector aircraft to an instrument approach at the primary airports. A typical Class B airspace is depicted in Figure 6.5.

TCAs are classed as group I or II depending on the number of aircraft operations and passengers they service. To operate within either group, the aircraft must be equipped as per FAR 91.

Class C. Also known as Airport Radar Service Area (ARSA), and it is airspace within the vicinity of medium-sized airports that do not qualify for TCA. It is airspace extending from the surface to 4000 ft above airport elevation surrounding airports that have an operational control tower, are serviced by a radar approach control, and have a certain number of IFR operations or passenger enplanements. While the configuration of each Class C airspace area is individually tailored, the airspace usually consists of a 5-nautical-mi radius core area that extends from the surface up to 4000 ft above the airport elevation and a 10-nautical-mi radius shelf extending from 1200 to 4000 ft above the airport. An outer area extends 20 nautical mi outward from the center of the primary airport and extends from the lower limits of radar/radio coverage up to the ceiling of the approach control's delegated airspace.

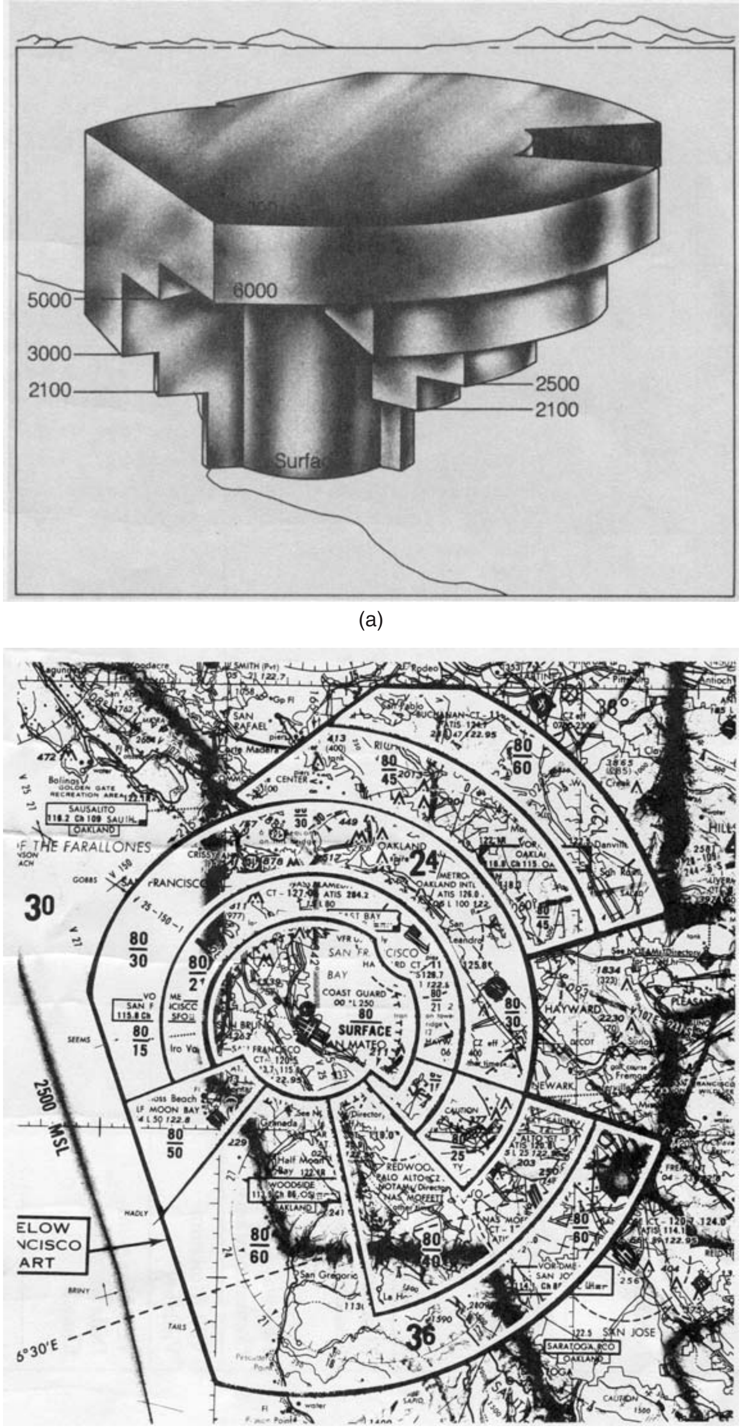
ARSAs are established in busy medium to small airports to protect aircraft which are landing or taking off. Aircraft wishing to enter an ARSA must establish two-way radio communication with air traffic control. The services provided by the ARSA on establishing two-way radio and radar contact are sequencing arrivals, IFR/IFR standard separation, IFR/VFR traffic advisories and conflict resolution, and VFR/VFR traffic advisories.

Class D. Airspace extending from the surface to 2500 ft above the airport elevation, surrounding those airports that have an operational control tower. The configuration of Class D airspace is individually tailored, and when instrument procedures are published, the airspace will normally be designed to contain the procedures.

IFR aircraft are authorized to operate in Class D airspace if their ATC clearance routes them through it. VFR pilots are permitted to fly through Class D airspace as long as the basic VFR weather conditions described in FAR 91 exist and ATC permission is granted.

Class E. Controlled airspace that does not come under classes A, B, C, and D airspace.

Class G. Uncontrolled within which ATC separation services will not be provided to any aircraft, whether IFR or VFR. The burden of providing separation is



(a)

(b)

Figure 6.5 Typical Class B airspace—(a) Graphic view of Class B airspace, and (b) sectional chart for same airspace (1).

strictly on the pilot. Most Class G airspace is located away from major airports and below 1200 ft AGL.

6.3 CNS/ATM OF THE NAS

As air traffic activity continues to grow, there is an increasing need for navigational aids, communication systems, and surveillance technology to ensure safety and efficiency and narrow the limits of navigational error in horizontal or vertical separation. At low-traffic densities, the degree of navigational sophistication required is generally low, but as air traffic congestion grows, more navigational aids are needed to give all-weather operation that is highly reliable and safe. From the airport design perspective, the focus should be on navigational aids—visual, radio based, and satellite based.

Radio-Based Technology

Communication. Communication is accomplished by radio receivers and transmitters located both in the aircraft and on the ground, utilizing the common telephony, cellular-based technology, and more recently satellite communication. Civilian aircraft primarily use VHF radio ranges, whereas military aircraft use UHF radio ranges. Air-to-ground communications are necessary to enable pilots to receive flight instructions from air traffic controllers, as they progress along the airways to their destinations, if not on flight plans, to obtain reports of weather ahead, and to alter flight planning as required.

En Route Navigational Aids. Radio-based navigational technology forms the backbone of the CNS system in the world today, as it has been evolving over three-quarters of century. It includes en route air navigation aids that are ground-based equipment operating outside terminal areas that permit in-flight aircraft to achieve accurate navigation using instruments only (9). They include:

Automatic Direction Finding (*ADF*). Also known as a nondirectional radio beacon (NDB), it is a general-purpose, low- or medium-frequency radio beacon on which an aircraft equipped with a loop antenna can home in or can determine its bearing relative to the sender. Operating in the frequency band 200–425 kHz, these facilities transmit with 1020 Hz modulation, which is keyed with a continuous three-letter code to provide identification, except during voice transmission. NDBs are subject to atmospheric noise and communications interference but can be useful for longer ranges (200 mi).

Very High Frequency Omnidirectional Range (*VOR*). VOR navigation uses a very high frequency, day–night, all-weather, static-free radio transmitter, operating within the 108.0–117.95-MHz frequency band with a power output matched to the operational service area. Since the units are limited to line-of-sight reception, the range is dependent on aircraft altitude. Reception at an altitude of 1000 ft is limited to approximately 45 mi, but the range increases with altitude. High-altitude aircraft can suffer mutual VOR interference (multiple receptions from facilities with similar frequencies) because of the greatly increased horizon of the aircraft. VOR facilities form the basis of the Victor airways, with stations set along the airways and at intersections. The accuracy of the indicated course alignment is usually excellent—generally on the order of $\pm 1^{\circ}$.

Distance-Measuring Equipment (*DME*). The slant range to the DME facility is measured by a device located at the VOR site. Its maximum range is 199 mi, using the very high frequency range (962–1213 MHz) with line-of-sight operation and subject to the same performance criteria as VOR. The DME operates by sending out paired pulses at a specific spacing from the aircraft; these pulses are received by a transponder at the ground VOR station. The ground station transmits paired impulses back to the aircraft at the same pulse spacing but at a different frequency. The time between signal transmission and signal reception is measured by the airborne DME unit, and the slant distance in nautical miles is computed and displayed. The equipment is accurate to 0.5 mi or 3% of the distance, whichever is greater.

Tactical Air Navigation (*TACAN*) *and VHF Omnidirectional Range/Tactical Air Navigation* (*VORTAC*). Navigational aids that represent the incorporation of VOR and DME functions into a single channelized system, utilizing frequencies in the ultrahigh frequency range. The VORTAC is a combined facility composed of two different components—VOR and TACAN. Although the technical principles of operation of TACAN are quite different from those of VOR-DME, from the pilot's viewpoint, the outputs or information received are similar. Operating in conjunction with fixed or mobile ground transmitting equipment, the airborne unit translates a UHF pulse into a visual presentation of both azimuth and distance information. It has a triple output: VOR azimuth, TACAN azimuth, and range. Although it consists of more than one component, operating at more than one frequency, VORTAC is considered to be an integrated navigational unit providing three simultaneous information outputs. While TACAN is independent of conventional VOR facilities, it is similarly constrained to line-of-sight operation. The jet route high-altitude airways have been created for use with VORTAC stations separated by long distances. In 1983, the FAA installed the first of 950 new solid-state VORTACs to be located in the United States, replacing the old vacuum tube equipment.

Marker Beacons. Marker beacons identify a specific location in airspace along an airway by means of a 75-MHz directional signal which transmits to aircraft flying overhead. They are used to determine the exact location on a given course. Markers are primarily used in instrument approaches or departure procedures, as holding fixes or position reporting points, in conjunction with en route navigational aids or instrument landing systems.

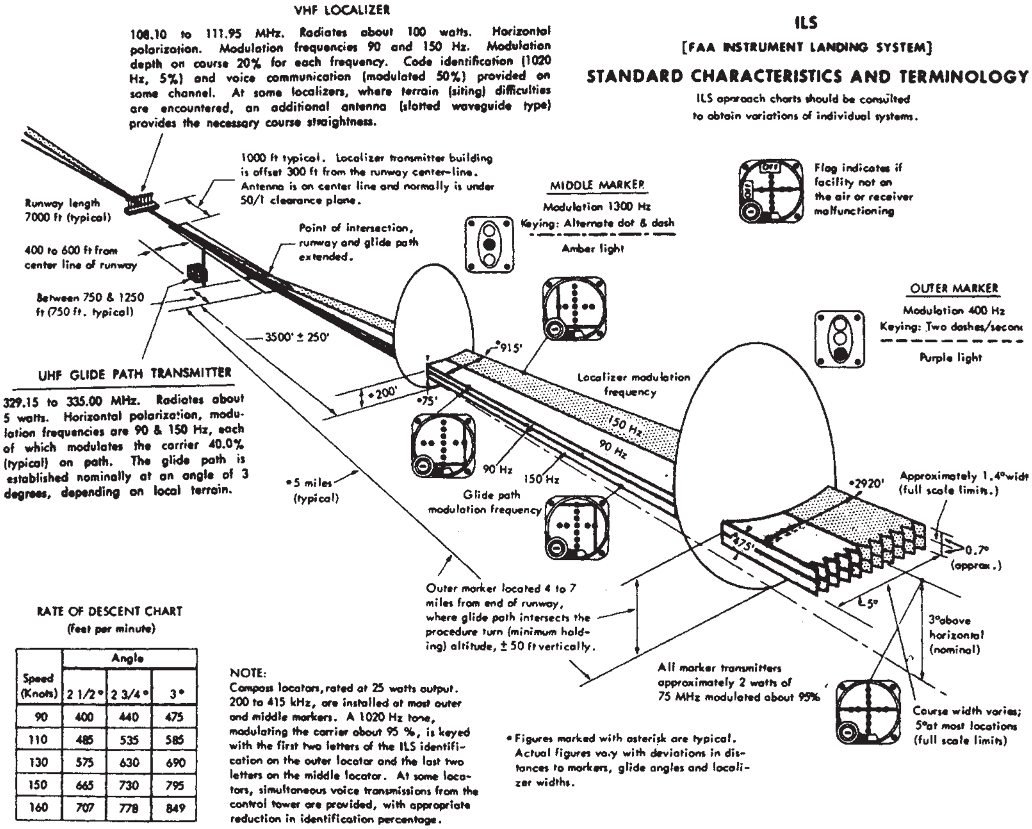
Terminal Area Navigation and Landing Aids. In the immediate vicinity of the terminal area around airports, the following special aids are necessary to assist in the operations of landing and takeoff and to provide safe navigation in the crowded airspace. Design standards and specification of all airport navigation aids are contained in Annex 14, Aerodromes Volume 1, for ICAO standards (10) and Advisory Circular Airport Design Standards, Chapter 6, for FAA standards (11).

Instrument Landing System (ILS). This technology was developed during World War II and has been used in airports around the world ever since. It is the most commonly used system for instrument landings. The ILS is an approach and landing aid designed to identify an approach path for exact alignment and descent of an aircraft making a landing. Functionally, the system is composed of three parts:

1. *Guidance Information.* Localizer and glide slope.
2. *Range Information.* Marker beacons.
3. *Visual Information.* Approach lights, touchdown zone and centerline lights, runway lights.

The ground equipment consists of two highly directional transmitting systems and at least two marker beacons. Guidance information is provided in the cockpit by an adaptation of the VOR equipment.

The *localizer* transmitter is located typically 1000 ft beyond the end of the runway; it emits signals that give the pilot course guidance to the runway centerline. Deviation to the left or right of the extended centerline is indicated on the VOR receiver display, as shown in Figure 6.6. The UHF *glide slope* transmitter is normally set back 750 ft from the runway threshold, usually offset at least 400 ft from the runway centerline. The directional beam provides a radio signal indicating the glide slope; deviation above or below this slope can be displayed on the cockpit VOR receiver.



Speed (Knots)	Angle 2 1/2°	2 3/4°	3°
90	400	440	475
110	485	535	585
130	575	630	690
150	665	730	795
160	707	778	849

Figure 6.6 The Instrument Landing System (ILS). (*Source*: FAA. (11)).

To further help the pilot on an ILS approach, two or three low-power fan *marker beacons* furnish range information to indicate how far along the approach path the aircraft has progressed. The glide path is normally adjusted to 3° above the horizontal so that it intersects the *middle marker* (*MM*) at 200 ft altitude, about 3500 ft from the threshold. The *outer marker* (*OM*) is approximately 5 mi from the threshold, at which point the glide path is 1400 ft above the threshold altitude. Thus, a pilot using the ILS approach has continuous information on position relative to the correct glide path and the extension of the runway centerline. The pilot is further alerted by visual signals when passing over first the outer marker and then the middle marker. On some ILSs (ICOA categories II and III: see below), there is an *inner marker* (*IM*) close to the threshold.

Both the FAA and ICAO promulgate a number of categories into which a designated ILS at an airport is assigned, according to the conditions of runway visual range (RVR) and decision height at which a landing may be made with that particular ILS. It is not possible to categorize a facility until equipment has been installed and calibrated and is operating. The level of categorization is dependent on three principal factors: the quality of signal produced by the navigation equipment, the monitoring and standby arrangements, and the environmental conditions imposed on the equipment in general by the terrain and other surroundings. Table 6.2 indicates the ICAO and FAA categories in terms of RVR and decision heights.

Microwave Landing System (MLS). The ILS, developed mainly by the military, was adopted as a standard approach aid by the ICAO in 1947. It is not, however, without problems. Very large aerial arrays are required to radiate sufficiently narrow beams at the wavelengths employed. Also, the signals from both the glide slope and localizer antennas are affected by the movement of vehicles and taxiing aircraft in their vicinity. Sharp variations in terrain topography and the presence of buildings near the antennas also create difficulties with the signals, which are at their best when reflected from a smooth, featureless ground plane. Consequently, it cannot be guaranteed that a system will reach a required level of performance; exact categorization depends on in situ testing and calibration of installed equipment.

Possibly more serious than the readily apparent limitations imposed by terrain and buildings is the inherent limitation of the system itself, which can give guidance along one alignment only, so that all aircraft must align themselves with the runway axis from many miles out. This forces them to form a single "queue" to the final approach,

Table 6.2 Visibility Minima by ILS Categories

ILS Category (CAT)	Lowest minima RVR	Decision height
Precision CAT I	FAA: 1800 ft (600 m) ICAO: 2500 ft (800 m)	200 ft (60 m)
Precision CAT II	1200 ft (400 m)	100 ft (30 m)
Precision CAT IIIa	700 ft (200 m)	0 ft (0 m)
Precision CAT IIIb	150 ft (50 m)	0 ft (0 m)
Precision CAT IIIc	0 (0 m)	0 ft (0 m)

Source: ICAO (10), and FAA. (11)

with a corresponding restriction on landing rates. This would impact the capability of the ATM function of the system.

Microwave landing systems, which overcome most of the problems associated with ILSs, were considered by the industry in the 1980s. The much higher frequencies would allow the use of smaller transmitting aerials, and with much relaxed restrictions on beam forming and propagation, constraints now imposed by terrain, building, and ground activity would be eliminated. Equally important is the continuous information on distance, absent in the ILS, which gives only point locations over the markers. MLSs with continuous information to the cockpit are ideal for "hands-off" landings. Also important, however, is the multipath approach facility provided by MLSs, shown in Figure 6.7. While international agreement on the form of MLS to be used was

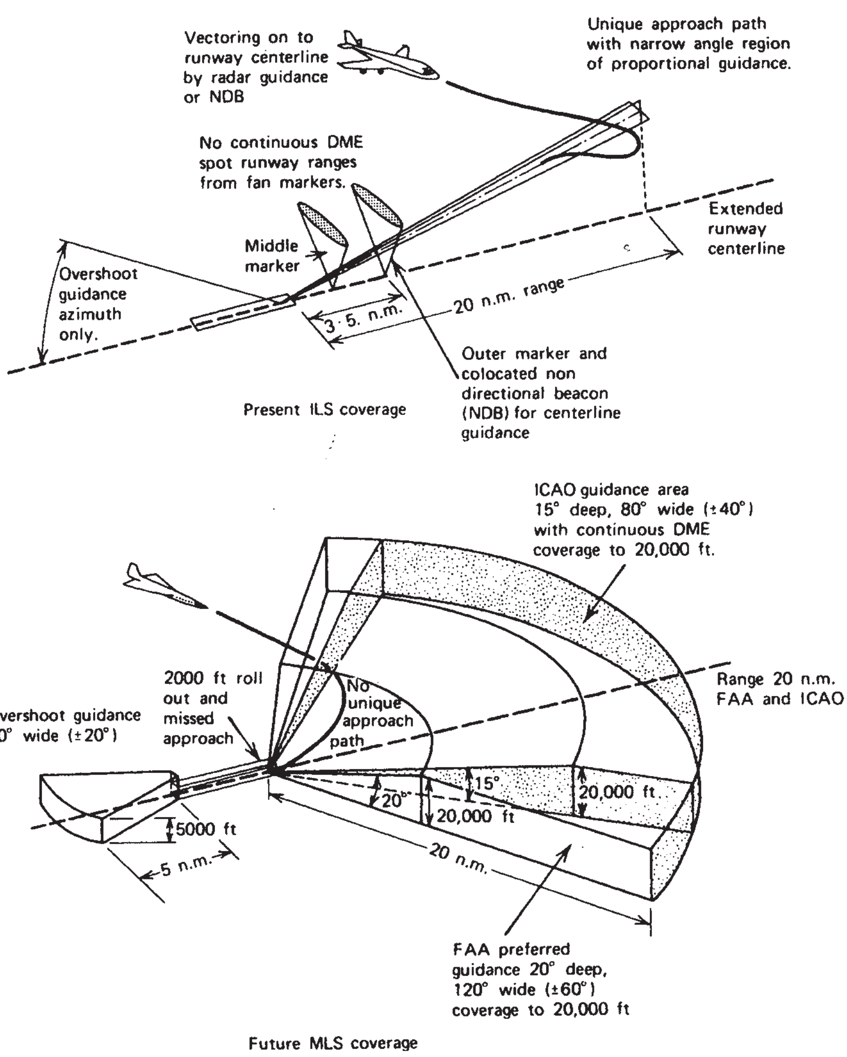


Figure 6.7 Microwave Landing System (MLS). (1).

reached, the depth and width of approach coverage were not. The technology did not require a unique approach path, where multiple paths to approach could be set, which was considered a big advantage to increase runway approach capacity.

However, due to cost of implementation and need for global agreement on its use, there was no agreement within the aviation community to use the MLSs universally. Clearly, the implications of a changeover, not only of ground equipment but also of airborne facilities, were seen by the industry as substantial.

What did gain universal support to use instead is the GPS-based landing system (GLS). It quickly gained popularity and support by industry due to its much lower implementation cost to both airlines and airports and relatively easy utilization and operation, as described below for satellite-based technologies.

Other aids include (1):

- *LORAN C.* LORAN C determines aircraft positions using a velocity input as well as magnetic bearing from the LORAN station. The system uses a hyperbolic ground wave of low frequency for long-range utilization (approximately 2000 mi) and is extremely useful for over-water flights, with position checking being accomplished by using cross-bearings on LORAN stations. It is also used for ship navigation.
- *Omega*. A companion to LORAN C, Omega is a network of eight transmitting stations located throughout the world to provide worldwide signal coverage. Because these stations transmit in the very low frequency (VLF) band, the signals have a range of thousands of miles. The Omega navigation network is capable of providing consistent fixing information to an accuracy of 2 nm. However, its use in the industry was limited.
- *Inertial Navigation Systems* (*INSs*). Large modern air transports are fitted with INSs as part of its FMS. Using the aircraft FMS computer, it calculates latitude and longitude and therefore does not need any ground equipment. This computerized navigational aid is especially useful for very long range flights especially in long transoceanic sectors.

Surveillance. Radio-based surveillance technology mainly includes radars that are used for different purposes en route, in the terminal area, for airport surveillance and even on the airport.

Air Route Surveillance Radar. This is a system of long-range radar designed to provide a display of aircraft operating over a large area, especially en route aircraft flying the airways. Scanning through a 360 azimuth, the equipment provides the ground-based air traffic controller with information on the azimuth and distance position of each aircraft in the airway. Used either in conjunction with other navigational equipment or separately, the radar can be employed to locate with precision an aircraft's position, without reliance on the accuracy of the pilot's reporting. Consequently, there is a substantial reduction in the frequency of voice communication necessary between the controller and the pilot. These radars, also called *primary surveillance radars* (*PSRs*), are typically installed on a nationwide basis with a range of 200 mi or more. As they permit a reduction in separations between aircraft flying at the same altitude without major pilot—controller interaction, they would increase airways' capacity and reduce controllers' workload.

Air Traffic Control Radar Beacon System (ATCRBS), or Secondary Surveillance Radar (SSR). ATCRBS, introduced in 1956 is one of the most significant developments in air traffic technology. It provided controllers with all aircraft data relevant to the ATC function readily available on display and contributed to cutting controllers' workload significantly. The secondary radar system detects and measures the position of aircraft and requests additional identity and altitude information from the aircraft. Unlike PSR systems, which measure only the range and bearing of targets by detecting reflected radio signals, SSR relies on its targets being equipped with a radar transponder that replies to each interrogation signal by transmitting its own response containing encoded data. SSR technology is based on the military concept of identification friend-or-foe (IFF) technology originally developed during World War II.

The SSR has three main components: *interrogator, transponder*, and *radarscope.* Whereas PSR, a passive system, relies on the reflection of transmitted radar signal, the SSR is an active system in which the interrogator transmits, in synchronism with primary radar, discrete radio signals requesting all transponders on that mode to reply. The airborne radar beacon (transponder) in equipped aircraft receives the signal from the interrogator and replies with a specific coded pulse group signal, which is much stronger than the primary radar return. The radarscope displays the targets, differentiating between coded aircraft and ordinary primary radar targets. Shown in Figure 6.8., the SSR radarscopes (based or ARTS described later) are equipped to indicate aircraft identification, altitude, and other information on an alphanumeric display. This feature would provide significant advantage to the controller to be able to differentiate between aircraft rapidly and with certainty and to be assured of correct identification of equipped aircraft in the airspace under surveillance.

The monopulse secondary surveillance radar (MSSR) is a modern improved version of SSR that can reduce garbling in multiradar environments and greatly enhance its reliability. The MSSR replaced most of the existing SSRs by the 1990s and its accuracy provided for a reduction of separation minima in en route ATC environments from 10 nautical mi (19 km) to 5 nautical mi (9.3 km).

Precision Approach Radar (PAR). The PAR was developed by the military as a precision landing aid independent of airborne navigation equipment. The PAR equipment is located on the ground adjacent to the runway and is used as a primary landing aid or, as frequently, in conjunction with ILS. Two antennas are used, one that scans the vertical plane and the other that scans the horizontal plane. The PAR radarscope gives the controller a picture of the descending aircraft in azimuth, distance, and elevation, permitting an accurate determination of the aircraft's alignment relative to the runway centerline and the glide slope. Range is limited to 10 mi, azimuth to 20°, and elevation to 7°. Therefore, the PAR equipment can be used only on final approach, where corrections to the approach are given to the pilot by voice communication from the monitoring air traffic controller.

Airport Surveillance Radar (ASR). Short-range radar that approach and departure controllers use primarily within the vicinity of busy airports and their terminal control area. Within a range starting at 30 and reaching up to 100 nautical mi, ASR provides information for aircraft transiting from the airways to terminal control areas and holding areas through to the airport. It is used by controllers to separate local traffic and to airport final approach. ASR is used in conjunction with other navigational aids for instrument approaches. Surveillance radars scan through a full 360 of azimuth,

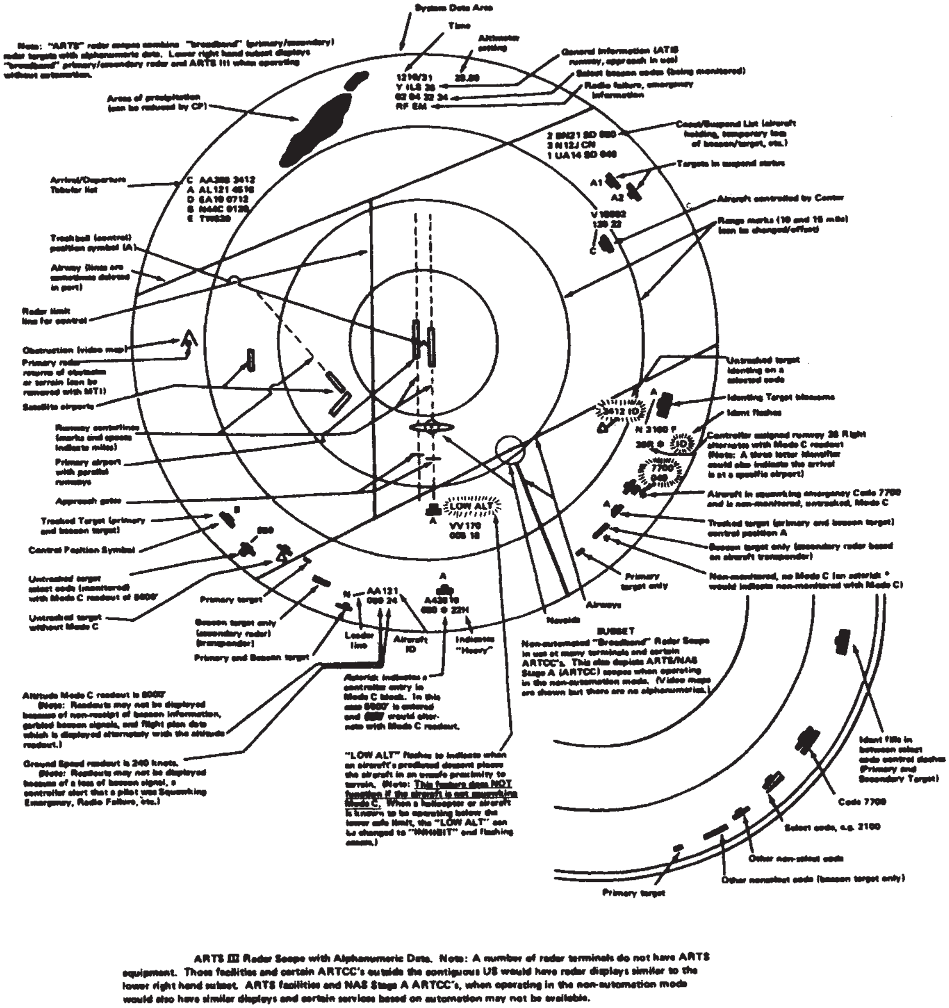


Figure 6.8 Controller's SSR display (*Source: FAA (5)*).

presenting target information on radar displays in the control tower or the air traffic control center. ASR-1 was first obtained by the CAA for civilian air traffic control, and when decommissioned, the FAA installed the ASR-7 and ASR-8 systems in the NAS airports. The FAA then installed the digital ASR-9 radar in more than 140 airports in the United States. The ASR combines moving target data with weather to provide enhanced aircraft detection in bad weather. The ASR-11 digital radar is the next-generation dual, all-solid-state, digital terminal area air traffic control radar that is highly modular and is readily reconfigurable.

The coverage of the PSR is 60 mi, and that of the MSSR is 120 mi. Since the ASR-11 system meets all current FAA, DOD, ICAO, and EUROCONTROL surveillance requirements, it is installed at more than 300 sites around the world. The FAA plans to use both the ASR-9 and ASR-11 digital radars as the backbone of the air traffic control well into the twenty-first century.

Airport Surface Detection Equipment (ASDE). ASDE is a specially designed radar system for use at large, high-density airports to aid ground controllers in the safe maneuvering of taxiing aircraft that may be difficult to see and identify because or airport configuration, aircraft size, or poor visibility conditions. ASDE is a short-range radar capable of locating and displaying moving objects, both aircraft taxiing and moving ground vehicles on the airfield, particularly when inclement weather conditions preclude visual observation of the aircraft movement areas. The FAA originally installed 38 ASDE-3 radar systems at the nation's busiest airports to improve safety and minimize runway incursions.

A more cost-effective ASDE technology, the ASDE-X, is one of the first new runway safety program technologies aimed at improving situational awareness by providing airport ground controllers the tools to ensure optimal operations safety on the airport. The data that ASDE-X uses come from a variety of sources: surface movement radar located at the airport tower or a remote tower, multilateration sensors, ADS-B sensors, terminal radars, the terminal automation system, and aircraft transponders. Fusing the data from these sources enables ASDE-X to determine the position and identification of aircraft and vehicles on the airport surfaces as well as of aircraft flying within 5 mi (8 km) of the airport (selectively up to 60 nautical mi). Controllers in the airport tower see this information presented as a color display of aircraft and vehicle positions overlaid on a map of the airport's runways/taxiways and approach corridors. This creates a continuously updated display of all airport surface operations that controllers can use to spot potential collisions. Visual and audio alarms assist ASDE-X by alerting controllers to possible collisions or runway incursions.

Automated Radar Terminal System (ARTS). The ARTS is a system designed to provide tracking and identification capability for aircraft equipped with transponders in the terminal environment. The system can identify each aircraft by matching its transponder code with flight plan data, provided either by the flight data processing computer of the ARTCC or by controllers' entries into the ARTS system. As aircraft are identified, the ARTS computer maintains constant identification and projects the aircraft's future location. The first model was installed in 1964 but quickly proved successful and useful in relieving controllers of maintaining correct association between radar targets and flight progress strips. The ARTS-III system was developed and installed in all busy airport control towers. This system is capable of accomplishing several tasks, including automatic track initiation, data block generation, automated handoffs, track drops, target coast, altitude filtering, conflict alert, minimum safe altitude warning, and special beacon code displays. Figure 6.8 is a graphical presentation of the ARTS-IIIA display.

Instrument Approach and Departure Procedures. Modern airports use the above technologies collectively and integrally to conduct safe and efficient approach and departure of aircraft in the airport terminal control area. They are not only indispensable to IFR landing approaches but are also helpful to the VFR pilot landing at an unfamiliar airport. The FAA designed instrument approach and departure procedures and produced charts and "plate diagrams" for every airport in the NAS equipped with instrument landing aid installation (e.g., NDB, VOR, DME, TACAN, VORTAC, PAR/ASR, ILS). The FAA TERPS (12), and the ICAO PANS-OPS (13) are the standards used to design these procedures.

These charts indicate prescribe instrument approach procedures from a distance of about 25 mi from the airport and present all related data, such as airport elevation, obstructions, navigational aid locations, and procedural turns. Each recommended procedure per airport—and even a simple airport has several—is designed for use with a specific type of navigational and surveillance aid installed at the airport. A pilot's choice of procedure depends on instrumentation and prevailing weather conditions. These procedures are standardized for the pilot's advantage and to reduce controllers' workload. The FAA developed standard instrument departure (SID) and approach (STAR) procedures to facilitate the transition between takeoff and en route operation, alleviating the need for extensive oral communication between controllers and pilots.

Most recently, the FAA is developing GPS-based area navigation (RNAV) procedures for the NAS airports.

Radar Separation Standards. Use of radar invariably increases ATC system efficiency, reduces controller workload, and enhances safety. At most medium- or high-activity air traffic control facilities the radar is used by controllers to separate aircraft. When radar is used, controllers can visualize aircraft position and that would help them reduce aircraft separation. Radar separation criteria under radar control are used when applying vertical, lateral, longitudinal, or initial separation of aircraft:

- *Vertical Separation*. Below FL 290, separation is of 1000 ft minimum and 2000 ft minimum for those above FL 290.
- *Longitudinal Separation*. Three nautical miles for aircraft less than 40 nautical mi from radar site, and 5 nautical mi for aircraft 40 nautical mi or more from radar site. However, to ensure safety and guard against wake turbulence, separation is further associated with aircraft types in trail:
  - 4 nautical mi between a heavy aircraft following a heavy aircraft
  - 5 nautical mi between a small aircraft following a heavy aircraft and 6 nautical mi when both are landing on same runway
  - 5 nautical mi between a large aircraft following a heavy aircraft
- *Lateral Separation*. Minimum separation is similar to longitudinal separation, except that wake turbulence is not a factor.
- *Initial Separation on Departure*. With radar, lateral separation minima can be reduced when separating two aircraft departing from the same runway. Upon departure, if both aircraft will have their courses diverging by at least 15^{o} immediately after takeoff, a 1-nautical-mi separation interval must be maintained; otherwise regular separation standards must be maintained.

FAA Air Traffic Control Facilities (1). As airports have the above systems installed to facilitate aircraft safe and efficient operation at airports, the FAA runs air traffic control and management ATC/ATM facilities to provide universal control operation in the NAS.

Air traffic control facilities provide the basis for communication with aircraft and the relay and clearance of flight plans for air traffic. The basic types of manned FAA ATC/ATM facilities are the air route traffic control center, the airport traffic control tower, terminal radar control, and the flight service station.

Air Route Traffic Control Centers (ARTCC). In the United States, the FAA has divided the nation's airspace into 22 ARTCC centers to control the domestic air traffic and the movement of aircraft along the airways and in the centers making up the NAS, shown in Figure 6.9. Each center has control of a definite geographical area of the center space and is concerned primarily with the separation of every IFR and participating VFR aircraft operating within the controlled airspace. At the center boundary points marking the limits of the center control area and interface with adjoining centers, air traffic is released in hand-off procedures between centers' controllers to an adjacent center, a TRACON or an airport ATCT.

Each ARTCC is broken down into sectors in order to increase the ATC efficiency of the center. Sectors are smaller geographic airspace chunks, where air traffic is monitored by remote radar units. It can be observed that an aircraft flight plan is transferred between sectors within an air route traffic control center and between air route traffic control centers when crossing the ARTCC boundaries.

Terminal Radar Approach Control (TRACON). A TRACON (or terminal maneuvering area, TMA in ICAO jargon) is an air traffic control facility usually located within the vicinity of a large airport that controls aircraft within a 30–50-nautical-mi (56–93-km) radius of the airport between the surface and 10,000–15,000 ft (4600 m). A TRACON, called approach control or departure control in radio transmissions, normally has its own radar system, typically one or more ASR equipment, sweeping once every 4–5 sec, that enable controllers to observe aircraft direction changes quickly. TRACONs are responsible for providing all ATC services within their

Figure 6.9 The ARTCC in the contiguous United States. (*Source*: FAA.)

airspace for four types of traffic flows: departures, arrivals, overflights, and aircraft operating under VFRs.

The busiest TRACON in the world (Southern California TRACON- SCT, Callsign SoCal Approach) services 62 airports and is located in San Diego, California, and utilizes 11 radar sites. Most U.S. TRACON facilities utilize an ASR-9 Larger TRACONs are capable of directly incorporating en route long-range air route surveillance radar (ARSR) into their automated tracking systems as a backup and can also incorporate data from en route surveillance radar used by ARTCCs.

Air Traffic Control System Command Center (ATCSCC). The FAA Command Center became operational in 1994. Located in Herendon, Virginia, next to Washington Dulles International Airport, it is one of the largest and most sophisticated facilities of its kind. Its primary function is to maintain overall flow control of the NAS airways and sectors and to coordinate the work of the ARTCCs in cases of disaster or severe weather conditions. Utilization of advanced automation tools enables the Command Center to manage the entire NAS activities in an efficient manner. Traffic management specialists work in real time to plan and regulate the flow of air traffic to minimize delays and congestion while maximizing the overall operation of the NAS. Flow rates are set for each airport, and aircraft are subject to a "wheels-up" or control departure time to ensure that the majority of delays in the system due to flow overload are on the ground before departure rather than in the air on arrival. This procedure reduces the inefficient practice of large numbers of stacked aircraft waiting to land.

Airport Traffic Control Tower (ATCT). Airport traffic control towers are facilities that supervise, direct, and monitor the traffic within the airport area. The control tower provides a traffic control function for aircraft arriving at or departing from an airport for a 5–15-mi radius.

Some control towers have approach control facilities and associated ASR which guides aircraft to the airport from a number of specific positions, called "fixes," within approximately 25 mi of the airport. Typically, aircraft are directed to these positions by the ARTCCs, and it is often at these fixes that aircraft are held, or "stacked," for landing during periods of heavy air traffic. The control towers without approach control facilities differ in that, under IFR conditions, the clearing of waiting aircraft for landing is done by the ARTCC or TRACON and they are turned over to the control tower after they have started their landing approach.

Flight Service Stations (FSSs). The FSSs, which are increasingly totally automated, are located along the airways and at airports. Their function may include:

- Relay traffic control messages between en route aircraft and the air route traffic control centers.
- Brief pilots, before flight and in flight, on weather, navigational aids, airports that are out of commission, and changes in procedures and new facilities.
- Disseminate weather information.
- Monitor navigational aids.

Satellite-Based Technologies

The entire CNS/ATM system is evolving into one that is satellite based with intensive use of advanced FMS technology on board modern aircraft. The basic building blocks of the future CNS/ATM system that impacts airports include ADS-B, P-RNAV, performance-based-navigation (PBN), and required navigation performance (RNP). Later in this chapter a brief synopsis of the modernization drives of the next-generation air transportation system in the United States (NextGen) and Europe (SESAR) is presented.

Automatic Dependent Surveillance-Broadcast (ADS-B). A proven technology that is a crucial component of the U.S. next-generation air transportation system (NextGen), implementation of ADS-B over the next 20 years will turn the FAA NextGen vision into a reality. After years of research, development, and real-world testing, the FAA determined in 2005 that ADS-B is ready to be made operational throughout the NAS (2).

The FAA is cooperating with the ICAO and EUROCONTROL on the further development of the ADS-B concept and its global implementation. One of the first implementations of ADS-B for streamlining air traffic and approach to airports was established in Australia. EUROCONTROL has also used ADS-B to enhance safety of aircraft flow in Heathrow London airport (14).

ADS-B, a concept developed jointly by the FAA and industry under RTCA*, operates as follows: properly equipped aircraft periodically broadcast a digital message on a regular basis that includes the state vector and position (latitude, longitude, altitude and velocity) which will be received by the receiver of other entities (e.g., aircraft, ATC centers, airport ground vehicles, etc.), without expectation of acknowledgement or reply. Other aircraft or centers , Other aircraft or systems can receive the broadcast on their position without the need of accurately taking measurement and could process this information in different ways and for different purposes.

ADS-B is therefore *automatic* as no pilot or controller action is required for the information to be issued. ADS-B is *dependent surveillance* where surveillance-type information so obtained depends on the suitable navigation and broadcast capability in the source.

Use of ADS-B in national and international airspace is so often discussed that it will bring a paradigm shift to the entire CNS/ATM, and it is envisaged to effect revolutionary changes to airports and the airspace. The efficiencies brought by ADS-B to the present surveillance technologies are real and significant.

As ADS-B-equipped aircraft determines its own position using GPS and periodically broadcasts this position and other relevant information to potential ground stations and other aircraft equipped with ADS-B, information relevant to surveillance and separation control is transmitted over several different data link technologies. ADS-B would provide accurate information and frequent updates to airspace users and controllers; hence it would support improved use of airspace, reduced ceiling/visibility restrictions, improved surface surveillance, and enhanced safety through conflict management.

The gains in safety, capacity, and efficiency as a result of moving to a satellite-based system will enable the FAA and other air navigation service providers around

*RTCA Special Committee 186—ADS-B Support. RTCA, Inc. (organized in 1935 as the Radio Technical Commission for Aeronautics) is a private, not-for-profit corporation that develops consensus-based recommendations regarding communications, navigation, surveillance, and air traffic management (CNS/ATM) system issues. RTCA functions as a Federal Advisory Committee, and its recommendations are used by the FAA as the basis for policy, program, and regulatory decisions and by the private sector as the basis for development, investment, and other business decisions.

the world to meet the significant growth in air traffic predicted in the coming decades. Because ADS-B is a flexible and expandable platform, it can change and grow with the evolving aviation system.

ADS-B benefits include:

- Increased safety and efficiency by improving visual acquisition in the air and air-to-air surveillance capability and by reducing runway incursions on the ground
- Increased capacity and efficiency by supporting such concepts as enhanced visual approaches, closely spaced parallel approaches, reduced spacing on final approach, reduced aircraft separations, enhanced operations in high-altitude airspace, surface operations in lower visibility conditions, and improved ATC services in nonradar airspace
- Surveillance to remote or inhospitable areas that do not currently have coverage with radar
- Real-time traffic and aeronautical information in the cockpit
- Reduced separation and greater predictability in departure and arrival times
- Support of common separation standards, both horizontal and vertical, for all classes of airspace
- Improved ability of airlines to manage traffic and aircraft fleets
- Improved ability of air traffic controllers to plan arrivals and departures far in advance
- Reduced cost of the infrastructure needed to operate the NAS

However, although ADS-B is suitable for surveillance of remote areas where the siting of radars is difficult, some ATC providers are not yet convinced that it is currently suitable for use in high-traffic-volume areas. Changing from conventional SSR to ADS-B would also require investment in ATC infrastructure. Furthermore, ADS-B provides no ground verification of the accuracy of the information provided by aircraft and this could have adverse security implications.

Basic ADS-B equipment consists of three components:

- A transmitting subsystem that includes message generation and transmission functions at the source (e.g., airplane)
- The transport protocol for air-ground/ground-air VHF data communication and the VHF-digital link (VDL). VDL-mode 2 is implemented operationally to support another modern technology, CPDLC—controller pilot data link communication.
- A receiving subsystem that includes message reception and report assembly functions at the receiving destination (e.g., other airplanes, ATC centers, vehicles, or ground systems)

Area Navigation. RNAV (15) is a method of IFR navigation that allows the aircraft to choose any course within a network of navigational beacons, rather than navigating directly to and from the beacons, with only coverage of station-referenced navigation signals or within the limits of a self-contained system capability, or a combination of these. RNAV can conserve flight distance, reduce congestion, and allow flights into airports without beacons.

The evolution of RNAV was in a manner similar to conventional ground-based routes and procedures. A specific RNAV system was identified and its performance was evaluated through a combination of analysis and flight testing. RNAV procedures were first developed in the United States in the 1960s, and the first such routes were published in the 1970s based on the use of ground-based beacons (e.g., DMEs). In the 1980s, RNAV moved to using satellite-based GPS.

The continuing growth of air traffic increases demand on airspace capacity, thus emphasizing the need to optimize the utilization of available airspace. Improved operational efficiency derived from the application of RNAV techniques resulted in the development of navigation applications in various regions worldwide and for all phases of flight. These applications could potentially be expanded to provide guidance for ground movement operations.

RNAV routes are identified by specifying RNAV accuracy in terms of total system error in percent of the flight time:

- *RNAV* 1 requires a total system error of not more than 1 nautical mi for 95% of total flight time.
- *RNAV* 2 requires a total system error of not more than 2 nautical mi for 95% of total flight time.

An RNAV specification is designated as RNAV X, for example, RNAV 1, where X refers to the lateral navigation accuracy in nautical miles, which is expected to be achieved at least 95% of the flight time by the population of aircraft operating within the airspace, route, or procedure

The FAA RNAV Criterion is consistent with ICAO guidance on the implementation of RNAV1 and RNAV2 operations. The ICAO has continued to harmonize RNAV performance-based navigation criteria.

The DME is the facility to support RNAV operations along a specific route. When unavailable, the navigation service becomes insufficient for DME to support the RNAV. The required performance assumes an aircraft's RNAV system meets the minimum standard (baseline) for DME/DME RNAV systems.

Performance-Based Navigation (PBN). PBN is an internationally accepted framework for defining performance requirements in "navigation specifications" that could be applied to an air traffic route, instrument procedure, or defined airspace (16). PBN provides a basis for the design and implementation of automated flight paths as well as for airspace design and obstacle clearance. The two main components of the PBN framework are RNAV and RNP. Once the required performance level is established, the aircraft's own capability determines whether it can safely achieve the specified performance and qualify for the operation.

PBN represents a shift from sensor-based to performance-based navigation, and it specifies that aircraft RNP and RNAV system performance requirements be defined in terms of the accuracy, integrity, availability, continuity, and functionality required for the proposed operations in the context of a particular airspace when supported by the appropriate navigation infrastructure (17).

Historically, aircraft navigation specifications have been specified directly in terms of sensors (i.e., navigation beacons and/or waypoints). A navigation specification that includes an additional requirement for on-board navigation performance monitoring and alerting is referred to as a RNP specification. One not having such requirements is referred to as an RNAV specification.

Since generic navigation requirements in PBN are defined based on the operational requirements, operators are able to evaluate options in terms of available technologies and navigation services that could allow these requirements to be met. The chosen solution would be the most cost-effective for the operator, rather than a solution being imposed as part of the operational requirements. Technologies could evolve over time without requiring the operation itself to be revisited, as long as the requisite performance is provided by the RNAV system. The ICAO is evaluating other means for meeting the requirements of the navigation specifications.

The navigation performance required from the RNAV system is part of the navigation specification. To determine separation minima and route spacing, airspace planners fully exploit that part of the navigation specification which describes the performance required from the RNAV system. Airspace planners also make use of the required performance (accuracy, integrity, availability, and continuity) to determine route spacing and separation minima. Within a definite airspace, PBN requirements will be affected by the CNS/ATM environments, navigational aid infrastructure, and functional and operational capability needed to meet the ATM application. The PBN performance requirements also depend on the level to which non-RNAV means of navigation are available and what degree of redundancy is required to ensure adequate continuity of operations. Since performance-based flight operations are associated with the ability to assure reliable, repeatable, and predictable flight paths for improved capacity and efficiency, implementing performance-based flight operations requires the functions traditionally provided by the RNAV system as well as specific functions to improve procedures, airspace, and air traffic operations.

The FAA is implementing new PBN routes and procedures that leverage emerging technologies and aircraft navigation capabilities (18). To achieve the efficiency and capacity gains partially enabled by RNAV and RNP, the FAA is using data communications and enhanced surveillance functionality (19).

The critical element for RNP is on-board performance monitoring and alerting. It is the main element that determines if a navigation system complies with the necessary safety level associated with an RNP application and relates to both lateral and longitudinal navigation performance. RNP systems provide improvements in the integrity of operations, which permits closer route spacing and can provide sufficient integrity to allow only RNAV systems to be used for navigation in a specific airspace. The use of RNP systems may therefore offer significant safety, operational, and efficiency benefits.

Aircraft on-board performance monitoring and alerting are concerned with the performance of the RNAV system:

- *On board* explicitly means that the performance monitoring and alerting is affected on board the aircraft and not elsewhere, for example, using a ground-based route adherence monitor or ATC surveillance.
- *Monitoring* refers to the monitoring of the aircraft's performance vis-à-vis its ability to determine positioning error and/or to follow the desired path.
- *Alerting* relates to alerts issued to the pilot if the aircraft's navigation system does not perform well enough.

PBN offers a number of advantages over the sensor-specific method of developing airspace and obstacle clearance criteria:

- PBN reduces the need to maintain sensor-specific routes and procedures and their costs. For example, moving a single VOR or DME can impact dozens of procedures, as they can be used on routes, and the rapid growth in available navigation systems would soon make sensor-specific routes and procedures unaffordable.
- PBN avoids the need for developing sensor-specific operations with each new evolution of navigation systems, which would be cost prohibitive. The expansion of satellite navigation services is expected to contribute to the continued diversity of RNP and RNAV systems in different aircraft. The original basic global navigation satellite system (GNSS) equipment is evolving due to the development of augmentations such as the satellite-based augmentation system (SBAS), ground-based augmentation system (GBAS), and ground-based regional augmentation system (GRAS).
- PBN allows for more efficient use of airspace and clarifies how best RNAV systems are used.
- PBN facilitates the operational approval process by providing a limited set of navigation specifications intended for global use.

The PBN concept recognizes that advanced aircraft RNAV systems are achieving a predictable level of navigation performance accuracy which, together with an appropriate level of functionality, allows a more efficient use of available airspace. It also takes account of the fact that RNAV systems have developed over long periods, and therefore a large variety of implementations exists. It is the primary role of PBN to identify navigation requirements irrespective of the means by which these are met.

RNAV versus PBN. RNAV and RNP systems are fundamentally similar. The key difference between them is the requirement for on-board performance monitoring and alerting. A navigation specification that includes a requirement for on-board navigation performance monitoring and alerting is referred to as an RNP specification. One not having such a requirement is referred to as an RNAV specification. An area navigation system that is capable of achieving the performance requirement of an RNP specification is referred to as an RNP system.

From decisions made by the industry in the 1990s, most modern RNAV systems provide on-board performance monitoring and alerting; therefore, the navigation specifications developed for use by these systems can be designated as RNP. RNAV first used land-based navaids such as VOR and DME for estimating position. Such prescriptive requirements caused delays to the introduction of new RNAV system capabilities and higher costs for maintaining appropriate certification. To avoid such prescriptive specifications of requirements, PBN was introduced as an alternative method for defining equipment requirements, which enabled the specification of performance requirements, independent of available equipment capabilities. RNAV is now one of the navigation techniques of PBN; the other is the RNP discussed later.

Many RNAV systems, while offering very high accuracy and possessing many of the functions provided by RNP systems, are not able to provide *assurance* of their performance. To avoid operators incurring unnecessary expense, where the airspace requirement does not necessitate the use of an RNP system, many new as well as existing navigation requirements will continue to specify RNAV rather than RNP systems. It is therefore expected that RNAV and RNP operations will coexist for many years.

However, RNP systems provide improvements in the integrity of operation, permitting possibly closer route spacing, and can provide sufficient integrity to allow only the RNP systems to be used for navigation in a specific airspace. The use of RNP systems will offer significant safety, operational, and efficiency benefits. It is expected that there will be a gradual transition to RNP applications as the proportion of aircraft equipped with RNP systems increases and the cost of transition is reduced.

Required Navigation Performance (RNP). An RNP is a type of PBN that allows an aircraft to fly a specific path between two three-dimensionally defined points in space. RNAV and RNP systems are fundamentally similar, but the key difference between them is the requirement for on-board performance monitoring and alerting, an RNP specification—a navigation specification that includes a requirement for on-board navigation performance monitoring and alerting. Otherwise, it is an RNAV specification.

RNP also refers to the level of performance required for a specific procedure or a specific block of airspace. For example, RNP 10 means that a navigation system must be able to calculate its position to within a circle with a radius of 10 nautical mi, and RNP 0.3 means the aircraft navigation system must be able to calculate its position to within a circle with a radius of 0.3 nautical mi. This RNP specification determines the separation required between aircraft in the particular airspace. High-accuracy RNP approaches with RNP values currently down to 0.1 allow aircraft to follow precise three-dimensional curved flight paths through congested airspace, around noise sensitive areas, or through difficult terrain.

RNP procedures were introduced by the ICAO (16, 17) and became applicable in 1999. These RNP procedures were the predecessor of the current PBN concept, whereby the performance for operation on the route is defined, in lieu of simply identifying a required radio navigation system. However, due to the insufficient description of the navigation performance and operational requirements, there was little perceived difference between RNAV and RNP. In addition, the inclusion of conventional flight procedures, variability in flight paths, and added airspace buffer resulted in no significant advantages being achieved in designs. As a result, there was a lack of benefits to the user community and little or no implementation.

In the United States, the airline industry became the leader in implementing RNP, and the FAA followed by developing the RNP procedures later (18, 19). In 1996, Alaska Airlines became the first airline in the world to utilize an RNP approach into Juneau, Alaska. Realizing its operational and safety benefits, Alaska Airlines developed more than 30 RNP approaches. In 2005, Alaska Airlines utilized RNP approaches into Washington Reagan National Airport to avoid congestion and in April 2009 became the first airline to gain approval from the FAA to validate its own RNP approaches.

In other parts of the world, RNP approaches to 0.3 and 0.1 nautical mi at Queenstown Airport in New Zealand are the primary approaches used by Qantas and Air New Zealand airlines for both international and domestic services. Due to terrain restrictions, ILS approaches are not possible, and conventional VOR/DME approaches have descent restrictions more than 2000 ft above the airport level. RNP approaches and departures were the solution where they follow curved paths over difficult terrain.

The specific requirements of an RNP system include:

- Capability to follow a desired ground track with reliability, repeatability, and predictability, including curved paths
- Use of vertical angles or specific altitude constraints to define a desired vertical path, where vertical profiles are included for vertical guidance

Performance monitoring and alerting capabilities in RNP are provided in different forms depending on the system installation, architecture, and configurations, including:

- Display and indication of both the required and the estimated navigation system performance
- Monitoring of the system performance and alerting the crew when RNP requirements are not met
- Display of cross-track deviation scaled to RNP, in conjunction with separate monitoring and alerting for navigation integrity

The RNP system utilizes its navigation sensors, system architecture, and modes of operation to satisfy the RNP navigation specification requirements. It must perform the integrity and reasonableness checks of the sensors and data and may provide a means to deselect specific types of navigation aids to prevent reversion to an inadequate sensor. RNP requirements may limit the modes of operation of the aircraft.

An RNAV system capable of achieving the performance requirements of an RNP specification is referred to as an RNP system, where specific performance requirements are defined for each navigation specification. An aircraft approved for a RNP specification is not automatically approved for all RNAV specifications. Similarly, an aircraft approved for an RNP or RNAV specification having stringent accuracy requirements is not automatically approved for a navigation specification having a less stringent accuracy requirement.

RNP performance monitoring and alerting requirements include:

- *Accuracy*. The accuracy requirement defines the 95% total system error (TSE) for those dimensions where an accuracy requirement is specified. For RNP navigation specifications, accuracy is one of the performance characteristics monitored.
- *Performance Monitoring*. The TSE is constantly monitored to provide an alert if the accuracy requirement is not met or if the TSE exceeds two times the accuracy value.
- *Aircraft Failures*. Failure of the aircraft equipment is considered within airworthiness regulations, but the requirements on aircraft failure characteristics are not unique to RNP navigation specifications.
- *Signal-in-Space Failures*. Signal-in-space characteristics of navigation signals are the responsibility of the air navigation service provider, not the RNP system.

Existing terminal airspace concepts are supported by RNAV applications currently used in Europe and the United States. The European terminal airspace RNAV is P-RNAV (precision RNAV). The U.S. terminal airspace application was aligned with the PBN concept in 2008 and is now called RNAV 1. Basic RNP 1 has been developed primarily for application in nonradar, low-density terminal airspace. More RNP applications are being developed for both en route and terminal airspace. For the airport instrument approach concept, they increasingly call for RNP specifications requiring a navigation accuracy of 0.3–0.1 nautical mi or lower. Typically, three RNP applications are considered for this phase of flight: new procedures to runways never served by an instrument procedure, procedures either replacing or serving as backup to existing instrument procedures based on different technologies, and procedures developed to enhance airport access in demanding environments.

Wide-Area Augmentation System (WAAS). **WAAS** (20) is an air navigation system jointly developed in 1994 in the United states by the DOT and the FAA to augment the GPS with the goal of improving its accuracy, integrity, and availability and provide performance comparable to category I ILS for all aircraft possessing the appropriately certified equipment. Essentially, WAAS is intended to enable aircraft to rely on GPS for all phases of flight, including precision approach to any airport within its coverage area. Without WAAS, ionospheric disturbances, clock drift, and satellite orbit errors create too much error and uncertainty in the GPS signal to meet the requirements for precision approach operations. A precision approach includes altitude information and provides course guidance, distance from the runway, and elevation information at all points along the approach, usually down to lower altitudes and weather minimums than nonprecision approaches.

WAAS consists of approximately 25 ground reference stations positioned across the United States that monitor GPS satellite data and measure small variations in the GPS signals. Two master stations, located on either coast, collect data from the reference stations and create a GPS correction message and send the correction messages to geostationary WAAS satellites in a timely manner (every 5 sec or better). This correction accounts for GPS satellite orbit and clock drift plus signal delays caused by the atmosphere and ionosphere. The corrected differential message is then broadcast through one of two geostationary satellites (satellites with a fixed position over the equator). The information is compatible with the basic GPS signal structure, which means any WAAS-enabled GPS receiver can read the signal.

Therefore, WAAS is an extremely accurate navigation system developed exclusively for civil aviation. Before WAAS was developed, the NAS did not have the potential to provide horizontal and vertical navigation for approach operations for all users at all locations. With WAAS, this capability is a reality. Moreover, WAAS provides service for all classes of aircraft in all phases of flight, including en route navigation, airport departures, and airport arrivals. This includes vertically guided landing approaches in instrument meteorological conditions at all qualified locations throughout the NAS.

Benefits of WAAS are:

- ILS uses a series of radio transmitters each broadcasting a single signal to the aircraft, and this complex series of radios needs to be installed at every runway end, some offsite, along a line extending from the runway centerline, making the implementation of a precision approach both difficult and very expensive. In WAAS all this is not required, and thus significant cost savings are realized.
- WAAS provides service for all classes of aircraft in all phases of flight, including en route navigation, airport departures, and airport arrivals. This includes vertically guided landing approaches in instrument meteorological conditions at all qualified locations throughout the NAS.

- WAAS addresses the "navigation problem" in its entirety, providing highly accurate positioning that is extremely easy to use, for the cost of a single receiver installed on the aircraft. Ground- and space-based infrastructure is relatively limited, and no on-airport system is needed.
- WAAS allows a precision approach to be published for any airport for the cost of developing the procedures and publishing the new approach plates. This means that almost any airport can have a precision approach and the cost of implementation is dramatically reduced.
- WAAS works just as well between airports, where the aircraft is allowed to fly directly from one airport to another, as opposed to following routes based on ground-based signals. This can cut route distances considerably in some cases, saving both time and fuel.
- Aircraft equipped with WAAS equipment are permitted to fly at lower en route altitudes than was possible with ground-based systems, which were often blocked by terrain of varying elevation. This enables pilots to safely fly at lower altitudes, not having to rely on ground-based systems.

The above benefits not only create convenience but also have the potential to generate significant cost savings. The cost to provide the WAAS signal, serving all 5400 public-use airports in the United States, was estimated by the FAA as just under $50 million per year, compared to the current ground-based ILS system, installed at only 600 airports, which cost $82 million in annual maintenance. Without ground navigation hardware to purchase, the total cost of publishing a runway's WAAS approach is approximately $50,000, compared to the $1 million to $1.5 million cost to install one ILS radio system.

Local-Area Augmentation System (LAAS). LAAS (21), and the ICAO term GBAS (ground-based augmentation system), is an all-weather aircraft landing system based on real-time differential correction of the GPS signal against local reference receivers located around an airport at precisely surveyed locations, and the signal received from the GPS satellite constellation is compared to the surveyed location. The aircraft FMS receiver uses this information to correct the GPS signals it receives, and data are used to formulate a correction message which is transmitted to users via a VHF data link, which then provides a standard ILS-style display to use while flying a precision approach for landing purposes. LAAS is designed exclusively for aircraft and is only intended for use within 20–30 mi of its installed airfield location.

LAAS/GBAS is composed of a single GPS reference station facility located on the property of the airport with three or more reference (redundant) receivers located around the airport. This facility independently measures GPS satellite "pseudorange" and carrier phase and generates differential carrier-smoothed-code corrections that are eventually broadcast to a user via VHF (in the 108–118-MHz band). It also includes safety and approach geometry information. This information allows users within 45 km of the LAAS ground station to perform GPS-based position fixes with 0.5-m (95%) accuracy and to perform all civil flight operations up to nonprecision approach. Aircraft landing at a LAAS-equipped airport will be able to perform precision approach operations up to at least category I weather minima. "Pseudo-lites" are optional means of improving user ranging geometries with ground-based GPS-like transmitters.

One of the primary benefits of LAAS is that a single installation at a major airport can be used for multiple precision approaches within the local area. For example, if an airport has six runway-ends each with a separate ILS, then all six ILS facilities can be replaced with a single LAAS system. This represents a significant cost savings in maintenance and upkeep of the existing, often costly ILS equipment.

Another benefit is the potential to perform approaches that are not straight in. The GPS-LAAS/GBAS capability can guide an aircraft on any approach necessary to avoid obstacles or to decrease noise levels in areas surrounding an airport.

The other benefit is that a single set of navigational equipment is needed on an aircraft for both LAAS and WAAS capability. This will further lower initial cost and maintenance per aircraft since only one receiver is required instead of multiple receivers for nondirectional beacons (NDBs), DME, VOR, ILS, MLS, and GPS, and this definitely will decrease costs to the airlines, airports, and to passengers at these airports. It is likely therefore that the FAA's goal for LAAS is to replace the existing ILS equipment for all categories of precision approaches in the NAS airports.

In terms of safety, the LAAS ground facility (LGF) meets these requirements by detecting and excluding anomalous reference receiver measurements before differential corrections are broadcast. The corrections that are broadcast come with bounding standard-deviation values ("sigmas") on errors in the corrections that allow users to compute position error bounds in real time and to compare them to the alert limits for their current operation to verify that the operation remains safe to conduct.

Visual-Based Technology

Visual-based navigation includes all lighting aids, markings, signage, and other fixtures that would provide visual guidance to pilots upon final approach, landing, taxiing, and gate docking. Airport visual aids standards are given by the ICAO (10) and the FAA (11, 22).

Runway Lighting. **Visual Approach Slope Indicator (VASI**). It is a system of lights on the side of an airport runway threshold that provides visual descent guidance information to the pilot during the approach to a runway. Lights may be visible from up to 5 mi (8 km) during the day and up to 20 mi (32 km) or more at night.

It is frequently supplied in addition to other visual and nonvisual approach aids and is usually installed when one or more of the following conditions exist (10):

- The runway is used by turbojet aircraft.
- The pilot may have difficulty in judging the final approach because of inadequate visual reference over water or featureless terrain or because of deceptive surrounding terrain or misleading runway slopes.
- There are serious hazards in the approach area that would endanger the aircraft if it sank below the normal approach path.
- Serious hazard would occur in the event of undershooting or overshooting.
- Turbulence exists due to terrain or meteorological conditions.

The VASI system installation basically consists of two wing bars of lights on either side of the runway. Figure 6.10(a) depicts the installation and locations of these bars: one set of bars 500 ft from the runway end (downwind bars) and a second set of bars

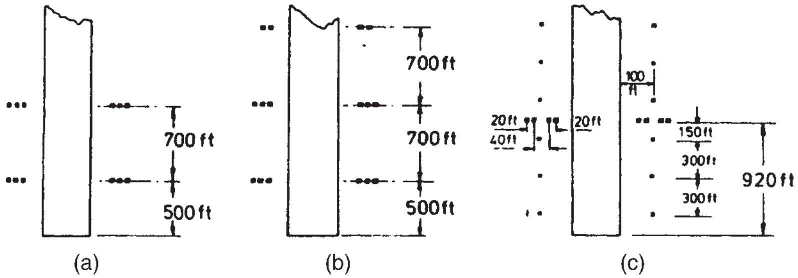


Figure 6.10 (a) Layout of a VASI system. (b) Layout of a three-bar VASI system. (c) Layout of a T-VASI system. (*Source*: ICAO(10).)

1200 ft from the runway end (upwind bars). Each light bar in the system produces a split beam of light; the upper segment is white, and the lower segment is red. If the aircraft is above the glide path on approach, the pilot sees both light bar sets white; if the aircraft is too low, both sets appear red. While on the glide path, the upwind bar appears red and the downwind bar white. A number of different configurations of VASI-type systems are recognized by the FAA and the ICAO.

A variation of the basic VASI configuration is necessary for large aircraft (codes D and E) such as the B-747 and A-380. VASI gives insufficient margin of safety for undershoot because of the great distance between the pilot's eye and the main landing gear in the approach; thus, the three-bar VASI configuration as seen in Figure 6.10(b) is used. Pilots of large aircraft ignore the downwind bar and are guided by the center and upwind bars only; small aircraft can use either the upwind-center or center-downwind combination.

A more elaborate visual system is provided by the T-VASI configuration. As seen in Figure 6.10(c), it consists of one wing bar on either side of the runway, 920 ft from the threshold (10). Six "fly-up" and six "fly-down" lights are located at either side of the runway. When the pilot is above the glide slope, the wing bar appears white, and the higher the aircraft, the more fly-down units are seen. On the correct approach slope, the pilot sees only the white wing bar. Below the correct approach path, the wing bar is white and the fly-up units appear white. The more fly ups that are visible, the lower the approach. When the aircraft is well below the correct approach slope, the wing bar and all fly-up units appear red. Figure 6.11 shows the arrangement of the split light beams for the three-bar VASI and T-VASI.

Precision Approach Path Indicator (PAPI) System. Although the VASI and T-VASI light-landing aids give pilots considerable visual assistance on final approach, experience indicates that they are not without criticism. The VASI tends to give rise to an oscillatory approach as the pilot moves between the upper and lower limiting approach planes. Both VASI and T-VASI are imprecise below 60 m (200 ft) and are not suitable for a nonstandard approach. The three-bar VASI has an approach corridor which is 20 ft steeper than the lower corridor, and both two- and three-bar configurations require extensive maintenance and flight checking to keep them operational. Also, in bright sunlight, the pink transition zone is difficult to differentiate from the red. All these factors tend to result in a large touchdown scatter. The T-VASI overcomes some of the problems of VASI; for example, T-VASI is more suited to multipath approaches

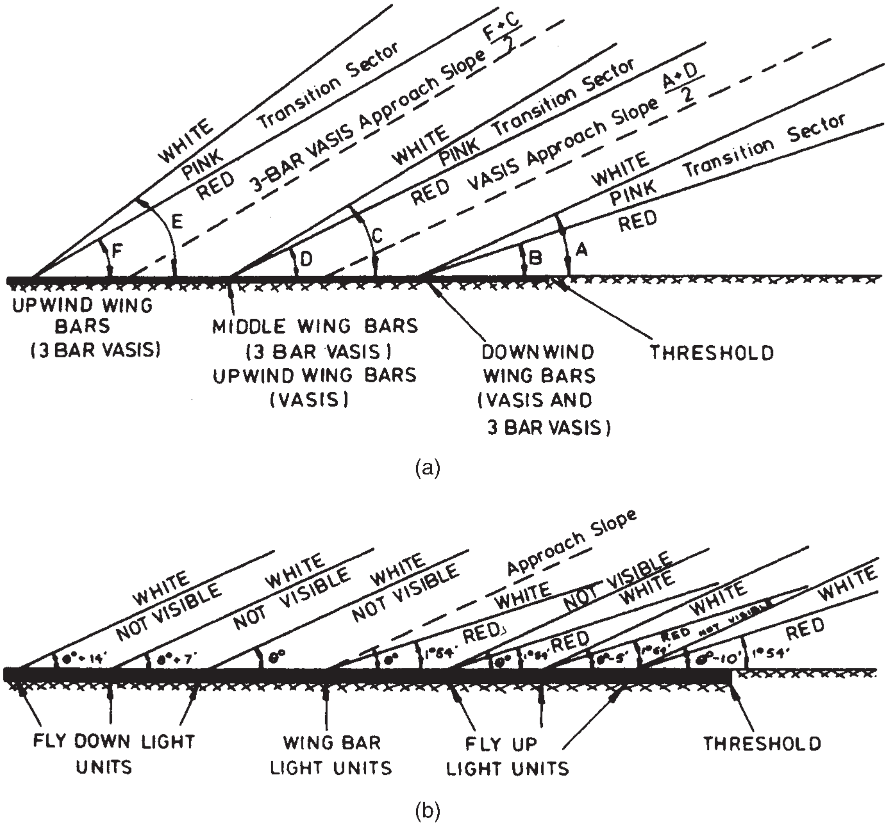
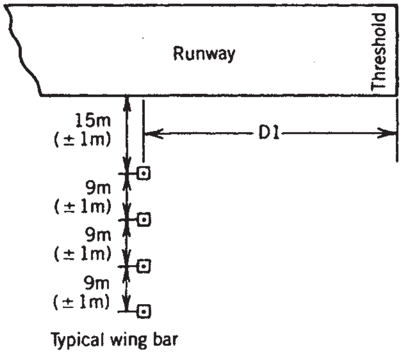


Figure 6.11 Light beams and angle of elevation settings: (a) VASIS and three-bar VASI: (b) T-VASI. (*Source*: ICAO (10).)

and does not rely on color change except in the case of severe underflying. However, it is more complex to site and to maintain. It is also important to note that there is no fail-safe indication if the downwind fly-up lights fail.

The PAPI system shown in Figure 6.12 overcomes most of these disadvantages. It is a two-color light system using sealed units, giving a bicolored split beam: white above, red below. These sealed units are much more easily sited, set, and maintained and are capable of multipath interpretation. The units are high powered and visible for up to 7 km from the threshold. The approach has been found under tests in the United States, United Kingdom, France, and Russia to be more precise and more flexible than VASI. PAPI systems are expected to replace VASI at large airports.

Runway End Identifier Light (REIL) (23). Sometimes lights are placed at runway ends to assist in the rapid and positive identification of the approach end of the runway. The system consists of two synchronized flashing lights, one at each end of the runway threshold. Not normally provided where sequenced flashers are incorporated in the approach lighting system, REIL systems are used to distinguish the threshold in locations characterized by numerous ground lights, such as neon signs and other lights that could confuse or distract the pilot.



Indications to pilot:

a) The distance D_1 shall ensure that the lowest height at which a pilot will see a correct approach path indication will give for the most demanding aircraft a wheel clearance over the threshold of not less than:

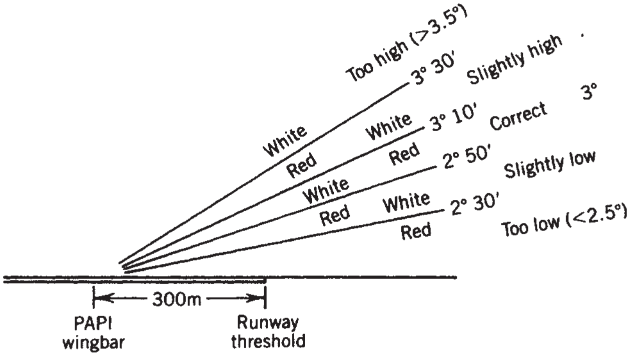
1) 9 m where the code number is 3 or 4; and

2) 3 m or the aircraft eye-to-wheel height in the approach attitude, whichever is the greater, where the code number is 1 or 2.

b) In addition, when the runway is equipped with an ILS, to make the visual and nonvisual glide paths compatible, the distance D_1 shall:

1) equal the distance between the threshold and the effective origin of the ILS glide path where the code number is 1, 2 or 3; or

2) be at least equal to, but not more than 120 m greater than, the distance between the threshold and the effective origin of the ILS glide path where the code number is 4.



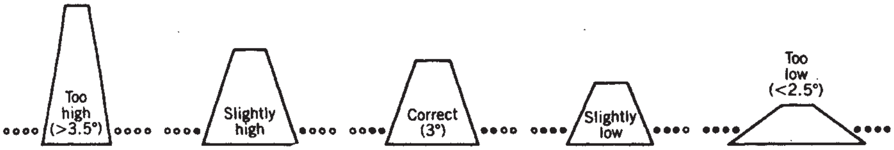


Figure 6.12 PAPI: location of lights and visual indications to pilot. (*Source:* ICAO (10).)

Approach Lighting System (ALS) (10, 24). Approach lighting systems are used in the vicinity of the runway threshold as adjuncts to electronic aids to navigation for the final portions of IFR precision and nonprecision approaches and as visual guides for night flying during VFR conditions. The approach lighting system supplies the pilot with visual cues relative to aircraft alignment, roll, horizon, height, and position with respect to the threshold. Since the use of lighting systems relies on the brain's rapid action on visual information leading to decision and action, a visual system is ideal for guidance during the last few critical seconds of movement down the glide path.

Approach lighting systems have been developed on the basis of the glide path angle, visual range, cockpit cutoff angle, and aircraft landing speeds. It is essential that pilots be able to identify the ALS and to interpret the system without confusion. Thus, approach lighting systems have been standardized internationally so that longitudinal rows of lights indicate the extended alignment of the runway, with transverse crossbars of lights at standard distances from the threshold for roll and position guidance. In most aspects, the U.S. standards for approach lighting systems are virtually identical to ICAO standards; where differences occur, they are of minimal importance.

Approach lighting systems are classified under two basic categories:

FAA High-Intensity Systems. These are designed for operation with ILS approaches categories I, II, and III. The FAA high-intensity system comes in a single standard layout (Figure 6.13):

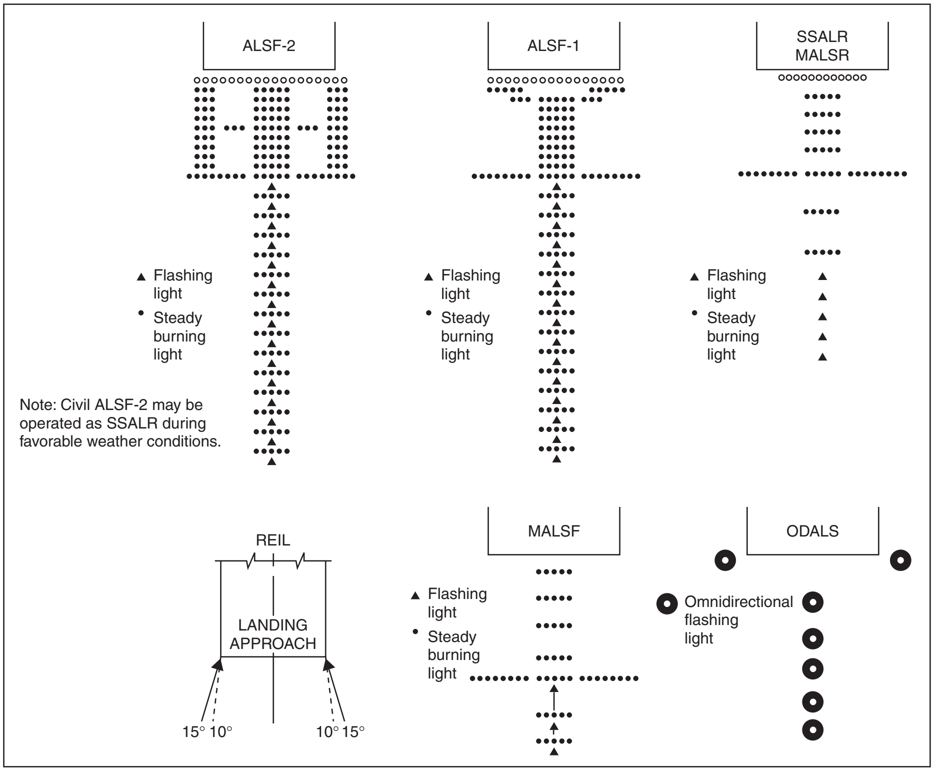


Figure 6.13 FAA approach lighting systems (11).

ALSF-II. This 300-ft high-intensity ALS is composed of barrettes of five white lights along the extended runway centerline, with sequenced flashing lights on the outer 2000-ft centerline. The effect of the bright sequenced flashers gives the appearance of a fast-moving ball of light traveling toward the runway. The inner 1000 ft of the approach is additionally lit by barrettes of red lights on either side of the centerline, with crossbars of white lights at 1000 and 500 ft from the threshold. The threshold itself is marked by a threshold bar of green lights. This configuration also conforms to ICAO standards for category II and III approach instrument runways.

FAA Medium-Intensity Systems. Three types of medium-intensity ALSs are specified for U.S. airports; MALSR, MALSF, and MALS configurations (11). These systems, which are used mainly for utility airports catering to general aviation aircraft, meet the minimum requirements of the *simple approach lighting system* specified by the ICAO (10).

MALSR. A medium-intensity ALS with runway alignment indicator lights. It is the U.S. standard configuration for ILS operations during category I visibility minima. Eight flashing units are installed along the extended runway centerline, at 200-ft spacing extending to the end of the configuration, from 1400 ft from the threshold.

MALSF. Medium-intensity ALS with sequenced flashers at the outer three barrettes of centerline lights. This and the MALSR configuration are used where approach area identification problems exist.

MALS. A medium-intensity ALS similar to MALSF, except for the absence of sequenced flashing lights. This is the simplest of the U.S. standard configurations.

Where airports must be designed with "economy approach lighting aids," the FAA recommends the use of MALS or MALSF.

Another system used widely in the United kingdom, Europe, and some other parts of the world, particularly Commonwealth countries, is the Calvert system. This system is distinguished by six transverse lines of lights of variable length at right angles to the axis of approach. The length of the transverse bars diminishes as the pilot approaches the threshold.

Runway Centerline and Touchdown Zone Lighting System (RCLS) (22, 24). Runway centerline and touchdown zone lighting systems facilitate landings, rollouts, and takeoffs (11). RCLS is installed on some precision approach runways to facilitate landing under adverse visibility conditions. They are located along the runway centerline and are spaced at 50-ft intervals. When viewed from the landing threshold, the runway centerline lights are white until the last 3000 ft of the runway. The white lights begin to alternate with red for the next 2000 ft, and for the last 1000 ft of the runway, all centerline lights are red. Runway centerline lights are semiflush units set into the pavement and offset by a maximum of 2 ft to clear centerline paint markings. All lights are bidirectional; therefore, red lights in the 3,000-ft zone show white toward the runway end for approaches from the other direction.

ICAO requirements for centerline lights are generally similar to those of the FAA, as they are required for precision runway categories II and III and are recommended for category I and other runways with specified visibility operational requirements. Spacing is specified at 50 ft for category III runways and permitted at 100 ft centers for others. Centerline lights assist the pilot after touchdown rollout and furnish primary takeoff guidance.

Touchdown zone lights (TDZLs) are installed to prevent pilots from losing orientation after passing over the threshold bar (23). The system consists of two rows of transverse light bars disposed symmetrically about the runway centerline. The system consists of flush-mounted transverse pavement light bars for the first 3,000 ft of the runway to ensure continuous visual roll guidance. Rows of light bars are set symmetrically about the centerline, each bar consisting of three unidirectional steady-burning white lights. The first row is mounted 100 ft from the threshold. A standard FAA touchdown zone configuration appears in Figure 6.14. ICAO requirements are again generally similar to those of the FAA, except that the maximum bar spacing is set at 100 ft for category II and III runways only. For other installations, this dimension is merely advisory.

Both systems are designed for use in conjunction with the electronic precision aids and the standard approach lighting systems under limited visibility.

Runway Edge, Threshold, and Runway End Lighting Systems (24) Lighting at the runway edges gives pilots location information in both the landing and takeoff operations and is used to outline the edges of runways during periods of darkness or restricted visibility conditions. These light systems are classified according to the intensity or brightness they are capable of producing: they are the high-intensity runway lights (HIRLs), medium-intensity runway lights (MIRLs), and low-intensity runway lights (LIRLs) (23). The HIRL and MIRL systems have variable intensity controls, whereas the LIRLs normally have one intensity setting. Low-intensity lights are intended for use on VFR airports having no planned approach procedures. Medium-intensity edge lights are used on runways having a nonprecision IFR procedure for circling or straight-in approaches. High-intensity edge lights are used on runways with IFR approach procedures.

The runway edge lights are white, except on instrument runways, where bidirectional yellow-white lights are used with the yellow pointing toward a departing pilot,

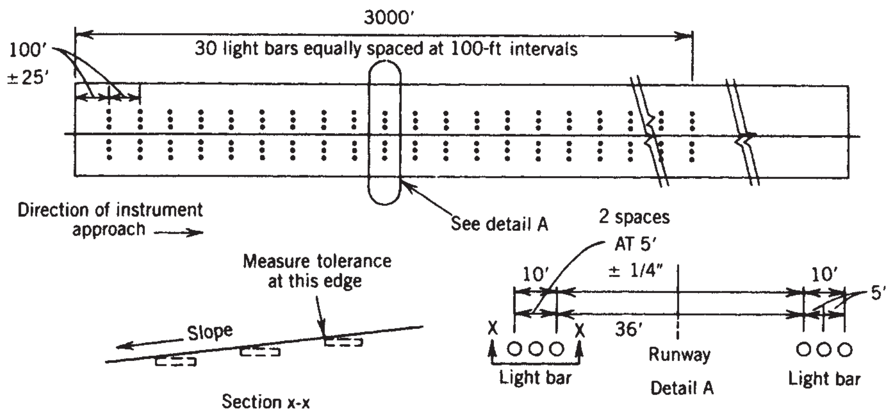


Figure 6.14 FAA touchdown zone lighting configuration. (*Source:* FAA (11).)

indicating a caution zone. The yellow replaces white on the last 2000 ft or half the runway length, whichever is less, to form a caution zone for landings. The lights marking the ends of the runway emit red light toward the runway to indicate the end of the runway to a departing aircraft and emit green outward from the runway end to indicate the threshold to landing aircraft. The FAA requires a maximum spacing of 200 ft each unit located not more than 10 ft from the runway edge. ICAO requirements are less stringent, permitting spacing up to 100 m on noninstrument runways. Edge lights are normally elevated single lights, although semiflush installations are permitted. Semiflush units are installed at the intersections of runways and taxiways.

Figure 6.15 shows an arrangement for a medium-intensity edge lighting system. For noninstrument runways, six bidirectional threshold lights are used; for an instrument runway, eight lights are used. For category I and greater precision runways, the threshold bar is a continuous line of green lights in the direction of the approach; some of the lights are bidirectional red to indicate the runway to aircraft on rollout.

ICAO requirements contained in Annex 14 are generally similar to the FAA.

Runway Status Light (RWSL) System (5). A fully automated system that provides runway status information to pilots and surface vehicle operators to indicate when it is unsafe to enter, cross, take off from, or land on a runway. The RWSL system processes information from surveillance systems and activates runway entrance lights (RELs), takeoff hold lights (THLs), and the final approach runway occupancy signals (FAROSs) in accordance with the motion and velocity of the detected traffic.

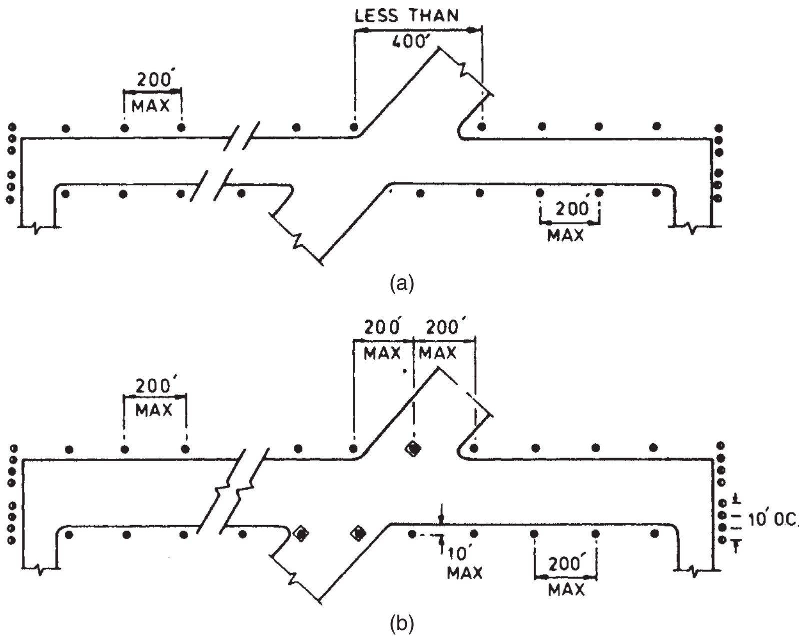


Figure 6.15 FAA medium-intensity runway and threshold lighting system: solid circles 360° white, except for last 2000 ft of instrument runway; half solid circles, red 180°, green 180°; circle in square, semiflush bidirectional. (a) Application of single elevated lights. (b) Application of single elevated lights and semiflush lights. (*Source:* FAA (11).)

The REL and THL are in-pavement light fixtures that are directly visible to pilots and surface vehicle operators. FAROS activation is by means of flashing the precision approach path indicator (PAPI). RWSL is an independent safety enhancement that does not substitute for the airport ATC clearance. Clearance to enter, cross, take off from, land on, or operate on a runway must be issued by ATC. Although ATC has limited control over the system, personnel do not directly use and may not be able to view light fixture output in their operations.

Taxiway Edge and Centerline. For safety and efficiency, the locations and limits of taxiways must be indicated clearly to pilots. This is achieved principally by the use of taxiway edge and centerline lights. Taxiway edge lights are blue, to differentiate them from runway edge lights. They are elevated fixtures, extending (under FAA specifications) to a maximum height of 14 in. above finished grade (24), set at a maximum distance of 10 ft from the taxiway edge. On long tangents, spacing can be up to 200 ft centers (Figure 6.16). On shorter tangents, spacing is kept below 200 ft. Figure 6.17 indicates the required spacing of lights for curved taxiway edges. In setting out taxiway edge lighting systems, it is essential to eliminate all possibilities of confusing a portion of a taxiway with a runway, from either the air or the ground.

In new construction, taxiway centerline lights may be installed instead of taxiway edge lights, or, where operations occur in low visibility or taxiing confusion exists, the centerline lights may supplement the edge lights. Lights for taxiway centerlines consist of single semiflush units inset into the taxiway pavement along the centerline. These lights are steady burning and are standard aviation green.

ICAO standards (Annex 14) specify the use of taxiway centerline lights on high-speed exit taxiways and other exit taxiways, taxiway, and aprons when the runway visual range (RVR) is less than 1200 ft, except where only low-traffic volumes are encountered (10). On long tangents, the maximum spacing is 200 ft, varying down to 50 ft maximum at lower RVRs. Spacing down to a maximum of 25 ft is indicated on

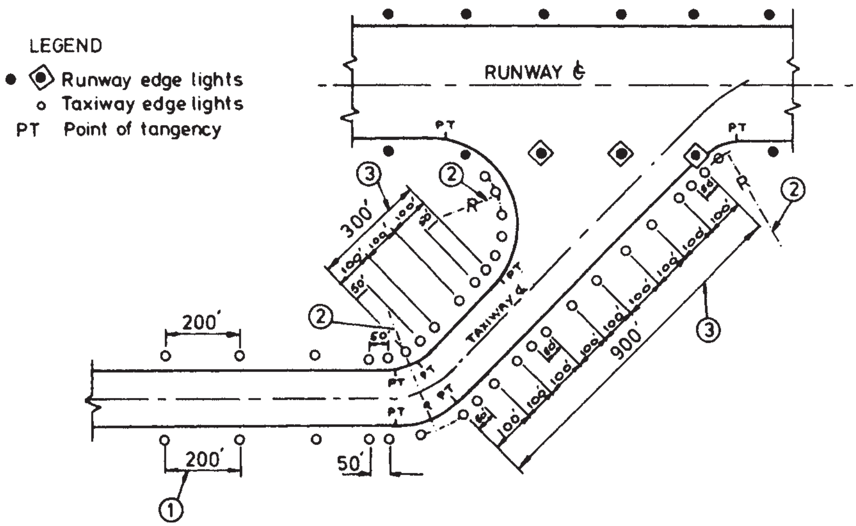


Figure 6.16 Typical FAA taxiway lighting configuration. (*Source:* FAA. (24).)

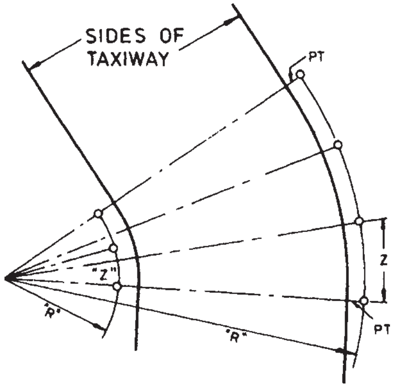


Figure 6.17 FAA spacing of lights on curved taxiway edges: PT is point of tangency. (*Source:* FAA (24).)

curved taxiway sections. For further details of the recommendations of the international agency, refer to the pertinent sections of the ICAO Annex 14.

Land and Hold Short Lights. Land and hold short lights are used to indicate the hold short point on certain runways which are approved for land and hold short operations (LAHSOs). The Land and hold short lights consist of a row of pulsing white lights installed across the runway at the hold short point. Where installed, the lights will be on anytime LAHSO is in effect. These lights will be off when LAHSO is not in effect.

Obstruction Lighting and Airport Beacons (25). Obstruction lights must be placed on towers, bridges, and other structures that may constitute a hazard to air navigation. Single and double obstruction lights, flashing beacons, and rotating beacons are used to warn pilots of the presence of obstructions during darkness and other periods of limited visibility. These lights are standard aviation red and high-intensity white. The number, type, and placement of obstruction lights depend principally on structure height. FAA standards for the lighting obstructions are given in the FAA advisory circular on obstruction marking and lighting.

The location and presence of an airport at night are indicated by an airport beacon. In the United States, a 36-in. beacon is typically used rotating at 6 rpm and equipped with an optical system that projects two beams of light 180° apart. One light is green, and the other is white. A split white beam giving a double white flash denotes a military airport.

Runway and Taxiway Marking (26). Markings are applied to the paved areas of runways and taxiways to identify clearly the functions of these areas and to delimit the physical areas for safe operation. This topic is only covered briefly here; for a complete discussion, refer to ICAO Annex 14 (10). The FAA specifications are discussed, which are generally similar in function and form to the international standards; where differences occur, they are not sufficiently great to cause confusion.

Runway Marking. Three types of runway marking can be provided: *basic* or *visual, nonprecision instrument*, and *precision instrument.* This categorization conforms to that outlined in Chapter 8. Figure 6.18 depicts the standard patterns of markings for each type.

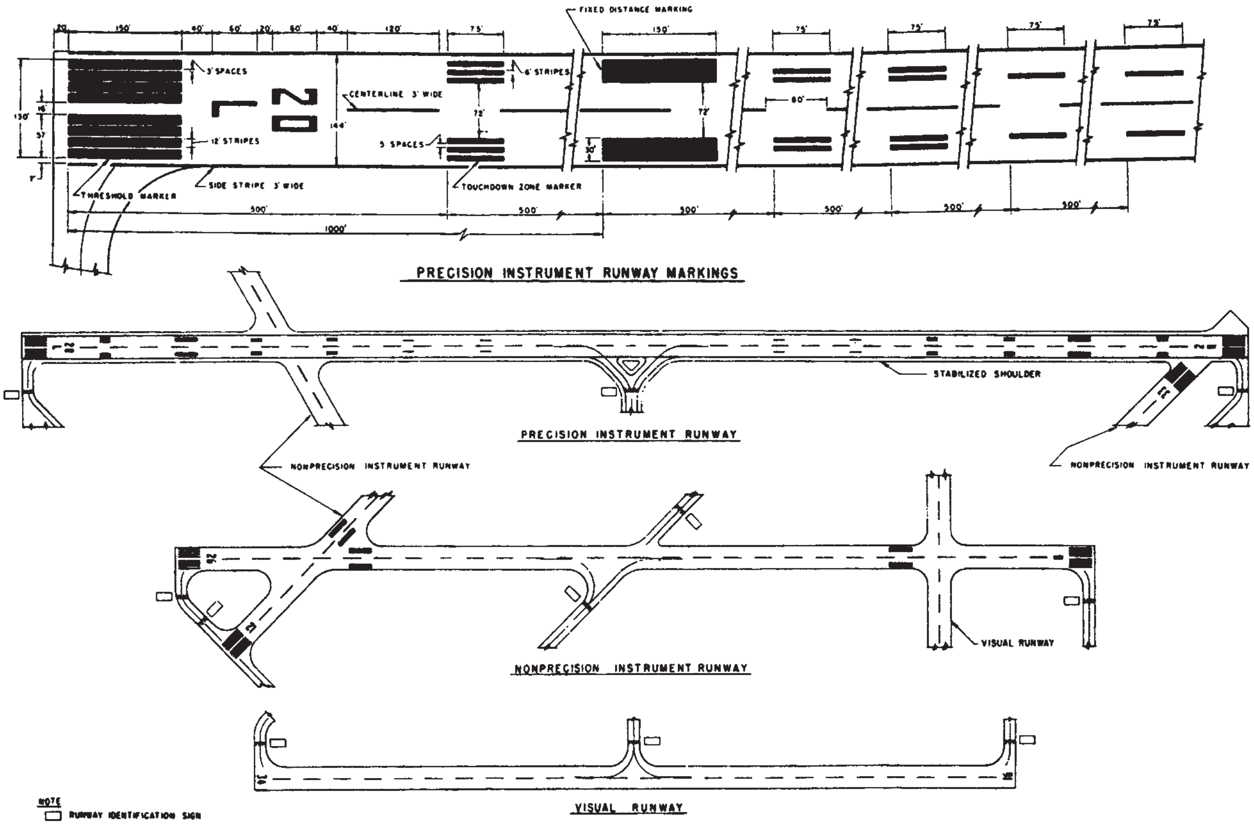


Figure 6.18 Typical FAA runway marking detaills. I Runway centerline spacing should be laid out from both ends toward the center, and the holding line should be 100 ft from the edge of the runway or 150 ft from the edge of the runways where "heavy" jets operate. With respect to the frost area marking, all stripes and spaces are to be of equal width: maximum 6 in., minimum 4 in. All dimensions of numerals and letters are in feet and inches. The numerals and letters must be horizontally spaced 15 ft apart, except the numerals in "11" (as shown); work is to be done to dimensions, not to scale. (*Source:* FAA. (11, 26).)

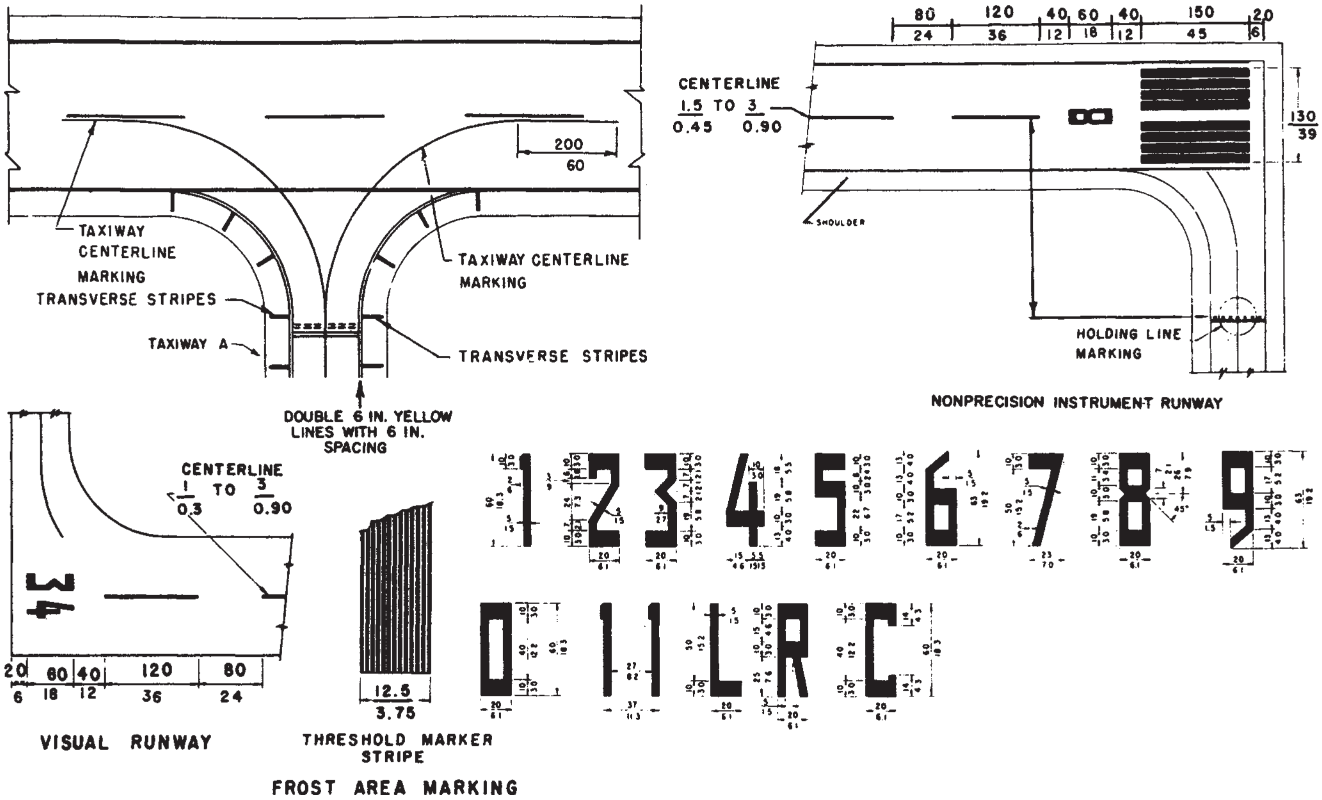


Figure 6.18 *(continued)*

- *Basic Runways.* Unpaved runways have runway stop markers only. Paved basic runways are marked with the runway number and centerline.
- *Nonprecision Instrument Runway.* Marking consists of basic runway marking plus threshold markings. Where considered necessary, additional elements of the precision instrument pattern may be added.
- *Precision Instrument Runways.* These are marked like nonprecision runways but with the additions of touchdown zone markings, fixed-distance markings, and side stripes.

All runway markings are normally in white to differentiate them from yellow taxiway and apron markings. The runway number given to all paved runways is the number nearest one-tenth the magnetic azimuth of the runway centerline. For example, a runway oriented N 10° E would be numbered 1 on the south end and 19 on the north end. Additional information is needed when two or three parallel runways are used, and the designations L, C, and R are added to identify the left, center, and right runways, respectively. Where four or five parallel runways are numbered, two of the runways are assigned numbers of the next nearest one-tenth magnetic azimuth to avoid confusion. Figure 6.18 gives marking dimensions.

Taxiway Marking. Taxiway markings are set out in yellow. They consist of 6-in.-wide continuous stripe centerlines and holding lines at 100 ft minimum from the runway edge. Where runways are operating under ILS conditions, special holding lines must be marked to clear glide slope and localizer critical areas to prevent interference between the navigational signal and ground traffic. Markings in the form of diagonal yellow stripes 3 ft wide are also applied to runway and taxiway shoulders and blast pad areas to indicate that those areas are not for aircraft support.

Taxiway Guidance (26). Signs are placed along the edges of taxiways and aprons to aid pilots in finding their way when taxiing and to help them comply with instructions from the ground traffic controller. The signs fall into two categories: *destination signs*, indicating paths to be taken by inbound and outbound taxiing aircraft, and *intersection signs*, which either designate the location of intersecting routes or indicate category II ILS critical areas.

Destination signs are either outbound or inbound. Outbound routes are identified by signs indicating the directions to runway ends. Inbound signs are standardized to give the following information:

RAMP or RMP: general parking, servicing and loading areas

PARK: aircraft parking

FUEL: areas where aircraft are fueled or serviced

GATE: gate position for loading or unloading

VSTR: area for itinerant aircraft

MIL: area for military aircraft

CRGO: area for freight and cargo handling

INTL: area for international flights

HGR: hangar area

ILS: ILS critical area

Taxiway guidance signs have been standardized into three categories:

Type 1. Illuminated and reflective, with a white legend on a red background; used to denote holding positions.

Type 2. Illuminated with a black legend on a yellow background; used to indicate a specific location or destination on the aircraft movement area.

Type 3. Nonilluminated with a black legend on a yellow background; adequate for airports without operations in poor weather.

Retroreflective signs are easier to see and less expensive in cost and energy than illuminated or nonilluminated signs. It is likely that, in the long term, the use of retroreflective signs will become more widespread. The maximum height of signs above grade is 42 in., and the minimum distance of signs from the apron or taxiway edge is specified at 10 ft. Both these dimensions depend on the size of the sign.

Aircraft Gate Self-Docking Systems. The most simple guidance system to the aircraft nose-in gates is the use of apron marshallers. However, use of electronic aircraft nose-in gate self-docking techniques would cut down the required apron manpower, would reduce human error in the final positioning of aircraft on the gate/apron, and would increase the accuracy of aircraft docking at gates.

The aircraft Azimuth Guidance for aircraft self-docking at nose-in stands AGNIS (Figure 6.19) is a visual system for parking and guidance that allows the pilot to park the aircraft accurately on stands served by the airside corridor jetty, or gate. The centerline guiding system consists of a light unit that emits red and/or green beams through two parallel vertical slots with optical lenses mounted on the face of the pier and aligned with the left-hand pilot's position. The signals are interpreted as follows:

1. *Two Greens.* On centerline.
2. *Left Slot Red, Right Slot Green.* Left of centerline; turn right toward green.
3. *Left Slot Green, Right Slot Red.* Right of centerline; turn left toward green.

The side marker board is a white base board with vertical slats mounted at specific intervals; it is erected on the pier side of the air jetty. The edge of each slat is painted black, the side toward the taxiway is green, and the side toward the pier is red. Each slat bears a name tab to indicate the aircraft type(s) to which the slat applies. When entering the stand, the pilot sees the green side; when the correct STOP position is reached, only the black edge is visible. If the correct STOP position is passed, the red side of the slat comes into view. In this example, F50 and MD90 aircraft are not served by the side marker board; a mark on the air jetty itself shows the correct stopping position.

A more advanced technique, the Advanced Visual Docking Guidance System (A-VDGS) produced by SAFEGATE, features electronic and laser-based sensors that serve the same functions of AGNIS but with greater accuracy and ease of use. This system has been installed in large airports around the world. Figure 6.20 illustrates the operational features of a new A-VDGS system, SAFEDOCK. This system guides an aircraft during

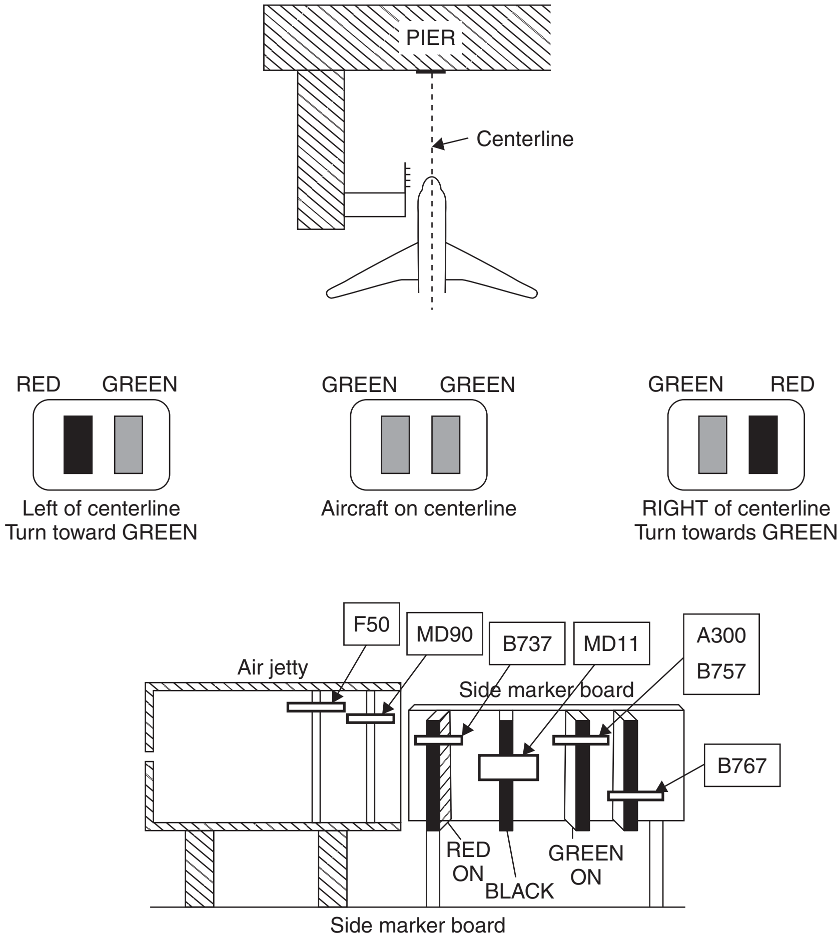


Figure 6.19 Nose-in aircraft self-docking system used at smaller airports, consisting of centerline guidance system AGNIS and side marker boards. (*Source*: Jeppesen Sanderson, Inc., Denver, Colorado.)

its approach to the gate/stand in a smooth, safe, and efficient manner. Benefits of using this system include:

- Capable of docking aircraft of all types and sizes
- Stopping precision of 10 cm could be maintained
- As a fail-safe feature, system defaults to STOP if malfunctioning or safety is compromised
- Efficient gate utilization and improved apron capacity
- Enhances gate/apron safety, by detecting vehicles and other obstacles to be cleared before aircraft reaches gate
- Requires only simple software updates to change stop positions and centerline alignments

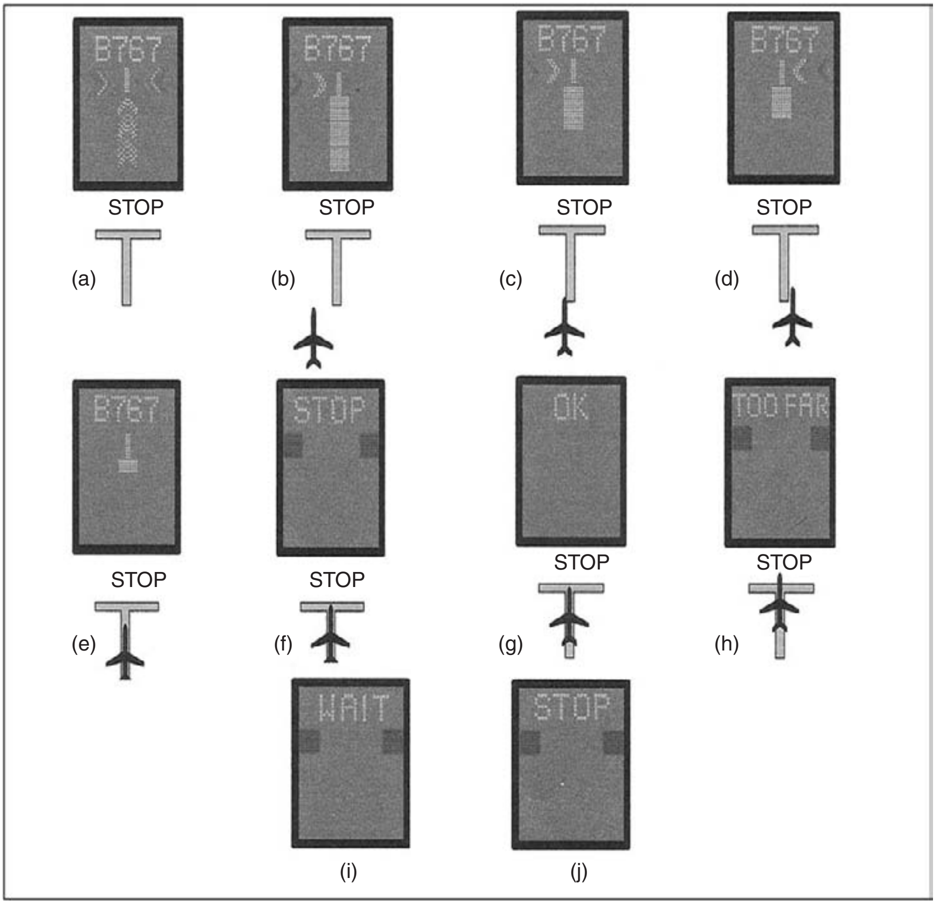


Figure 6.20 Safedock—Advanced Visual Docking System A-VDGS, nose-in aircraft self-docking system. (*Source*, SAFEGATE, Inc.)

The SAFEDOCK system senses the aircraft about to dock and would indicate its type to the pilot on the head of the stand display [Figures 6.20(a) and (b)]. As the aircraft approaches the gate, the display indicates the remaining distance and the necessary azimuth correction (Figures 6.20(c) and (d)]. When the aircraft is at a distance of 12 m from the stop position, the closing gate information is given and the *distance to run* is indicated by turning off one row of yellow LED for each one-half meter the aircraft advances toward the stop position [Figure 6.20(e]). When the correct stop position is reached and the aircraft halts, all yellow LED rows are closed, the display indicates STOP and then OK, and two red rectangular blocks will light [Figures 6.20(f) and (g)].

If the aircraft has gone past the correct stop position, the display shows TOO FAR, and two rectangular blocks will light [Figure 6.20(h)]. During the docking procedure, should the system detect any variation from normal conditions, such as an unverified aircraft type or object in the scanning area, the display shows WAIT [Figure 6.20(i)] or STOP [Figure 6.20(j)] as a failsafe position.

6.4 NEXT-GENERATION SYSTEMS

According to the NextGen concept of operation (2), the airport and CNS/ATM landscape at the end of this program will be entirely different than today:

> The FAA's Next Generation Air Transportation System (NextGen) is a wide-ranging transformation of the US national airspace system. At its most basic level, NextGen represents an evolution from a ground-based radar system of air traffic control to a satellite-based system of digital standards for air traffic management. More significant, however, is the movement away from disconnected and incompatible information systems to a scaleable network-centric architecture in which everyone has easy access to the same information at the same time.

NextGen will provide such key characteristics as user focus, distributed decision making, integrated safety management system, international harmonization, capitalization on human and automation capabilities, enabling a common weather picture, sustainable environment management framework compatible with operations, robustness and resiliency in responding to failures, and scalability in adapting to short- and long-term demand changes. These aspects will have a future reflection on every chapter of this book.

A brief overall comparison with the present system is:

Present System	NextGen System
Ground-based navigation and surveillance	Satellite-based navigation and surveillance
Voice communications	Digital communications
Disconnected information systems	Networked information systems
Disparate, fragmented weather forecast delivery system	Single, authoritative system in which forecasts are embedded into decisions
Airport operations limited by visibility	Operations continue in lower visibility
Air traffic "control"	Air traffic "management"

The umbrella of new NextGen programs that will realize these goals and enable these characteristics includes (2):

- Trajectory-based operations (TBOs)
- High-density airports (HDs)
- Flexible terminals and airports (FLEXs)
- Collaborative air traffic management (CATM)
- Reduced weather impact (RWI)
- Safety, security, and environment (SSE)
- Transform facilities (FACs)

NextGen identified eight key capabilities that will help achieve these goals:

- Network-enabled information access
- Performance-based operations and services
- Weather assimilation into decision making
- Layered, adaptive security

- Positioning, navigation, and timing services
- Aircraft trajectory-based operations
- Equivalent visual operation
- Superdensity arrival/departure operations

Airports are the nexus for many transformational elements to be deployed in NextGen, and the successful transformation of airports is pivotal to achieving almost a threefold increase in system capacity. Within the context of NextGen, the realm of airports is therefore unique.

The high-density airport concept includes:

- Preservation of airports: An "airport preservation program" is established to enhance the sustainability of all airports in coordination with NPIAS.
- Airport mission, management and finance: NextGen will provide support for the diverse airport entities regarding financial needs and promoting privatization, long-term strategy to support airports with new-generation navaids, and assisting airport operators with infrastructure and congestion management.
- Ensure efficient, flexible, and responsive airport planning and development processes.
- Increase support to regional airport system planning to promote intermodal and transportation initiatives, better management of demand among a system of airports, and protection of airports from noncompatible development while recognizing the land use needs of neighboring communities.
- Flexible passenger terminal design to enable rapid reconfiguration of building components (particularly gates, security screening, and check-in facilities) to meet ongoing and varied future needs.
- Most importantly, optimized airfield design through:
  - Parallel runway separation criteria
  - Obstacle measurement and data distribution to users, which will provide higher accuracy
  - Airport protection surfaces defined by Part 77, TERPS, and Part 25 (see Chapter 9), which will be revised to allow for reduction in obstruction clearances and associated protection areas
  - Deployment of sensors around the airport to enhance safety and situational awareness
  - Navaid transition from ground-based to satellite based to facilitate the safe and efficient movement of aircraft on the airfield

As envisioned when fully implemented, the NextGen environment in the new NAS (2025 and beyond) will be entirely different than today's. It will allow more aircraft to fly closer together on more direct routes, with safety and accuracy reducing delays. The NextGen environment will also provide unprecedented benefits for the environment and the economy through the reduction of carbon emissions, fuel consumption, and noise. The development of NextGen and its implementation for the NAS will be iterative, collaborative, and evolutionary and will encompass the input and feedback of the entire aviation community.

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7

Airport Capacity

This chapter defines airport capacity, assesses the various factors that influence capacity, and describes approaches to performing airport capacity analyses.

It is recognized that bottlenecks and delays can result from inadequacies in any component of the airport system—airside or landside. Sections 7.1–7.12 discuss the various aspects of capacity as a concept; its measurement; analytical methods to determine, enhance, and optimize; and their implementation, both airside and landside. Chapter 15 focuses on airport simulation as the method of choice for airport capacity evaluation for all airport facilities.

Airport capacity analyses are undertaken for three purposes: (a) conduct the demand–capacity analyses to assess airport facility requirements as part of the master plan process, (b) measure objectively the operational capability of various components of the airport system for handling projected passenger and aircraft flows, and (c) estimate the delays and other capacity-constraining manifestations experienced in the system at different levels of demand. Thus, capacity analyses make it possible for the airport planner to optimize the airport plans and to achieve a more robust design for the airport facilities to cater for the demand the airport will accommodate and when, where, and how it will do it.

Airport capacity is an essential element of the master plan analysis (Chapter 5), which is an important component of the process and a critical part of the airport planner's conduct of the performance evaluation of the airport operation as a whole. The airport planner assesses the capacity of a particular part of the airport against its corresponding measure of the demand forecasts (Chapter 2) in the master plan process. These constitute the two sides of the comparative "demand–capacity analysis" conducted in the master plan process.

7.1 INTRODUCTION

In the early 1990s, the U.S. air transport system carried about 1.3 million domestic and international passengers per day. At that time the system was not ready to handle this demand, and the provision of airport capacity soon became a national issue that brought together the air transport industry partners and all levels of government to think, deliberate, and set plans for actions to alleviate this problem—but it is not easy to solve. Capacity expansions at the right locations for the entire United States just when demand will need them are prohibitively costly and require a long lead time. Another critical part of the problem was, simply, that capacity was not very well understood and is a very complex issue technically and operationally.

While the federal government provides substantial funding for airports, decisions related to the siting, expanding, building, and operating the facilities are made at the state and local levels. A consensus was reached by all the stakeholders that a combination of remedies was required that includes financing of incremental expansions at crowded airports, improvements in techniques and technologies for managing airport and air traffic control operations, support for advanced aircraft designs better optimized for passenger flows and the physical constraints of airports, incorporation of noise mitigation in aircraft designs and flight patterns, and support for alternative high-speed modes in appropriate markets (1).

But the extraordinary increase in air passenger travel in the decade since the 1980s was not ad hoc. It resulted from several factors that are still in play: robust economies even with their cyclical downturns, a maturing airline industry after deregulation, liberalization and globalization, and the continued trend of reduced fares, specifically with the proliferation of the business model of low-cost carriers (LCCs) resulting in an increasing propensity for the general public to use air transportation, both domestically and internationally.

The growth in air travel contributed to outstripping airport capacity expansion, resulting in increasing congestion and delay. The consequences for the air transport industry and the traveling public are greater inconvenience, higher costs, declining quality of service, and concerns about diminished safety.

Air cargo operations and general aviation have also experienced rapid growth, placing greater demands on the airport and airway system. However, growth in these areas is more manageable, and to a great extent, it is separable from the problem of providing capacity for commercial passenger transport. In many cases, general aviation and cargo aircraft can, and do, make use of reliever or underused airports. Also, they tend to use metropolitan area airports more at off-peak hours. The most important consideration, therefore, relating to airport capacity is to better understand the nature of this problem that will result in accommodating the needs of all stakeholders: air passenger carriers, the airports they use, and the traveling public at large.

7.2 CAPACITY, LEVEL OF SERVICE, AND DEMAND PEAKING

The term "capacity" in its most general sense refers to the quantitative measure for supply of service of a processing facility to accommodate sustained demand—the maximum throughput or supply of service over a specified period of time under given service conditions (2). In airports, it is the ability of the airfield to accommodate arriving and departing aircraft on the airside and that of the terminal building to accommodate passengers on the landside. For the former it is expressed in operations (i.e., arrivals, departures) per unit of time, typically in operations per hour. Thus, the hourly capacity of the runway system is the maximum number of aircraft operations that can be accommodated in 1 hr under specified operating conditions.

For the latter, landside capacity is expressed in passenger flow per unit time at the passenger terminal facilities under a specified level of service (LOS). Since airport terminal facilities are of three basic types—processing, holding, and transit facilities—the capacity of the individual component relies on the type and so does the LOS. The capacity of the processing facilities (e.g., security, check-in) is measured in terms of passengers processed per unit time, and the LOS is expressed in processing rate and waiting time per passenger. The capacity of holding facilities (e.g., gate lounge) is expressed in terms of density per unit area, and the LOS is expressed as available area and seating. The capacity of transit facilities (corridors and mechanical moving devices) is expressed in terms of space and area, and the LOS is expressed in terms of available cross-sectional area and availability of movement-assisted devices (horizontal and vertical).

Capacity, being a measure of supply, should not be confused with demand, as it is independent of both the magnitude and fluctuation of demand. The LOS is however dependent on capacity and the magnitude and pattern of demand. A special relationship exists between capacity and demand under a wide variety of specified demand magnitude and peaking pattern the system is subjected to, as depicted graphically in Figure 7.1. Implicit in this relationship is the LOS the system provides under the specified demand. Average aircraft delay in the system is the primary measure of LOS for the airside, and it is considered by airport and aviation planners as the major measure of system performance. As demand approaches capacity, the relationship between capacity and LOS would change, largely depending on the demand peaking pattern. Large capacity increase coupled with sharp demand peaking would result in significant

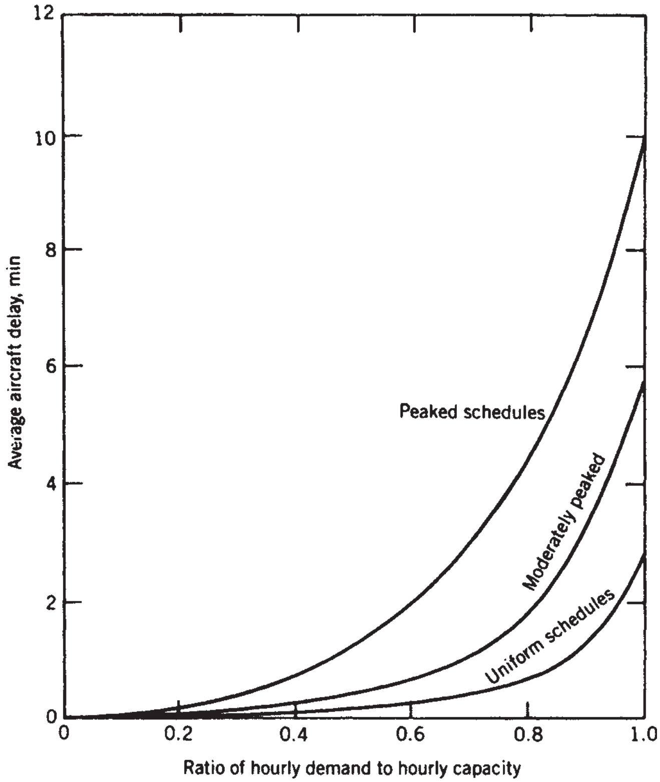


Figure 7.1 Relationship of demand–capacity ratio and demand variation to average hourly aircraft delay.

increase in aircraft delay. This indicates poor operational performance, with poor LOS manifested by excessive aircraft delay.

Given this complexity, airport planners should exercise caution in planning airport facilities in situations where demand would approach capacity for considerable periods of time. Estimating the magnitude of system delays would determine the level of deterioration of system performance and would reflect on the measure to take to increase system capacity. This determination would impact the economic justification for necessary airport improvements to enhance airport capacity.

7.3 AIRSIDE CAPACITY

The capacity of the airfield depends on a number of prevailing conditions, including ceiling and visibility, air traffic control, aircraft mix, and type of operations. To determine the capacity, the prevailing conditions must be specified.

Historically, the FAA previously recommended (3, 4, 5) the concept of a “practical capacity” measure that corresponds to a “reasonable” or “tolerable” level of delay (i.e., amount of delay to departing aircraft during the normal two peak adjacent hours of the week). This concept was based on analytical models developed in the early 1960s based on observations in airports and for the aircraft of that time. As wide-body jets (heavies) entered service, the entire capacity modeling approach had to be revised to account for the strong wake vortices generated by these aircraft.

The FAA later generated new airside models to accommodate the more advanced aircraft technologies (6), where capacity is defined as “a measure of the maximum number of aircraft operations (arrivals and departures) that can be accommodated on the airport airside component in an hour.” Since the capacity of an airport component (runway, taxiway, and gate-apron group) is independent of the other components, each is calculated separately.

Runway Capacity

To conduct the airport demand–capacity evaluation for the airside, both demand and capacity are required. Methods to predict air traffic demand are widely known and have previously been discussed in Chapter 2. However, defining and estimating capacity, mainly runway capacity, are more difficult, and as a concept it is less understood.

Runway capacity is defined as “the maximum sustainable throughput of aircraft operations; both arrivals and departures that could be performed during a specified time interval (e.g., 15 minutes, or an hour) at a given airport of a specific runway configuration, under given weather conditions, and at an acceptable level of aircraft delay.” It is the controlling element of airside capacity. Different aspects of runway capacity evaluation are examined and discussed, including factors affecting capacity and methods to define and estimate capacity and delay.

There has been extensive research during the past five decades on estimating and evaluating runway capacity as well as several approaches to define and measure it. An important variable in the demand–capacity relationship is the mean arrival/departure rate, which is expressed as the safely permissible interoperation time for arrivals and departures. Runway capacity is the reciprocal of the average interarrival rate, assuming a sustainable throughput.

Runway capacity could be estimated by measuring the interoperation times from operational records and observation at busy airports. Analytical methods are then devised to estimate capacity based on the relationship defined by interoperation time, which in turn is influenced by the stochastic variability in aircraft speeds, variation in runway occupancy (caused by variations in aircraft performance characteristics), and other operation-based factors. For bidirectional runways, the relationship between aircraft arrival and departure would impact the estimation of capacity, where capacity of both the arrival and departure streams would vary depending on weather condition and runway configuration and runway operation scheme.

The different aspects of evaluating runway capacity are examined and discussed with respects to factors affecting it, procedures for estimating hourly and annual capacities, and the estimation of delay.

Factors that influence runway capacity include:

- Meteorological conditions in terms of visibility, cloud ceiling, and wind
- Airfield layout, runway configuration, and operational strategy of using the runway at different wind directions
- Aircraft arrival and departure ratios
- Aircraft fleet mix as related to approach and departure sequencing, and runway occupancy time per aircraft type
- Runway occupancy times as related to aircraft performance characteristics and runway exit location
- ATC-related matters in relation to runway arrival fix loading, sector loading, ATM procedures during congestion times, and controllers' work load

Many research efforts were conducted to address runway capacity, its relationships to other operational factors, and methods to analyze, estimate, and measure it. Researchers have reported that determining airport capacity analytically is difficult, and defining the relationship is complex (7, 8, 9, 10). One of the first research efforts was work by MITRE to develop a conceptual runway capacity model (7), where a relationship was theorized based on analytical work. A subsequent work by MITRE provided capacity models to include in the NASPAC model (see Section 15.4), which is a first attempt by the FAA to assess NAS-wide airport capacity and system delays (8). Previously, other research efforts addressed different aspects of runway capacity, providing better understanding of the analytic characteristics of the runway capacity relationship (9). Other researchers developed models for the runway capacity relationship based on analytical methods (10, 11, 12, 13).

These efforts established that runway arrival and departure capacities are actually interdependent and have a nonlinear functional relationship that depends on the factors listed above. In deriving the runway capacity relationship, the analytical methods make certain assumptions about the distribution functions of the random variables involved to estimate interoperations times.

This relationship, depicted schematically in Figure 7.2(a) has the following form:

$$C_d = \varphi(C_a) \tag{7.1}$$

where

C_d = departure capacity

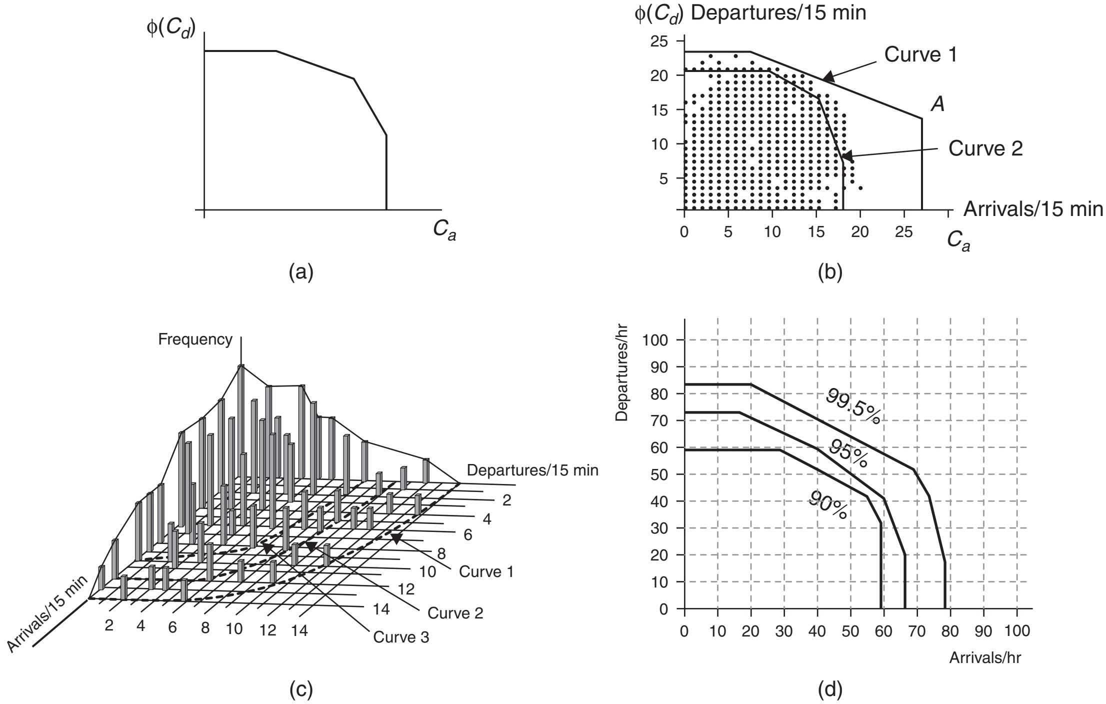


Figure 7.2 Airport runway capacity relationship: (a) capacity schema; (b) performance data and capacity curve; (c) performance data with frequency analysis; (d) capacity curve with confidence intervals (10).

C_a = arrival capacity
φ = nonlinear function

In order to undertake practical measures to enhance airport capacity and reduce delays in the NAS, the FAA initiated a program to closely monitor runway operation at busy U.S. airports as part of a larger program for the Advanced Traffic Management System (ATMS) (14). In this program, the FAA has identified certain major airports in the NAS as "Pacing Airports," where traffic throughput paces the traffic flows in the entire NAS. Pacing airports are characterized by a high volume of traffic that frequently exceeds the operational (or practical) capacity of the airport (15).

Developing Runway Capacity Model. Using the considerable amount of data compiled from the pace-airport monitoring program, an empirical method was used to estimate runway capacity (10). The empirical method would estimate the capacity curve through numerical analysis of the capacity data, based on the assumption that observed peak arrival and departure counts reflect airport performance at or near capacity level, and hence the curve of the peak data envelope is the runway capacity curve (10).

Outlier Statistical Tests. To define the runway capacity model, the empirical method used real-world data observed at pace airports that experienced severe congestion and substantial delays recorded during 1990–1991. The observed historical performance data per airport and respective weather conditions would then generate the model's upper bound for capacity. Figure 7.2(b) depicts this relationship as the envelope of all performance data points recorded at 15-min intervals over a long time period. All the data points were subject to statistical tests to exclude extreme points and outliers. Curve 1 is the capacity model without statistical treatment, and curve 2 is the model after statistical tests excluded rare events and extreme observed data (e.g., point A).

Low-Frequency Rejection. The rejection of extreme data points is also related to the frequency of occurrence in the real-world environment. Figure 7.2(c) depicts the performance data points with frequency as the third dimension and the resulting frequency histograms. The statistical analysis is rerun to include frequency of occurrence and exclude occurrence of less than three times. To enhance reliability of the capacity model and increase its statistical characterization, less frequent performance points in the time-series data are rejected. Curve 3 of Figure 7.2(c) reflects the capacity relationship with less frequent data points excluded at levels of 0.5, 5, and 10% of observation rejection. Figure 7.2(d) depicts the runway capacity relationship for a "pacing airport" operating in the visual flight rule (VFR) condition at 90, 95, and 99.5% levels of observation rejection. Four weather conditions for the capacity curves were generated, reflecting conventional limitations on visibility and cloud ceiling—VFRs, marginal VFRs (MVFRs), instrument flight rules (IFRs), and low IFRs (LIFRs).

MITRE was the first to apply this capacity relationship in a mathematical model to estimate airport capacity in the NAS (8) and to formulate a new approach to operational optimization of airport capacity in the NAS (16).

As part of the FAA ATMS program (14), airport airside capacity models were derived that represent capacity using an empirical approach to practically estimate airport capacity and then optimize capacity through dynamic allocation of arrival and departure capacities over time. Through employing dynamic optimization of airport capacity, better utilization of airports' available resources could be achieved individually and on the NAS level.

Optimization of Runway Capacity. This analysis went further to develop an analytical approach to optimize allocation of airport capacity between arrivals and departures using a mathematical model of interdependent arrival and departure processes at the airport.

When arriving and departing aircraft compete to use the runway—as directed by ATC—capacity could be represented by the functional relationship between the capacities of arrival and departure aircraft streams. Uncertainties related to operation are accounted for in this relationship in terms of interoperation time, variability in aircraft speed, variation in runway occupancy times, and aircraft fleet mix. To be more reliable and realistic, the methodology combines both analytical and empirical analysis. The optimization criterion adopts total delay time as the measure of effectiveness of operation, or the key performance indicator. The general mathematical representation of runway capacity optimization during time interval T is formulated as

$$\min_{u*} \sum_{i=1}^{N} F_i(X_{i+1}, Y_{i+1}) \tag{7.2}$$

subject to

$$X_{i+1} = \max(0, X_i + a_i - u_i) \qquad i \in I \tag{7.3}$$

$$Y_{i+1} = \max(0, Y_i + d_i - v_i) \qquad i \in I \tag{7.4}$$

$$X_1 = X_0 \geq 0; Y_1 = Y_0 \geq 0 \qquad \text{(given initial conditions)} \tag{7.5}$$

$$0 \leq v_i \leq \phi_i(u_i) \qquad \phi_i(u) \in \Phi \qquad i \in I \tag{7.6}$$

$$0 \leq u_i \leq B_i \qquad i \in I \tag{7.7}$$

where:

N = number of sequenced capacity curves
u_i = arrival capacity at ith time slot
v_i = departure capacity at ith time slot
F = nondecreasing scalar function
X_i = demand for departures at ith time slot
Y_i = demand for arrivals at ith time slot
a_i = demand for arrivals at ith time slot
d_i = demand for departures at ith time slot
$\phi_l(u)$ = arrival/departure capacity curve, which determines capacity at ith time slot
Φ = set of capacity curves that represent all runway configurations at all weather conditions

The composite hourly capacity of the airfield is therefore governed by the capacity of its "constraining component." The FAA also adopts another expression for airport capacity—annual service volume (ASV)—which reflects "annual practical capacity" and is used for the purposes of preliminary planning (discussed in Section 7.5).

The capacity of the other components comprising the airfield—taxiways and apron gates—are discussed in coming sections. Taxiway capacity is discussed in Section 7.9 and apron-gate capacity in Section 7.10.

As demand approaches capacity, system congestion and delays increase sharply, a situation that alerts government and industry to initiate actions to alleviate the situation in the intermediate and long terms. Here planners should exercise caution when planning for airports where the level of airport demand is expected to approach capacity. Estimating the magnitude and pattern of aircraft delays and the propagation of delay systemwide becomes critical to the economic impact of congestion and delay and more critical to the justification of initiation airport improvements and developing the strategy to balance the costly airport development required with systemwide airport performance. This topic is discussed in detail in Section 7.4 (Causes of Delay), Section 7.8 (Calculating Aircraft Delays), and Section 7.11 (Assessing System Capacity–Delay for Airport Development).

7.4 FACTORS AFFECTING AIRSIDE CAPACITY AND DELAY

Factors that influence the capacity of a runway system are numerous. These factors can be grouped into four classes that are related to (a) air traffic control, (b) characteristics of demand, (c) environmental conditions in the airport vicinity, and (d) the layout and design of the runway system.

Air Traffic Control Factors

As was discussed in Chapter 6, the FAA specifies minimum vertical, horizontal, and lateral separations for aircraft in the interests of air safety. In the vicinity of an airport, the minimum allowable horizontal separation is typically 2–5 nautical mi, depending on the aircraft size, availability of radar, sequencing of aircraft operations, and airspace procedures in general. Since two airplanes are not allowed on the runway at the same time, the runway occupancy time will influence the capacity.

Consider the following hypothetical example. A runway serves aircraft that land at speeds of 165 mph while maintaining the minimum separation of 3 nautical mi as specified by the FAA. The average runway occupancy time for landing aircraft is 25 sec. Examine the effect of these factors on the runway capacity; the minimum spacing is $3 \times 6076\,\text{ft} = 18{,}228$ ft. In terms of time, the minimum arrival spacing is 18,228 ft $\div$ $(165 \times 5280/3600)$ ft/sec = 75 sec. The maximum rate of arrivals that can be served by the runway is no more than 3600 sec/hr $\div$ 75 sec/arrival = 48 arrivals/hr.

Figure 7.3 is a time–distance diagram for two approaching aircraft maintaining the 3-nautical-mi separation. The solid line on the left represents the first arrival. The second arrival (the solid line on the right) is shown at a point 3 nautical mi away when the first arrival crosses the runway threshold. As illustrated, if the runway is used for arrivals only, it will remain unoccupied two-thirds of the time. In capacity calculations, it is usually necessary to compute the percentage of all aircraft operations that are arrivals or the arrival-to-departure ratio and to make allowance for this effect.

Arrivals on final approach are generally given absolute priority over departures. Departures are released when suitable gaps occur in the arrival stream.

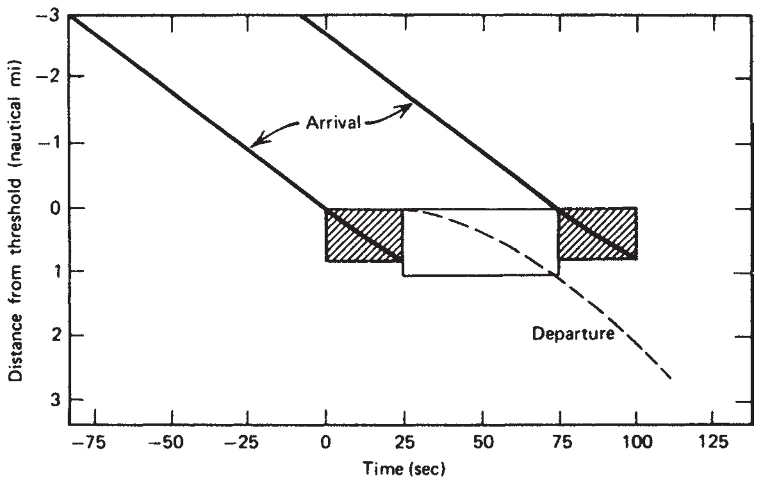


Figure 7.3 Time–distance diagram for two approaching and one departing aircraft: open box, runway occupied by departure; cross-hatched box, runway occupied by arrival.

The capacity of a runway can be substantially increased by inserting a departure between pairs of arrivals, as illustrated by the dashed line in Figure 7.3. One limiting feature of this sequencing pattern is the FAA regulation requiring a minimum separation of 2 nautical mi between the insertion of a departure and the next arrival.

Separation is the dominant air traffic control factor affecting capacity. Other factors include:

1. The length of the common path from the ILS gate to the threshold, normally 4–8 mi
2. The strategy employed by controllers in sequencing aircraft traveling at different speeds (e.g., first come–first served, speed-class sequencing)
3. The allowable probability of violation of the separation rule, recognizing that it is not possible to maintain the allowable separation with perfect precision at all times
4. The sophistication of the air traffic control system, which affects the precision with which aircraft can be delivered to the ILS gate and the ability to monitor aircraft speeds and detect aircraft positions and movements

Characteristics of Demand

The capacity of a runway depends on aircraft size, speed, maneuverability, location of taxiway exits, and braking capability as well as pilot technique. But the most important elements are the magnitude and peaking pattern of demand itself. The effect of aircraft size is reflected both in the wing tip vortex phenomenon and in differences in approach and touchdown speeds. As previously indicated in Chapter 3, heavy jet aircraft generate wing tip vortices that create problems of maneuverability and control for smaller aircraft operating in their wake. In the interest of safety, the FAA has introduced air traffic control rules that increase the separation between small aircraft following a heavy jet to 5 nautical mi. This regulation decreases the capacity of runways that serve significant numbers of heavy jets and small aircraft.

Unlike the situation illustrated by Figure 7.3, the speeds at which different aircraft approach a runway are neither equal nor constant along the approach path. Frequently, separations longer than the minimum allowed by air traffic rules must be tolerated to accommodate a mixture of slow and fast aircraft. Because of variations in approach speeds, a margin of safety must be allowed to ensure that the minimum separation is not violated at any point along the approach path. Touchdown speed, braking capability, and ground maneuverability affect the runway occupancy time for landing, which, in turn, determines the time that a departing aircraft can be released.

Many general aviation airports have a great deal of pilot training activities that involve “touch-and-go” operations. The term refers to an aircraft that lands and takes off without coming to a complete stop. Such operations, which are counted as two aircraft movements, may significantly affect runway capabilities. Studies have shown that “one aircraft performing touch and go operations can generate up to 16 movements per hour: one takeoff, seven ‘touches’ (14 movements), and one final landing” (5). In capacity calculations, empirical correction factors are applied to allow for the presence of touch-and-go traffic.

A characteristic of demand that can significantly affect the capacity of a runway is the percentage of all aircraft operations that are arrivals, that is, a runway used exclusively for arrivals will have a capacity different from one used for departures or mixed operations.

Another important factor that impacts determining runway capacity through quantifying runway occupancy times is the location of runway taxiway exits.

Environmental Factors

The most important environmental factors influencing runway capacity are visibility, runway surface conditions, winds, and noise abatement requirements.

Under conditions of poor visibility, pilots and air traffic controllers become more cautious. Longer aircraft separations and greater runway occupancy times result, and runways with marginal crosswinds are less likely to be used. When the visibility or cloud ceiling falls below certain prescribed values, instrument flight rules are employed and the responsibility for safe separation between aircraft passes from the pilots to air traffic control personnel. A runway or runway system may be closed to traffic when visibility is extremely limited. Similarly, wet or slippery runway surface conditions may cause longer deceleration distances and greater runway occupancy times. Heavy snow and ice accumulations warrant the closing of a runway.

For safety reasons, the wind speed component perpendicular to the aircraft path should not exceed a specified minimum, and the component in the direction of the aircraft's movement is of even greater concern (17). Excessive crosswinds and tail winds occasionally impose restrictions on the use of one or more runways, and calculations of runway capacity should include appropriate allowances for such restrictions.

Noise abatement regulations affect the capacity of a runway system by limiting or restricting the use of one or more runways during certain hours of the day.

Design Factors

For the airport planner, layout and design features comprise the most important class of factors that affect runway capacity. When quantum increases in airport capacity are needed to serve future demand, the airport planner considers improvements in the layout and design of the runway and taxiway system.

The principal factors in this class are as follows:

1. Number, spacing, length, and orientation of runways
2. Number, locations, and design of exit taxiways
3. Design of ramp entrances

Further discussion of factors and their relationship to capacity is given later in this chapter and in Chapter 8.

Causes of Delay (18, 19)

Recognizing the importance of delay manifestation in the NAS, the FAA constantly monitors delay in the system. It was observed that delay greater than 15 min could be attributed to weather, NAS system air traffic operations, and airport-related disruptions. Table 7.1 indicates the distribution of causes of delay. Weather represents the majority of delay followed by air traffic operations. But these percentages are constantly changing

Table 7.1 Distribution of Delay[a] by Cause—1985 and 1990

Cause of delay	1985	1990
Weather	68%	53%
Terminal air traffic operations	12%	36%
Air traffic center operations	11%	2%
Airfield–runway closures	6%	4%
NAS CNS/ATM	2%	2%
Other	1%	3%
Total delayed operations	334,000	404,000

[a]Delay greater than 15 min.
Source: FAA.

Table 7.2 Distribution of Delay[a] by Segment of Flight—1985 and 1990

Average delay per flight (min)					
				1990	
Flight segment / phase	1987	1988	1989	Delay per flight	Percent of total
Gate Hold	1.0	1.0	1.0	1.0	6.8%
Taxi-out	6.6	6.8	7.0	7.2	48.5%
Airborne	3.9	4.0	4.3	4.3	29.1%
Taxi-in	2.1	2.1	2.2	2.3	15.5%
Total	13.7	14.0	14.6	14.9	4-yr avg 14.3
Increase per Year		+2.2%	+4.3%	+2.1%	

[a]Delay greater than 15 min.
Source: FAA.

as technological improvements across the board would result in less negative effects on the system in terms of share of total delay and total delays (greater than 15 min) reported in the system.

As NAS air traffic operations constitute the second largest cause of delay (and are on the increase), it is important to diagnose the total operational delay per phase of flight within the system. Table 7.2 provides a breakdown of the relative share of delay per phase of flight, as reported by the FAA. With careful inspection, it is clear that aircraft taxiing on the airfield constitutes the highest delay followed by the airborne phase. The former is a manifestation of shortage of airport capacity and departure airspace beyond, and the latter is due to shortage in terminal airspace capacity, particularly in relation to aircraft holding for approach.

7.5 DETERMINATION OF RUNWAY CAPACITY AND DELAY

A number of different approaches may be employed to estimate runway capacity and delay, including:

1. Empirical approach
2. Queueing models
3. Analytical approach
4. Capacity handbook

In addition to the above approaches, Chapter 15 will discuss advanced computer simulation models for airport capacity studies.

Empirical Approach

The empirical approach bases capacity and delay estimates on the results of extensive operational surveys performed at existing airports. Using analytical and mathematical models, such surveys may serve as the sole basis to derive model graphs and tables from which runway capacity estimates may be directly made (5). Empirical surveys are also a vital component in the development and validation of both analytical and simulation models (18, 19).

Examples of simple queueing models are described later. Queueing models may be used to estimate queue lengths and average delays to aircraft in simple systems. Such estimates may serve as the building block of a computer simulation model. The runway capacity models described are examples of analytical models. These models are based on the concept that aircraft can be represented as attempting to arrive at points in space at particular times (12).

In later sections of this chapter computer analytical models used to produce estimates of runway capacity and aircraft delays and simulations to replicate entire airfield operations are described.

Queueing Theory Approach

It has long been recognized that a simple runway system can be described by mathematical models or formulas of queueing theory. An empirical study of aircraft arriving at the Kingsford-Smith Airport in Sydney (20) found that arrivals could be satisfactorily described by the Poisson probability distribution. Since airline flights are scheduled, one would intuitively suspect that aircraft arrivals are regular; not random. However, the difference between the expected and actual times of arrival was found to be large and that the process was more random than regular.

Queuing theory addresses congestion and its causes, and explores the relationships between demand on a service system and congestion in the system manifested by delays suffered by the system users (21). Given the physical nature of the airport in terms of "servicing" aircraft arrivals and departures, the applicable queue model is the spatially distributed queue. The basic form of the spatially distributed queue is M/G/1, where (M) refers to the Markovian (Poisson, random) interarrival service process, (G) refers to the general service time distribution (19), and (1) refers to there being one server (a runway). An advantage of this form is that only the mean and variance of the service–time distribution are required. For its simplicity and practical applicability, Harris adopted this queue model to derive the runway capacity models (22). The simplest queue form, as depicted earlier in Figure 7.4, represents a one-server processing facility serving arrivals at a Poisson arrival distribution. As demand for service is generated and the arrival rate exceeds the service rate for some periods of time, queues are formed and delays are experienced, and both will reach a maximum level before they diminish as the demand arrival rate is lowered.

The queuing approach to runway capacity analysis relies on the assumption of a purely random, totally independent Markovian–Poisson arrival rate, which in the

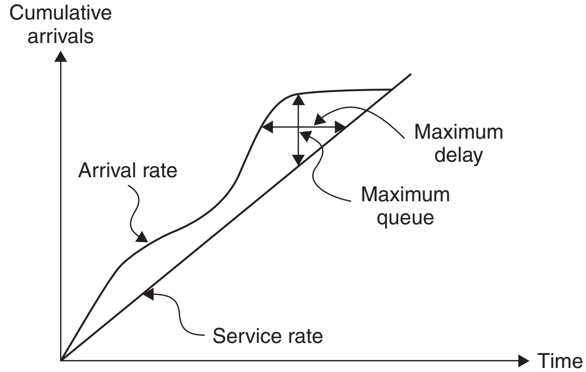


Figure 7.4 Supply–demand relationship and schema of queueing in a proccessing facility.

totally controlled ATC regime would actually represent an improved situation of the real-world system. In the queuing approach mathematical representation of runway operation, the arrival rate of aircraft to land on runways represents the service process, where service time is the runway occupancy time. Application of queuing theory to runway capacity assists in quantifying system operation in terms of simple measures of effectiveness. These measures are average applied demand and runway acceptance rate, a statistically defined maximum delay at a standard LOS in terms of time, and average system delay. Using this mathematical formulation of queuing theory, an airport capacity analysis would represent airport runway capacity as follows: Airport *A* has the capability of achieving *B* operations per hour with a statistical maximum delay of *C* minutes, resulting in an average delay of *D* minutes per aircraft.

In his analysis of runway capacity and delay, Harris (7) differentiated between two mathematical expressions used in the derivation of queue models: average system delay (cumulative aircraft delay for entire demand per aircraft) and aircraft expected delay (which is dependent on the probability a given aircraft entering the queue would be delayed).

A runway serving landings only can be described as a single-channel queueing system with first come–first served services. The "service time" is the runway occupancy time, "the length of time the most recent arrival blocks the runway from receiving any subsequent arrival" (16). The runway occupancy time depends on the operational characteristics of the individual aircraft using the runway, and the minimum aircraft en-trail separation as necessitated by air traffic rules.

Assuming Poisson arrivals and constant service times, the following equation was derived (12) for average (steady-state) landing delay:

$$W = \frac{\rho}{2\mu(1-\rho)} \tag{7.8}$$

where

ρ = load factor = λ/μ
λ = arrival rate (aircraft/unit time)
μ = service rate (aircraft/unit time) = $1/b$
b = mean service time

In a more general form, this equation is known as the Pollaczek–Khinchin formula:

$$W = \frac{\rho(1 + C_b^2)}{2\mu(1 - \rho)} \tag{7.9}$$

where

C_b = coefficient of variation of service time = σ_b / b
σ_b = standard deviation of service time

These equations can also be applied to runways serving departures only. A more complicated formula has been developed to calculate the average delay to departures in mixed operations.

Although mathematical equations such as these serve to understand the delay–capacity relationships, they may not provide accurate estimates of average delay, except for extremely simple situations. The equations have at least two major shortcomings:

1. They account for the effects of only a few of the many factors known to influence runway capacity and delays.
2. They are dependent on having a "steady-state" condition to get solutions, in which case many hours may be required to achieve steady-state conditions (16).

Analytical Approach

Based on extensive analyses in developing a queuing model approximation to the capacity of runways under various conditions, researchers derived analytical models to estimate runway capacity. The basic type is a landing intervals model that accounts for the effects of the following factors:

1. Length of the common approach path
2. Aircraft speeds
3. Minimum aircraft en-trail separations as specified by air traffic regulations

The simplest models adopt error-free approaches, which assumes that controllers are able to deliver aircraft to the entry gate exactly at scheduled times and pilots are able to maintain the required separations, aircraft speeds, and alignments with the runway for landing accurately.

Two situations are considered: (a) the overtaking case, in which the trailing aircraft has a speed equal to or greater than the lead aircraft, and (b) the opening case, in which the speed of the lead aircraft exceeds that of the trailing aircraft. Harris (7) has shown that for the error-free case the following minimum separation function applies:

$$m(v_2, v_1) = \frac{\delta}{v_2} \quad \text{for} \quad v_2 \geq v_1 \tag{7.10}$$

$$m(v_2, v_1) = \frac{\delta}{v_2} + \gamma\left(\frac{1}{v_2} - \frac{1}{v_1}\right) \quad \text{for } v_2 < v_1 \tag{7.11}$$

where

v_i = speed of aircraft i
γ = length of common approach path

δ = minimum safety separation
$m(v_2, v_1)$ = error-free minimum time separation over threshold for aircraft 2 following aircraft 1

The time–space diagrams for the overtaking and opening situations are shown in Figures 7.5 and 7.6. These figures help the reader to develop equations 7.10 and 7.11.

In computing the runway capacity, which is the average maximum sustainable throughput, it is suggested that the various aircraft be grouped into n discrete speed classes ($v_1, v_2, \ldots, v_n$) and that a matrix of minimum intervals be formed:

$$M = [m(v_i, v_j)] = \left\{ \begin{array}{l} \text{matrix of minimum intervals,} \\ m_{ij},\ \text{for speed class } i \\ \text{following speed class } j \end{array} \right\}$$

Associated with each of n speed classes is the probability of occurrence $[p_2, \ldots, p_n]$. These probabilities are the percentages of the various speed classes in the mix divided by 100. The expected minimum landing interval (or weighted mean service time) can be approximated by

$$\overline{m} = \sum_{ij} P_i m_{ij} P_j \tag{7.12}$$

The hourly saturation capacity is the inverse of the weighted mean service time:

$$C = \frac{1}{\overline{m}} \tag{7.13}$$

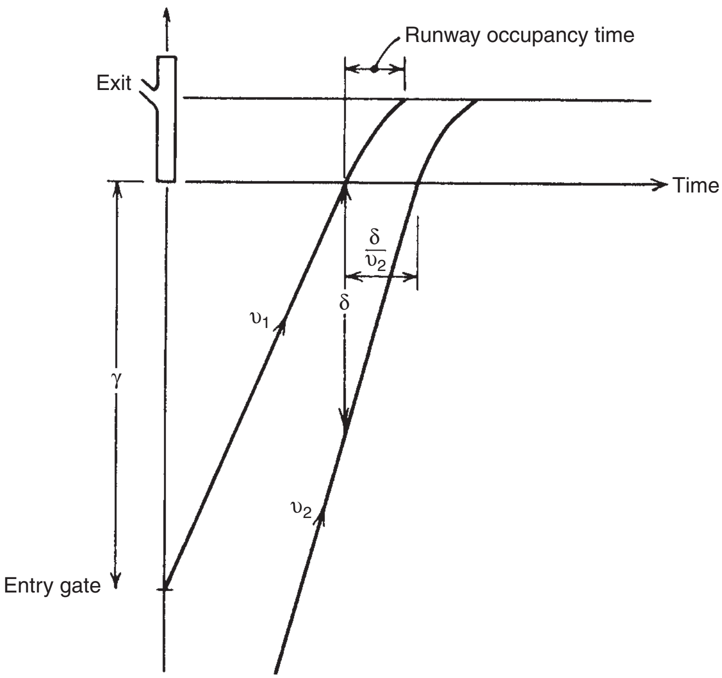


Figure 7.5 Time–space diagram for overtaking situation.

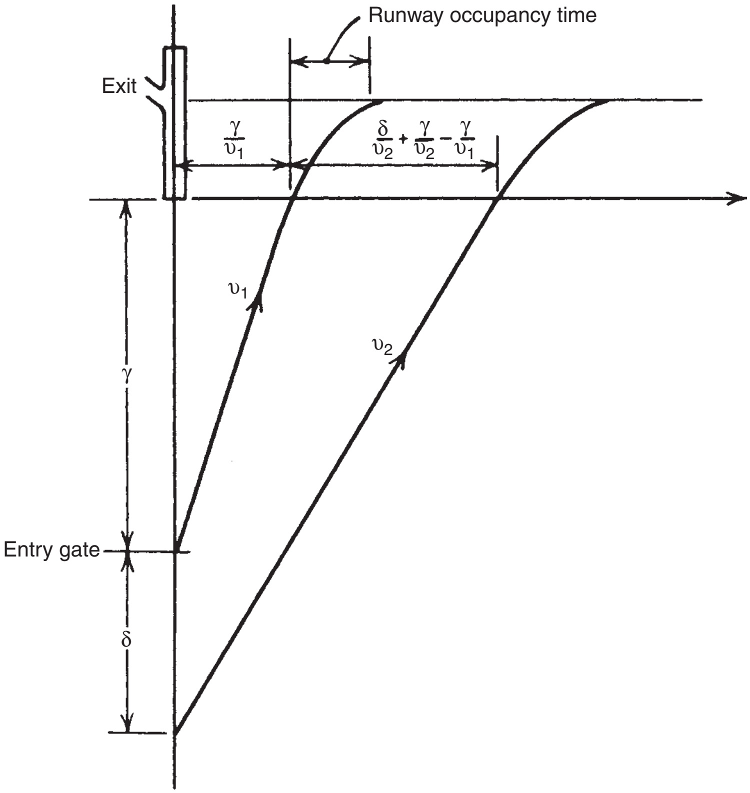


Figure 7.6 Time–space diagram for opening situation.

Example 7.1 Runway Capacity with Error-Free Landings Given a length of common approach path $\gamma = 6$ nautical mi and a minimum separation of 3 nautical mi, calculate the ultimate capacity for the following population of aircraft landing on a single runway assuming error-free approaches.

Percentage of aircraft	Approach speed (knots)
20	100
20	120
60	135

Assume that the runway occupancy times are smaller than the time separations during approach and have no effect on the capacity.

From equations 7.10 and 7.11, it is possible to calculate the minimum time separation over the threshold for various combinations of speeds.

Consider the situation $v_i = 100$, $v_j = 120$. Since $v_j > v_i$, the minimum separation is

$$m(v_j, v_i) = \frac{\delta}{v_j} = \frac{3}{120}\,\text{hr} = 90\,\text{sec}$$

For $v_i = 135$, $v_j = 100$, we have

$$m(v_j, v_i) = \frac{\delta}{v_j} + \gamma\left(\frac{1}{v_j} - \frac{1}{v_i}\right) \tag{7.14}$$

$$= \frac{3}{100} + 6\left(\frac{1}{100} - \frac{1}{135}\right) = 0.0456\,\text{hr} = 164\,\text{sec}$$

The complete matrix M is as follows:

		Speed of Leading Aircraft, v_i,			
		100	120	135	Probability, P_j
Speed of trailing aircraft, v_j	100	108	144	164	0.2
	120	90	90	110	0.2
	135	80	80	80	0.6
Probability		0.2	0.2	0.6	
			Pi		

This shows the minimum separation time for each combination of approach speeds.

The next step is to compute a weighted average separation, by equation 7.12, based on the probabilities associated with each pair of aircraft speeds:

$$\overline{m} = (108 \times 0.2 + 90 \times 0.2 + 80 \times 0.6)0.2 +$$
$$(144 \times 0.2 + 90 \times 0.2 + 80 \times 0.6)0.2 +$$
$$(164 \times 0.2 + 110 \times 0.2 + 80 \times 0.6)0.6 = 98.16$$

Finally, the ultimate capacity is computed by equation 7.13:

$$\text{c} = \frac{1}{\overline{m}} = \frac{1}{98.16} = 0.0102\,\text{arrivals/sec} = 36.7\,\text{arrivals/hr}$$

In an effort to provide more realism, Harris (7) postulated normally distributed errors in aircraft interarrival times at the approach gate and at the threshold. Ultimate capacity models were developed that allowed separation time buffers to account for such errors. As Figure 7.7 illustrates, these buffer times are a function of the probability that the buffer zone will be violated.

In the overtaking case ($v_2 \geq v_1$), the buffer zone is given as

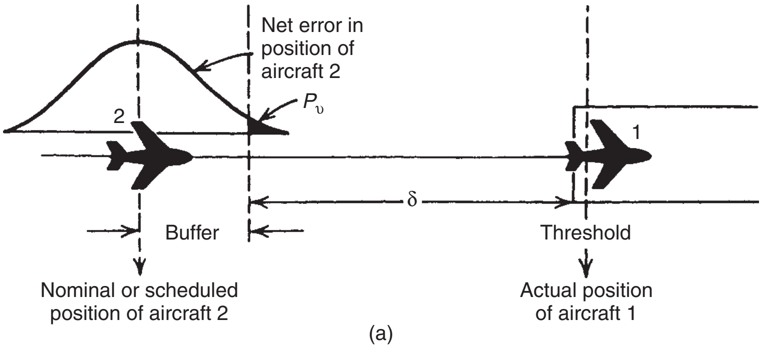
$$b(v_2, v_1) = \sigma_0 q(p_v) \tag{7.15}$$

where

σ_0 = standard deviation of normally distributed buffer zone
$q(p_v)$ = value for which cumulative standard normal distribution function has value $1 - p_v$
p_v = probability that buffer zone is violated

In the opening situation ($v_2 < v_1$), the buffer zone is also a function of the separation and the relative aircraft speeds:

$$b(v_2, v_1) = \sigma_0 q(p_v) - \delta\left(\frac{1}{v_2} - \frac{1}{v_1}\right) \tag{7.16}$$



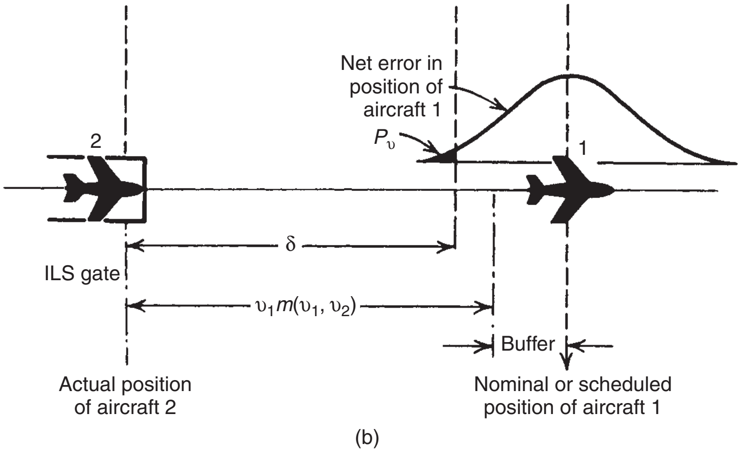


Figure 7.7 Error distribution and separation buffering: (a) overtaking, $v_2 \geq v_1$: (b) opening, $v_2 < v_1$ (18).

With this model, the minimum interval of time between the arrival of a leading aircraft traveling at a speed v_1 and the trailing aircraft traveling at a speed v_2 is

$$l(v_2, v_1) = m(v_2, v_1) + b(v_2, v_1) \tag{7.17}$$

Using matrix notation

$$B = [b(v_i, v_j)] = \left\{ \begin{array}{c} \text{matrix of buffer zones,} \\ b_{ij}, \text{for speed class } i \\ \text{following speed class } j \end{array} \right\}$$

The matrix of scheduled landing intervals becomes

$$L = M + B \tag{7.18}$$

Example 7.2 Runway Capacity Allowing for Approach Errors Compute the ultimate capacity for the conditions described in Example 7.1, allowing a buffer zone that has a standard deviation $\sigma_0 = 20$ sec. Use a probability of violation $p_v = 0.05$.

To obtain $q(p_v v)$, consult a statistics table that shows the area under the normal curve from $q(p_v v)$ to infinity. In such a table, corresponding to $p_v = 0.05$, $q(p_v v) = 1.65$.

Then compute the lengths of buffer zones b_{ij} (in seconds) for various combinations of speed classes. For example, from equation 7.15, the buffer zone for $v_2 = 100$ and $v_1 = 100$ is

$$b(v_2, v_1) = \sigma_0 q(p_v) = 20 \times 1.65 = 33\,\text{sec}$$

Similarly, by equation 7.16 the buffer zone for $v_2 = 100$, $v_1 = 135$ is

$$b(v_2, v_1) = \sigma_0 q(p_v) - \delta\left(\frac{1}{v_2} - \frac{1}{v_1}\right)$$

$$= 20 \times 1.65 - 3\left(\frac{1}{100} - \frac{1}{135}\right)3600 = 5\,\text{sec}$$

The complete matrix of buffer zones is

$$B = \begin{bmatrix} 33 & 15 & 5 \\ 33 & 33 & 23 \\ 33 & 33 & 33 \end{bmatrix}$$

Adding this matrix to matrix M from Example 7.1, we obtain the landing interval matrix

$$L = \begin{bmatrix} 141 & 159 & 169 \\ 123 & 123 & 133 \\ 113 & 113 & 113 \end{bmatrix}$$

The weighted average separation is

$$\begin{aligned} \overline{m} = {} & (141 \times 0.2 + 123 \times 0.2 + 113 \times 0.6)0.2 + \\ & (159 \times 0.2 + 123 \times 0.2 + 113 \times 0.6)0.2 + \\ & (169 \times 0.2 + 123 \times 0.2 + 113 \times 0.6)0.6 = 125.88\,\text{sec} \end{aligned}$$

The runway capacity is

$$c = \frac{1}{\overline{m}} = \frac{1}{125.88}\ \text{arrivals/sec} = 28.6\ \text{arrivals/hr}$$

More complex models have been published (18) that account for speed errors along the approach or variations in times required to fly the common path. Such models, which are conceptually similar to those given above, are derived for exclusive arrival and departure runways as well as for mixed-operations runways. Analytical models have also been developed for multiple runway configurations using the ultimate capacity concept (23, 24).

Capacity Handbook Approach

The FAA published a comprehensive handbook (25) containing procedures for the determination of airfield capacities and aircraft delays for purposes of airport planning. The handbook and its companion reports (18, 19, 23) were based on an extensive four-year study by the FAA and a project team composed of Douglas Aircraft Company in association with Peat, Marwick, Mitchell and Co., McDonnell Douglas Automation Company, and American Airlines

The handbook contains 62 graphs, exemplified by Figure 7.8, for the estimation of hourly capacities. Based on analytical models, the graphs account for the effects of the following variables:

1. Aircraft mix
2. Runways serving both arrivals and departures
3. Touch-and-go operations
4. Different exit taxiway configurations
5. Environmental conditions (VFR, IFR)
6. A variety of runway configurations and uses

In the handbook, the aircraft mix is expressed in terms of four aircraft “classes”:

- Class A: small single-engine aircraft, 12,500 lb or less
- Class B: small twin-engine aircraft, 12,500 lb or less, and Learjets
- Class C: large aircraft, more than 12,500 lb and up to 300,000 lb.
- Class D: heavy aircraft, more than 300,000 lb

The graphs employ a “mix index,” which is determined by the percentages of aircraft in classes C and D:

$$\text{Mix index} = (\%\text{ aircraft in class C}) + 3 \times (\%\text{ aircraft in class D})$$

Many of the capacity diagrams from the handbook have been published by the FAA in Advisory Circular 150/5060-5 (6).

Consider the following example (from reference 18):

Example 7.3 Runway Capacity Using Handbook Approach Referencing Figure 7.8, determine the hourly capacity of a single runway (10,000 ft long) in VFR under the following conditions:

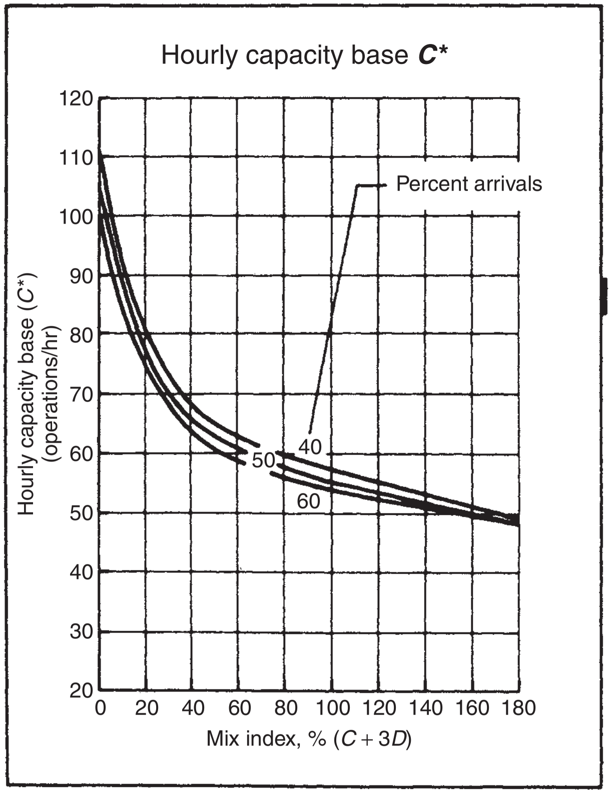
Aircraft mix: 35% A, 30% B, 30% C, and 5% D
Percent arrivals: 50%
Percent touch and go: 15%
Exit taxiway locations: 4500 and 10,000 ft from arrival threshold
The mix index for the assumed aircraft mix is

$$\text{Percentage (C} + \text{3D)} = 30 + (3 \times 5) = 45$$

From Figure 7.8, the hourly capacity base (C^*) in VFR conditions is 65 operations/hr. Also from Figure 7.8, for 15% touch and go, the touch-and-go factor T is 1.10. With one exit taxiway located between 3000 and 5500 ft from the arrival runway threshold, the exit factor E is 0.84.

Therefore the hourly capacity of the runway is

$$65 \times 1.10 \times 0.84 = 60 \text{ operations/hr}$$



Touch & go factor T

Percent touch & go	Mix index, % $(C+3D)$	Touch & go factor T
0	0 to 180	1.00
1 to 10	0 to 70	1.04
11 to 20	0 to 70	1.10
21 to 30	0 to 40	1.20
31 to 40	0 to 10	1.31
41 to 50	0 to 10	1.40

$C^* \times T \times E$ = hourly capacity

Exit factor E

<u>To determine exit factor f:</u>

1. Determine exit range for appropriate mix index from table below
2. For arrival runways, determine the average number of exits (N) which are: (a) within appropriate exit range, and (b) separated by at least 750 ft
3. If N is 4 or more, exit factor = 1.00
4. If N is less than 4, determine exit factor from table below for appropriate mix index and percent arrivals

Mix index, % $(C+3D)$	Exit range (feet from threshold)	Exit factor E								
		40% Arrivals			50% Arrivals			60% Arrivals		
		N=0	N=1	N=2 or 3	N=0	N=1	N=2 or 3	N=0	N=1	N=2 or 3
0–20	2000–4000	0.72	0.87	0.94	0.70	0.86	0.94	0.67	0.84	0.92
21–50	1000–3500	0.79	0.86	0.94	0.76	0.84	0.93	0.72	0.81	0.90
51–80	3500–6500	0.79	0.86	0.92	0.76	0.83	0.91	0.73	0.81	0.90
81–120	5000–7000	0.82	0.89	0.93	0.80	0.88	0.94	0.77	0.86	0.93
121–180	5500–7500	0.86	0.94	0.98	0.82	0.91	0.96	0.79	0.91	0.97

Figure 7.8 Hourly capacity diagram for a single-runway in VFR conditions (5).

7.6 ANNUAL SERVICE VOLUME

Another FAA expression for capacity derived for preliminary planning purposes that reflects annual rather than hourly time period is the ASV. The FAA defines ASV as (6): "a reasonable estimate of an airport's annual capacity, and accounts for differences in runway-use configuration, aircraft mix, weather conditions that will be encountered over a year's time." The primary determinant of ASV is runway-use configuration, where 19 different runway configurations are provided and the ASV is specified for each depending on a variation of aircraft mix and and IFR/VFR hourly capacity, such that

$$C_w = \frac{\sum_{i=1}^{n} C_i W_i P_i}{\sum_{i=1}^{n} W_i P_i} \tag{7.19}$$

where

P_i = proportion of the year with capacity C_i
W_i = weight to be applied to capacity, chosen from the table (point 3) below

The concept of annual service volume has been proposed by the FAA as an alternative to practical annual capacity as a reference in preliminary planning. As annual aircraft operations approach annual service volume, the average aircraft delay throughout the year tends to increase rapidly, with relatively small increases in aircraft operations, causing deterioration in the LOS. Annual service volume is the level of annual aircraft operations that will result in an average aircraft delay on the order of 1–4 min.

The recommended procedure for the calculation of annual service volume is outlined below (6):

1. Identify the various operating conditions (e.g., VFR, dual runways; IFR, single runway) under which the runway system may be used during a year, and determine the percentage of time that each condition occurs. Determine the hourly capacity of the runway component for each operating condition.
2. Identify the hourly capacity for the operating condition that occurs during most of the year, that is, the predominant capacity.
3. Determine the weight to be applied to the capacity for each operating condition from the following table:

	Weight			
	Mix index in VFR	Mix index in IFR		
Percentage of predominant capacity	0–180	0–20	21–50	51–180
91 or more	1	1	1	1
80–90	5	1	3	5
66–80	15	2	8	15
51–65	20	3	12	20
0–50	25	4	16	25

4. Calculate weighted hourly capacity C_w of the runway component by the following formula:

$$C_w = \frac{\sum_{i=1}^{n} C_i W_i P_i}{\sum_{i=1}^{n} W_i P_i} \tag{7.20}$$

5. Determine the ratio of the annual aircraft operations to average daily aircraft operations during the peak month (i.e., the daily ratio). If data are not available for determining the daily ratio, use the following typical values:

Mix index	Daily ratio
0–20	280–310
21–50	300–320
51–180	310–350

6. Determine the ratio of average daily aircraft operations to average peak-hour aircraft operations of the peak month (i.e., the hourly ratio). If data are not available for determining the hourly ratio, use the following typical values:

Mix index	Daily ratio
0–20	7–11
21–50	10–13
51–180	11–15

7. Compute the annual service volumes (ASVs) from the following formula:

$$\text{ASV} = C_w \times D \times H \tag{7.21}$$

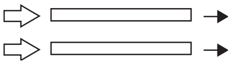
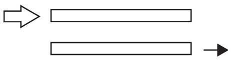
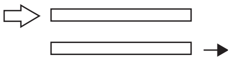
where

C_W = weighted hourly capacity by percent of time runway configuration is used

D = daily demand ratio = (annual demand)/(average daily demand in peak month)

H = hourly demand ratio = (average daily demand)/(average peak-hour demand in peak month)

Example 7.4 Annual Service Volume for Runways (18) Determine the annual service volume of a dual parallel runway configuration under the following operating conditions:

	Operating condition				
No.	Ceiling and visibility	Runway use	Mix index	Percentage of year	Hourly capacity
1	VFR		150	70%	93
2	VFR		150	20%	72
3	IFR		180	10%	62

where R means runway and the arrow indicates the direction of operation.

Based on historical traffic records:

Total annual operations = 367,604

Average daily operation = 1050

Average peak-hour operations, peak month = 75

The predominant capacity occurs in operating condition 1 and is 93 operations per hour. From the table in paragraph 3 above, the following weights for each operating condition are determined:

Operating condition number	Hourly capacity, operations per hour	Percent of predominant capacity	Weight
1	93	100	1
2	72	77	15
3	62	67	15

By equation 7.20, the weighted hourly capacity is

$$C_w = \frac{(0.70 \times 93 \times 1) + (0.20 \times 72 \times 15) + (0.10 \times 62 \times 15)}{(0.70 \times 1) + (0.20 \times 15) + (0.10 \times 15)}$$

$$C_w = 72 \text{ operations per hour}$$

For the assumed conditions,

$$\text{Daily ratio} = \frac{367,604}{1,050} = 350$$

$$\text{Hourly ratio} = \frac{1,050}{75} = 14$$

By equation 7.21, the annual service volume is

$$\text{ASV} = 72 \times 350 \times 14 = 352,800 \text{ operations per year}$$

7.7 PRELIMINARY CAPACITY ANALYSES

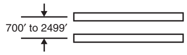
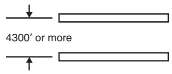
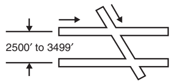
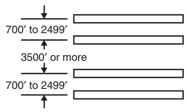
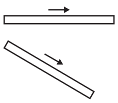
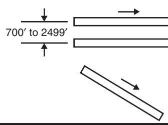
The FAA (18) has published approximate estimates of hourly capacity and annual service volumes for a variety of runway configurations. These estimates, exemplified by Table 7.3, are suitable only for preliminary capacity analyses. In addition to runway configuration, the capacities in Table 7.3 account for differences due to weather (VFR and IFR conditions) and aircraft mix. IFR conditions exist when the cloud ceiling is less than 1000 ft and/or the visibility is less than 3 mi. Runway capacity is normally less under IFR conditions than under VFR conditions.

To utilize Table 7.3, it is necessary to group the aircraft being served into four aircraft classes and to express aircraft mix as a mix index.

The capacities in the table are based on the following assumed conditions:

1. Availability of sufficient airspace to accommodate all aircraft demand
2. Availability of a radar environment with at least one ILS-equipped runway

Table 7.3 Capacity and Annual Service Volume for Long Range

Configuration	Runway configuration diagram	Mix index—percent (C + 3*D*)	Hourly capacity (operations per hour) VFR	IFR	Annual service volume (operation per year)
A		0–20	98	59	230,000
Single Runway		21–50	74	57	195,000
		51–80	63	56	205,000
		81–120	55	53	210,000
		121–180	51	50	240,000
B		0–20	197	59	355,000
Dual Lane Runways		21–50	145	57	275,000
		51–80	121	56	260,000
		81–120	105	59	285,000
		121–180	94	60	340,000
C		0–20	197	119	370,000
Independent IFR Parallels		21–50	149	114	320,000
		51–80	126	111	305,000
		81–120	111	105	315,000
		121–180	103	99	370,000
D		0–20	197	62	355,000
Parallels plus Crosswind Runway		21–50	149	63	285,000
		51–80	126	65	275,000
		81–120	111	70	300,000
		121–180	103	75	365,000
E		0–20	394	119	715,000
Four Parallels		21–50	290	114	550,000
		51–80	242	111	515,000
		81–120	210	117	565,000
		121–180	189	120	675,000
F		0–20	150	59	270,000
Open V Runways		21–50	108	57	225,000
		51–80	85	56	220,000
		81–120	77	59	225,000
		121–180	73	60	265,000
G		0–20	295	59	385,000
Parallels plus Crosswind Runway		21–50	210	57	305,000
		51–80	164	56	275,000
		81–120	146	59	300,000
		121–180	129	60	355,000

Source: *Airport Capacity and Delay*, FAA Advisory Circular 150/5060-5, September 23, 1983.

3. Availability of sufficient taxiways to expedite traffic on and off the runway
4. Touch-and-go operations ranging from 0 to 50%, depending on the mix index

Reference 18 provides additional information on the performance of preliminary capacity analyses

7.8 CALCULATING AIRCRAFT DELAY

A critical aspect of airport airside capacity analysis is the determination of the LOS of the demand–capacity relationship manifested by aircraft delays. Such an analysis should provide estimates of aircraft delay on hourly and annual bases, each used for a different purpose.

Hourly Aircraft Delay

Detailed and objective evaluation of facility improvement to expand capacity must include extensive analysis to quantify total airfield capacity and aircraft delay (which is the manifestation of the resulting LOS). To the extent possible, the analysis must also include related development costs per alternative versus the total operational benefits of each. A major requirement for the capacity analyses is the estimation of the magnitude of aircraft delays.

Aircraft delay is expressed as the difference between the time required for an aircraft to operate on an airfield or airfield component and the normal time it would require to operate without interference from other aircraft (19).

A number of Monte Carlo simulation models have been developed to estimate aircraft delays. With such a model, a team of researchers produced a series of graphs published elsewhere (18) by which aircraft delays can be estimated for various runway configurations and operating conditions.

The model operates by tracing the path of each aircraft through space and time on the airfield. The airfield is represented by a series of links and nodes depicting all possible paths an aircraft could follow. The traces of the path of all aircraft on the airfield are made by continually advancing clock time and recording the new location of the aircraft. The records of aircraft movement are then processed by the model to produce desired outputs, including delays and flow rates (19).

The graphical procedure recommended (18, 26) for the estimation of hourly delays is as follows:

1. Calculate the ratio of hourly demand to hourly capacity, D/C, for the runway component.
2. Determine the arrival delay index (ADI) and the departure delay index (DDI) from graphs such as those shown in Figure 7.9. These delay indices reflect the ability of a runway use to process aircraft operations under specified conditions of aircraft mix, arrival/departure ratio, and demand. Reference 4 provides 32 sets of delay index graphs to account for differences in runway configuration and use conditions.
3. Calculate the arrival delay factor (ADF) by the following formula:

$$\text{ADF} = \text{ADI} \times [D/C] \tag{7.22}$$

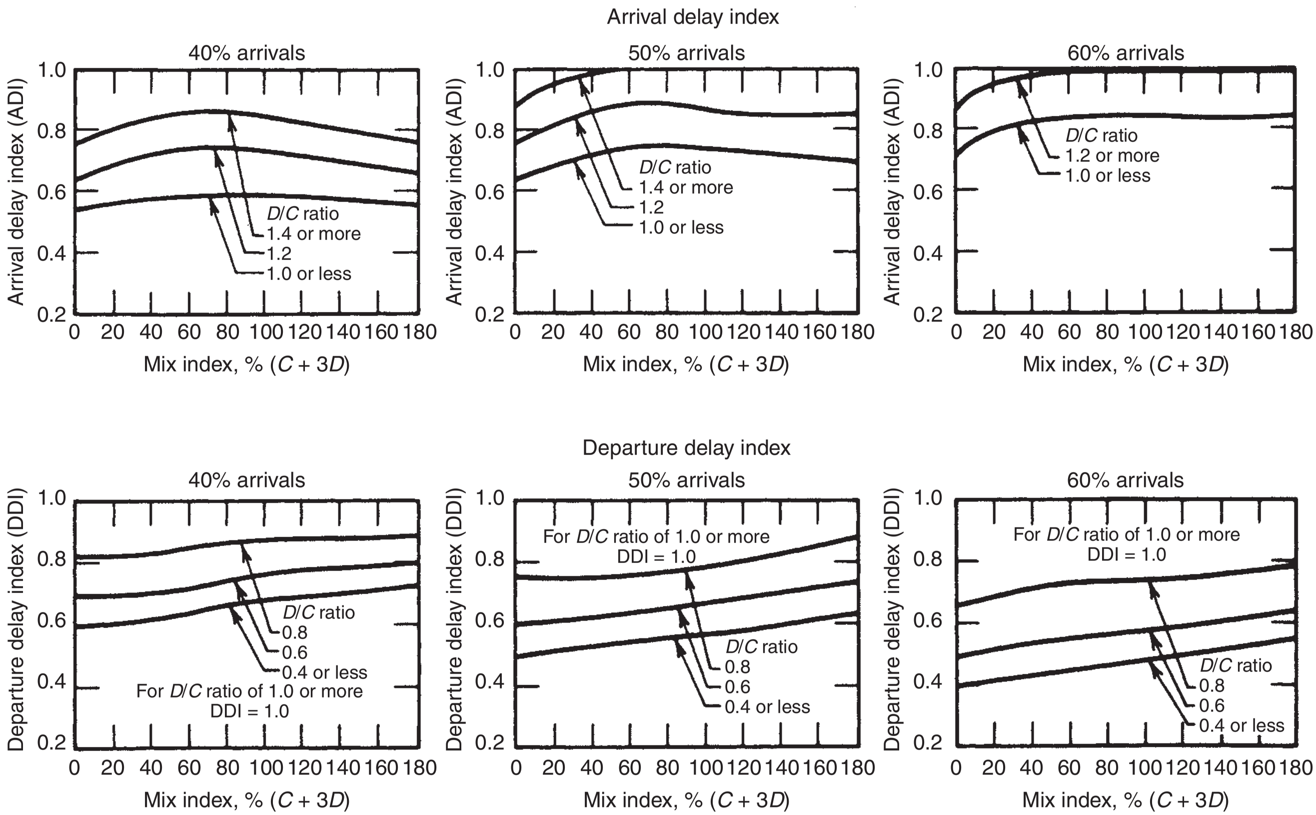


Figure 7.9 Delay indices for runway use diagram (18).

4. Calculate the departure delay factor (DDF) by the following formula:

$$\text{DDF} = \text{DDI} \times [D/C] \tag{7.23}$$

5. Determine the demand profile factor, defined as the percent of hourly demand occurring in the busiest 15-min period.
6. Estimate the average hourly delay for arrival and departure aircraft from Figure 7.10.
7. Compute the total hourly delay to aircraft (DTH) by the following formula:

$$\text{DTH} = \text{HD}\{[\text{PA} \times \text{DAHA}] + [(1 - \text{PA}) \times \text{DAHD}]\} \tag{7.24}$$

where

HD = hourly demand on the runway component
PA = percent of arrivals/100
DAHA = average hourly delay per arrival aircraft on the runway component
DAHD = average hourly delay per departure aircraft on the runway component

This procedure is applicable only when the hourly demands on the runways, taxiways, and gates do not exceed the capacities of these components. If the demand on one or more components exceeds its capacity, delays to aircraft for a period of more than 1 hr should be considered. The recommended procedure for such analyses is not covered here (see ref. 18).

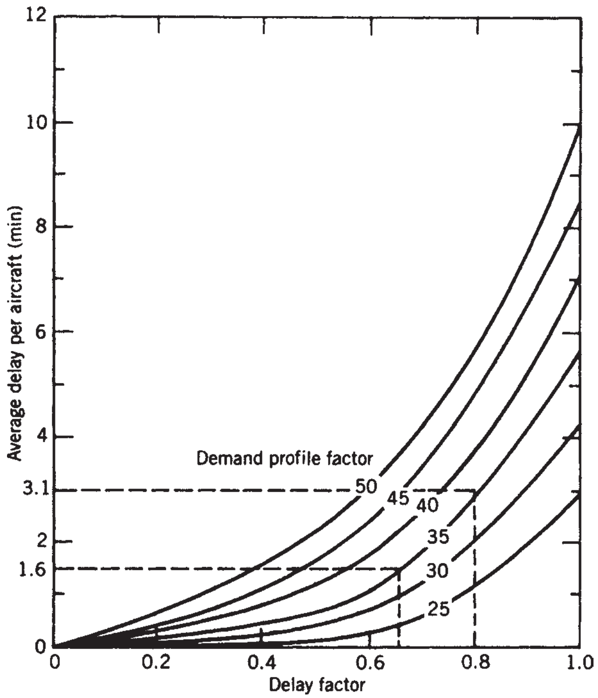


Figure 7.10 Average aircraft delay in an hour (18).

Consider the following example modeled after one from reference 18:

Example 7.5 Hourly Delay to Aircraft on a Single Runway, VFR Determine the DTH under VFR conditions using a single 10,000-ft runway with the following characteristics:

$$\text{Hourly demand} = 59 \text{ operations/hr}$$

$$\text{Peak 15-min demand} = 21 \text{ operations}$$

$$\text{Hourly capacity} = 65 \text{ operations/hr}$$

$$\text{Percent arrivals} = 50\%$$

$$\text{Mix index} = 45$$

The ratio of hourly demand to hourly capacity is $59/65 = 0.91$.

From Figure 7.9, for a mix index of 45, the arrival delay index is 0.71 and the departure delay index is 0.88.

By equations 7.22 and 7.23, the arrival delay factor is $0.71 \times 0.91 = 0.65$, and the departure delay factor is $0.88 \times 0.91 = 0.80$.

For the given peak 15-min demand, the demand profile factor is $(21/59) \times 100 = 36$. Therefore, from Figure 7.10, the average hourly delay to arrival aircraft on the runway is 1.6 min, and the average hourly delay to departure aircraft is 3.1 min.

By equation 7.24, the total hourly delay to aircraft on the runway is

$$\text{DTH} = 59\{[0.50 \times 1.6] + [(1 - 0.50) \times 3.1]\} = 139 \text{ min}$$

Annual Aircraft Delay

The system annual aircraft delay on the airfield (runway, taxiway, and gates) and airport airspace beyond depends on a number of factors, including the overall magnitude of demand, the hourly and daily patterns of demand, the hourly capacities for various operating conditions (e.g., runway use, ceiling, and visibility), and the pattern of occurrence of various operating conditions throughout the year. The computation of annual delay to aircraft must therefore account for the seasonal, daily, and hourly variations in demand and capacity throughout the year.

Ideally, annual aircraft delay could be obtained by determining the delays for each day of the year and summing the 365 daily delays. That approach, however, is likely to require a prohibitive amount of data, time, and effort.

The FAA recommends that the demand conditions in each of the 365 days of the year be characterized by those in a much smaller number of representative days. The delay for each representative day can be determined and then multiplied by the number of days "represented" to determine the total delay associated with each representative daily demand. The annual delay can be estimated by summing the total delay for all representative daily demands.

For example, in the Airport Capacity and Delay Handbook (6), each representative daily demand corresponds to the typical demands in the days of one month. Since daily demand usually varies in VFR and IFR conditions, 24 representative daily demands are assumed.

A manual procedure for computation of annual delay to aircraft can involve a time-consuming calculation process. For this reason, computer programs have been developed to facilitate the estimation of annual delays (18, 19).

Reference 18 also presents a simplified procedure for obtaining annual delay to aircraft when an approximate estimate is all that is needed.

7.9 TAXIWAY CAPACITY

A key component in the airport layout is the taxiway system, which connects the runways to the terminal apron-gate area and aircraft service hangars. In taxiway layout and design, major emphasis is given to providing smooth and efficient flow of aircraft along the taxiways. Where air traffic warrants, the usual procedure is to locate a taxiway parallel to the runway centerline for the entire length of the runway. This makes it possible for landing aircraft to exit the runway more quickly and decreases delays to other aircraft waiting to use the runway.

Whenever possible, taxiways should be designed with maximum capacity and safe and uninterrupted aircraft flow in mind. Ideally, taxiways should not cross active runways, and at busy airports, a one-way taxiway flow pattern should always be maintained for taxiways connecting the runway(s) and the terminal apron-gate area. Specific criteria for the design of runways, taxiways, and aprons are given in Chapter 8.

Taxiway capacity is the maximum number of aircraft operations accommodated on the taxiway component of the airfield. Graphical solutions for capacities of taxiways that cross active runways are discussed in more detail in reference 23.

Empirical studies have shown that the capacity of a taxiway system generally far exceeds the capacities of either the runways or the gates (23). There is one notable exception, namely, taxiways that cross an active runway. For cross-runway taxiways, capacity is dependent on the following conditions: intersecting taxiway location, runway operating rate, aircraft mix, airfield visibility conditions, and the location of the taxiway relative to the departure end of the runway.

It could be safely assumed that taxiway capacity is always available to move aircraft to runways and gates, and therefore there is need to evaluate taxiway capacity separately to determine total airside capacity.

However, when airport simulation is used, it will reveal the real situation, and if any taxiway is actually a bottleneck in the airfield network, simulation output would clearly point to that.

7.10 GATE CAPACITY

The term “gate” designates an aircraft parking space adjacent to a terminal building and used by a single aircraft for the loading and unloading of passengers, baggage, and mail or a remote parking stand on the apron where passengers and baggage are transferred to the terminal building by apron vehicles.

Gate capacity refers to the ability of a specified number of gates to accommodate aircraft loading and unloading operations under conditions of continuous demand. It is the inverse of the weighted average gate occupancy time for all the aircraft served.

The maximum number of aircraft operations accommodated by the gate-apron group component (gate capacity) is dependent on:

- Gate-apron aircraft parking arrangement
- Aircraft ground service and passenger loading characteristics
- Number and mix of the gates and stands by category
- Gate occupancy time per flight
- Scheduling practices of the airlines

The gate occupancy time, which is a determinant of overall airport gate-apron capacity, depends on the following variables:

- Type of aircraft
- Whether the flight is an originating, turnaround, or through flight
- Volume of deplaning and enplaning passengers per flight
- Amount of baggage and mail per flight
- Productivity of aircraft servicing operation and efficiency of apron personnel
- Exclusive use of one airline or class of aircraft and availability to all users

Example 7.6 Gate Capacity: Each Gate Available to All Users Determine the capacity of 10 gates that serve three classes of aircraft given the following aircraft mix and average gate occupancy times:

Aircraft class	Mix (%)	Average occupancy time (min)
1	10	20
2	30	40
3	60	60

Assume that each gate is available for all aircraft.

The gate capacity for a single gate is given by

$$c = \frac{1}{\text{weighted service time}} = \frac{1}{(0.10 \times 20) + (0.3 \times 40) + (0.6 \times 60)}$$

$$= 0.02 \text{ aircraft/min/gate}$$

If G = the total number of gates, the capacity for all gates is

$$C = G_c = 10 \times 0.02 = 0.2 \,\text{aircraft/min} = 12 \,\text{aircraft/hr}$$

Example 7.7 Gate Capacity with Exclusive Use Suppose the 10 gates in the preceding example are assigned for exclusive use of the three classes of aircraft as follows:

Aircraft class	Gate group	Number of gates	Mix (%)	Mean service time (min)
1	A	1	10	20
2	B	2	30	40
3	C	7	60	60

If the effect of mix is ignored, the capacity of group A would be the inverse of the service time: CA = 1/TA = 3.0 aircraft/hr. Similarly, CB = 1.5 and CC = 1.0. One might (incorrectly) conclude that the total capacity of these gates is the sum of capacities of the three groups, or $(1 \times 3) + (2 \times 1.5) + (7 \times 1.0) = 13$ aircraft/hr. When mix is taken into consideration, an overall demand of 13 aircraft/hr would result in excessive demand for gate groups B and C:

Gate group	Demand (aircraft/hr)	Capacity (aircraft/hr)
A	$0.10 \times 13 = 1.3$	$3.0 \times 1 = 3.0$
B	$0.30 \times 13 = 3.9$	$1.5 \times 2 = 3.0$
C	$0.60 \times 13 = 7.8$	$1.0 \times 7 = 7.0$

The capacity of the gate system is

$$C = \min_{\text{all } i} \left[\frac{G_i}{T_i M_i} \right] \tag{7.25}$$

where

G_i = number of gates that can accommodate aircraft of class i
T_i = mean gate occupancy time of aircraft of class i
M_i = fraction of aircraft class i demanding service

For the given example,

$$C_1 = \frac{1}{20 \times 0.10} = 0.5 \text{ aircraft/min}$$

or 30 aircraft/hr. Similarly, $C_2 = 10$ and $C_3 = 11.67$ aircraft per hour. The capacity is therefore 10 aircraft/hr.

A graph in reference 18 makes it possible to estimate the hourly gate capacity in operations per hour.*

7.11 ASSESSING SYSTEM CAPACITY–DELAY FOR AIRPORT DEVELOPMENT

Airport capacity analysis is critical to the development of airports on the system level. Given the long lead time to build airports and particularly runways, defining the exact need for airport infrastructure expansion to match the demand where it is precisely needed is quite difficult, costly, and time consuming. The U.S. airport system is very spatially concentrated—aviation activity in the U.S. NAS has, and will remain, highly concentrated in the largest airports and major urban areas where airport investments are most needed and yet most difficult to obtain (26). In 1988, the top 10 airports handled 35% of the passengers and 21% of the commercial aircraft operations. The top 50 airports in the same year handled 80% of the passengers and 56% of the aircraft

*One aircraft using a gate represents two operations—an arrival and a departure.

operations. These concentration percentages have been remarkably consistent over the last 50 years, regardless of the state of the airline industry.

Reflecting the concentration of demand, virtually all major U.S. airports are located in close proximity to the core of the urban regions that they serve. Almost all major airports fall within 20 mi of their regional central business districts. The only new airports developed during the past 40 years in the United States—DFW, Washington Dulles, and Denver—are closer to 30-mi range. Given the difficulty of adding real airfield capacity at mature, land-locked airports in vital urban markets, the focus of attention will shift toward increasing the number and productivity of other existing airports that are used for extensive commercial service. But many of the older urban airports have inefficient airfield layouts. Most started as military airfields with a triangular and nonparallel runway configuration driven by crosswind considerations of aircraft of that day.

Through such capacity enhancement measures as reduced runway intersections, reduced runway crossings, synchronized arrival–departure sequencing, and easier air traffic control management, runways are reconfigured at these “older” airports, where runway capacity could increase by at least 20%. The advantages for moving aircraft and passengers in such a reconfigured environment include dual ground access points, greater gate capacity and accessibility from a taxiway standpoint, less runway crossings, and a more manageable and flexible system. Moreover, emerging satellite-based navigational technologies are providing opportunities to make airports less intrusive on their surrounding communities through avoiding sensitive land uses and narrowing flight corridors, which could reduce parallel runway separation requirements, and this is one measure to increase runway capacity. Gradually, these airports could be redeveloped incrementally to conveniently serve demand, as there is significant capacity “locked in.” Enhanced operation with more runway capacity could then be realized using creative planning, technological advances, and supportive government policy (26).

As part of the FAA guidance, the NPIAS recommends that capacity planning start when aircraft activity reaches 60–75% of an airport’s airfield capacity (27). Since major airfield improvements often take 10 or more years from development inception to start of operation, the recommendation allows adequate lead time so the needed improvement can be completed before a problem becomes critical.

In terms of system delay, the number of arrivals and departures that are delayed 15 min or more is compiled by the DOT for busy airports and is reported monthly. The DOT defines a delayed operation as an aircraft arriving at or departing from a gate 15 min or more after its scheduled time. In 1990, the number of commercial airports in the NAS that had excessive delay was 23, with total annual delay beyond 20,000 hr, which had serious operational as well as financial impact on the air transport industry (28). In 2007, the 20 airlines reporting data posted the second worst on-time arrival record of 73.3%, which is behind the all-time worst mark of 72.6% reached in 2000. Of the 26.7% of flights delayed in 2007, 8.1% were delayed because the aircraft arrived late, 8% were delayed due to national aviation system delays, 7% were delayed due to air carrier delay, 2.4% of the delays were attributed to cancelled or diverted flights, and 1% of flights were delayed due to significant meteorological conditions.

Through the Future Airport Capacity Task (FACT), the FAA has identified a significant number of U.S. airports and metropolitan areas that are expected to require additional capacity in the future if demand reaches forecast levels (29). FACT is an assessment of the future capacity of the NAS airports and metropolitan areas, and its goal is to determine which airports and metropolitan areas have the greatest need for additional capacity. The FAA objective in this initiative is to ensure that the long-term capacity of the U.S. aviation system matches forecasts of demand. This analysis highlights the importance of not only moving forward with current improvement plans, and keeping such plans on schedule, but also seeking new solutions to add even more capacity than is currently being planned by airports and communities.

So what are the prospects of expanding airport capacity where and when it is needed?

DeNeufville (30) identified three main drivers that will impact the future of airports:

1. *Consistent Growth in Traffic*. This leads to larger, busier airports, which also leads to diversification and specialization. As metropolitan areas grow, multiple metropolitan airport systems will emerge and individual airports will increasingly serve niche air travel markets.
2. *Globalization*. Airlines are merging within the major global trading blocks, as they have in North America and in Europe, forming global alliances. In parallel, airports are partnering with these global airline alliances that use them as base hubs. Airports are also becoming associated with international airport management, corporations, and operating companies—trends that will jointly change the nature of demand and provision of airport services entirely.
3. *Commercialization*. Airport operations and management are becoming increasingly commercial and, in the context of worldwide companies managing airport facilities, more sustained professional training is required for airports to become more efficient and more competitive.

DeNeufville argues that since the end of World War II the growth in aviation (passengers and cargo) has been nothing less than spectacular and an outstanding characteristic of air travel (30). Long term, over good and bad years in this period, passenger traffic has increased by an average of about 7% a year in the United States and close to 10% worldwide, which translates into doubling within every 10 years. This growth in aviation traffic has been multifaceted, as manifested by:

1. Price of air travel has steadily dropped over the past 50 years. As Figure 7.11 indicates, the long-term drop in prices is mirrored by a steady rise in use per person, as one would expect from basic economics.
2. Flight safety and level of comfort have been increasing dramatically, and the number of accidents and fatalities has dropped to historically low levels.
3. Increased traffic throughput in runways today, where many airports (e.g., Los Angeles International, Boston, Philadelphia, Chicago O'Hare, Seattle, and the three New York airports) are all now serving between 50 and 100% more operations a year than their "practical annual capacity," as estimated by the airport planners of the 1970s.
4. Increased globalization greatly brought out by better international communications and aviation, further facilitating long-distance travel.

These factors have jointly led to the steady growth in aviation.

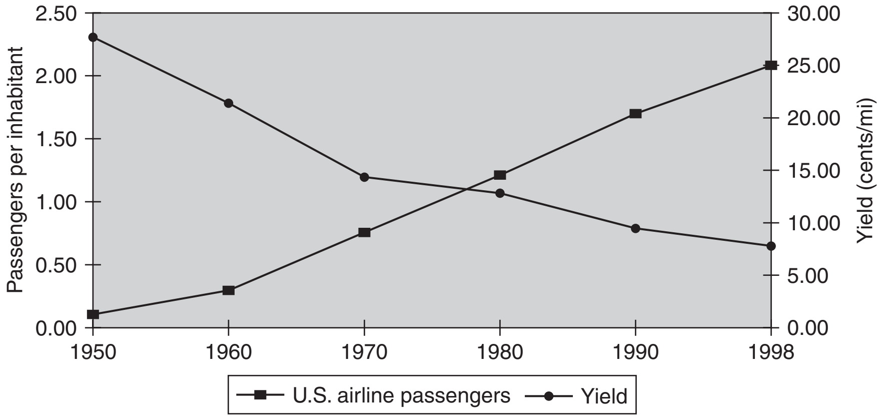


Figure 7.11 U.S. trends of air traffic volume vs. cost of air travel (31).

Since specific predictions of future events are "always wrong" due to inevitable changes in circumstances, it is preferable to think about the range of probable developments rather than improbable specifics. Recognition of the possible eventualities enables strategic thinkers to build flexibility into their plans so that they can smoothly accommodate what actually happens.

Airport capacity increases through infrastructure development have been a constant feature of aviation planning, and major new airports and runways have come into being regularly and undoubtedly will continue to do so. During the last 40 years several remarkable airport projects have been executed in the United States, such as the construction of Dallas/Fort Worth, Denver International, Orlando, and Washington/Dulles. Internationally, many modern airports were built following the latest in airport planning and design concepts, such as Singapore, Hong Kong, Kuala Lampur, Seoul, and Athens (30).

The improvements in runway capacity over the past half century are primarily attributed to:

1. Extended daily use and more organized utilization of runways.
2. Technical changes, better operating practices, and increased operational efficiency of pilots and air traffic controllers.
3. Improved spacing and sequencing of aircraft into airports that reduced variability in landing times, minimized runway occupancy, and therefore increased the number of operations a runway could accommodate.
4. Air navigation service providers (the FAA in the United States) have trained their air traffic controllers on how to use existing runways more efficiently under different conditions.
5. Institution of congestion pricing at the most congested airports, where slot controls limit access of smaller aircraft and thus raise the number of passengers (on flights) served by runways.
6. Major improvements in aircraft sequencing and capacity as more GPS-based airport terminal procedures are used, together with certifying close-parallel runways for independent use.

Such argument therefore suggests certain scenarios that focus on three main elements:

- Magnitude and peaking pattern of traffic—passengers, cargo, and aircraft
- Infrastructure that needs to be provided to accommodate these loads
- Management style for these facilities by airlines, airports, and ATC collectively

For the air transport community led by the DOT/FAA to assess NAS-wide airport performance and plan future capacity expansion where and when required, huge amounts of data need to be collected and analyzed constantly and continuously. The major DOT and FAA databases used to track NAS airport performance include:

1. *Aviation System Performance Metrics* (*ASPM*) provides information on individual flight performance and information on operational efficiency for 77 U.S. airports.
2. *Enhanced Traffic Management System* (*ETMS*) is a compilation of the NAS CAN/ATM system data, where the trajectory of each flight in the system is captured from radar (and other equipment) data and compiled and then processed and enhanced by the DOT.
3. *Airline Service Quality Survey* (*ASQP*) contains data provided by the airlines for flights that carry at least 1% of all domestic passengers. The number of airlines providing data has varied from 10 to 20. Actual and scheduled time is available for gate departure and gate arrival. The airlines also provide the actual wheels-off time so that taxi-out time can be computed and wheels-on time so that taxi-in time can be computed. In addition, the airlines provide causal data for all flights arriving 15 min past their scheduled arrival time.
4. *Aviation Performance Metrics* (*APM*) provides information on number of flights and aircraft departure and arrival times compared to the schedule and flight plan times for approximately 29 airlines serving the 77 ASPM airports.

The U.S. government recognizes the size and complexity of this problem. Growing demand for air travel has fully taxed the capacity of the NAS, including the ATC system. Airline passengers are experiencing increasing flight delays and cancellations from the growing imbalance between their demands and the ability of the NAS to handle air traffic (31). More than one out of every four flights nationwide were canceled, delayed, or diverted during 2000. These actions affected 163 million passengers, who, on average, were delayed almost an hour. The FAA reported that 1.9 million passengers moved through the system daily and it forecasts a 59% increase in the number of enplanements between 1999 and 2011. Delays and cancellations are also increasing. In 2000, which was the worst year on record, the FAA reported a 90% increase in delays and a 104% increase in cancellations compared with five years ago. The imbalance between demand and capacity is most pronounced during peak flying periods at the major airports through which major airlines route their flights, commonly referred to as hub airports.

In 2001, in an effort to address the situation, the FAA announced a set of initiatives in its operational evolution plan (OEP), which is designed to increase capacity in the NAS and its airports. The agency, in cooperation with the aviation industry, set a plan to improve designing airspace and aircraft routes and deploy new technologies, among other actions, to permit more efficient movements and eventually allow more aircraft to move safely in the NAS. This plan complemented another FAA exercise to benchmark capacity for the nation's 31 busiest airports. Since over 70% of the passengers move through these airports, the benchmarks allow policymakers to target short- and long-term solutions at these airports, thereby achieving the biggest increases in capacity (32). The aviation industry has shared with government the complexity and difficulty of the problem and has taken steps to collaborate in addressing the capacity crisis.

As a direct consequence of the NAS-wide capacity problem, flight delays are becoming longer. According to DOT data, the average length of a flight delay increased from more than 49 min in 1998 to almost 56 min in 2007, an increase of nearly 14% throughout the system (32). Despite this relatively small increase in average flight delay length, far more flights were affected by long delays in ten years. For example, the number of flights delayed by 180 min or more increased from 25,726 flights in 1998 to 64,040 flights in 2007, or about 150%. Moreover, the number of flights in which an aircraft has departed the gate but remained for an hour or more on the ground awaiting departure has increased over 151% since 1998. Total flight delays and cancellations in the NAS over the 10-year period 1998–2007, which is considered a system capacity performance indicator, increased consistently to the highest level in 2000, decreased in a dip due to the September 11, 2001 attacks for 3 years, and increased in the same pattern again to reach the second highest level in 2007, as shown in Figure 7.12.

Delay continued to show an upward trend during this 10-year period:

- Throughout NAS airports, annual number of flight delays and cancellations increased 62% (from 1.2 million to 2.0 million), as annual number of scheduled flights increased 38% (from 5.4 million to 7.5 million).
- For the three New York airports, annual number of flight delays and cancellations increased by 111%, as annual domestic operations increased by 57%.
- During the 10-year period, percent of flight delays in the NAS increased from 20 to 24%.

It is anticipated that the upward trend will continue beyond 2007.

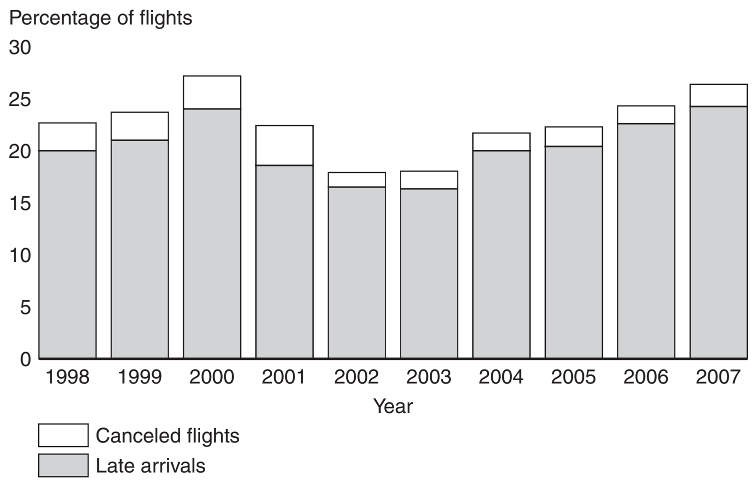


Figure 7.12 Manifestation of delay in the NAS—1998–2007 (32).

During a typical day, approximately one-third of the aircraft in the national airspace system move through the New York airspace. Research conducted by MITRE for the FAA indicates that an average of 40% of NAS total flight delays are attributed to delays originating in the New York metropolitan area. The distribution of delay by source is very different in New York than for the country as a whole, and this reflects the New York area's greater level of congestion. Table 7.4 indicates the sources of delay throughout the NAS as compared to those for the three airports in the New York area.

Through the ASQP database, since 2003 U.S. airlines have been reporting data to the DOT on the causes of delay in five broad categories:

- *Late arriving aircraft*, referring to a previous flight using the same aircraft that arrived late, causing the subsequent flight to depart late.
- *Airline operations* delays include any delay or cancellation that was within the control of the airlines, such as aircraft cleaning, baggage loading, crew issues, or maintenance.
- *National aviation system* delays and cancellations refer to a broad set of circumstances affecting airport operations, heavy traffic volume, air traffic control operations, any non-extreme-weather condition (such as wind or fog) that slows the operation of the system but does not prevent flying.
- *Extreme weather* includes serious weather conditions that prevent the operation of a flight, including tornadoes, snow storms, and hurricanes.
- *Security* conditions include evacuation of an airport, reboarding due to a security breach, and long lines at the passenger screening areas.

As indicated in Table 7.4, in 2007, for NAS-wide airports the larger cause of delay (38%) was attributed to late arrival of aircraft and the next larger (28%) was caused by airline operations. Only 6% was caused by extreme weather. Security accounted for less than 1% of delays in 2007, and since 2003, despite the increasing number of delays, there have been no significant changes in the trend of security-related delays. The situation for the the three New York airports, being the most affected by the capacity problem, is slightly different. The impact of NAS operation on this group is much higher than the average for the entire system (58%), and all other causes are consistently lower than the entire system.

However, a study by the General Accounting Office (GAO) (32) indicated that the structure of the DOT-reported sources of delay in the NAS provides an incomplete picture of the underlying causes of delays. First, the reported categories are too broad to

Table 7.4 Sources of Delay in NAS and Three New York Airports, 2007 (32)

	Percentage of total delay	
Source of delay	NAS-wide	Three NY airports average
NAS traffic operation	28%	58%
Late arrival of aircraft	38%	24%
Airline operations related	29%	14%
Extreme weather	6%	4%
Security	0.2%	0.1%

provide meaningful information on the root causes of delays, as the source categories do not capture the real causes accurately. Second, the largest source of systemwide delay—late-arriving aircraft, representing 38% of the total delay sources—masks the original source of delay.

7.12 AIRPORT LANDSIDE CAPACITY

The terminal building has evolved over the years since the inception of the "airport" as a simple structure air travelers use to transfer between the ground and air modes. This evolution was dictated by three major factors: huge growth in passenger traffic, advancing aircraft technology, and the effort by both airlines and airport operators to constantly improve the quality of service offered to the flying public. Figure 7.13(a) illustrates the simple evolution of the airport terminal building from the basic simple terminal into four distinct terminal design concepts—linear, pier, satellite, and remote apron-transporter. With time, the airport terminal expanded and grew over three cycles or generations, as Figure 7.13(b) shows (33). Some of the third-generation design concepts closely resemble existing airports like Dallas-Fort Worth and Atlanta.

Today, terminals are multi-functional facilities of numerous structures and complexes designed to provide a wide range of amenities and services beyond its primary function: the airport terminal has become a "travel experience" and a "sense of place" (34). Functionally, the modern terminal is a complex operational system with a variety

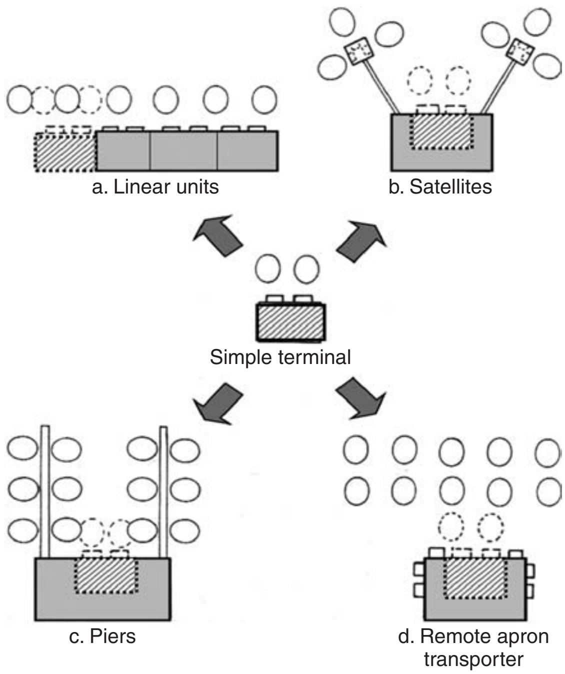


Figure 7.13(a) Expansion of the simple terminal into four concepts (33).

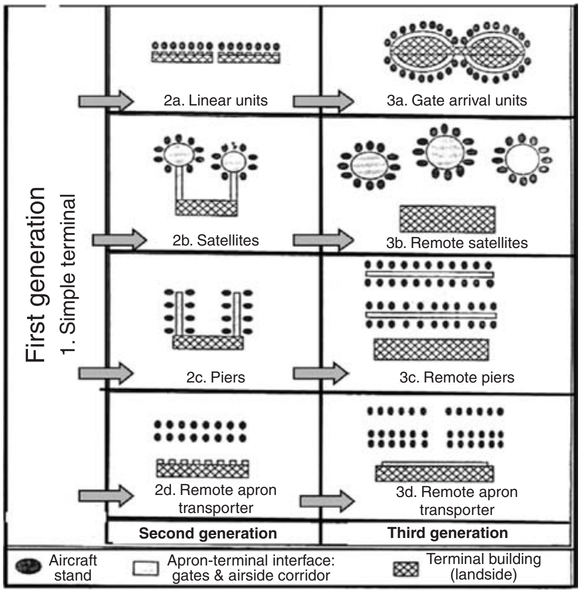


Figure 7.13(b) Evolution of terminals into three generations of design concepts (33).

of modern technologies ranging from integrated IT systems, to mechanical mobility-assisted devices, to an array of service systems within and outside the passenger terminal building. Today, the average modern large terminal resembles a small town and accounts for at least one-third of the financial investment to develop a major airport (34). Evolution of the terminal building has taught airport planners that the terminal can and will continue to grow to meet increased demand. However, there is a “glass ceiling” beyond which terminals cannot grow. While the limiting factor to expansion is infrastructure limitation, the concept of capacity and LOS is the primary criterion. Moreover, it is not the public space accessible to the passenger that will limit expansion, but it is the nonpublic operational space that supports the entire passenger and baggage processing operation, which could amount to 80% of the terminal gross space (34). Capacity therefore is the crucial element in this equation, on which the decision to expand the airport would largely depend. Typically, this decision relies on the results of the demand−capacity analysis for the particular facility, as demand is accommodated with the desired LOS.

Similar to what was discussed earlier for aircraft in airside capacity, when passenger demand in terminal facilities increases to high throughput rates sustained for certain periods of time, capacity is reached and congestion and delay rise sharply. Passenger arrival to the facility per unit time—or the arrival rate—defines the demand side of the processing equation. The processing rate of the processing facility defines the service rate per agent, reflecting the supply side of the equation. As the arrival rate exceeds the service rate for sustained periods, congestion, delay, and crowding increase, indicating the deterioration of quality of service.

While relationships and models exist that are applied to analyze and evaluate airside capacity, procedures for landside capacity assessment are not as clearly defined as those for airside. There are few generally accepted procedures and practices, mostly developed empirically to evaluate space requirements approaching capacity. The passenger terminal building is composed of many different facilities and spaces that perform dynamic and static functions, that is, processing, holding, or transit. These functions are designed to perform passenger facilitation processing required upon arrival and departure. The aggregate landside capacity is determined from the individual capacities of those facilities when they approach maximum attainable capability resulting in operation at low levels of service.

But what is *landside capacity* and what is the *level of service*?

Landside capacity is defined as the capability of the airport's landside facilities and services to collectively accommodate passengers, visitors, air cargo, ground access vehicles, and aircraft at predefined service conditions (35). Excluding air cargo, it is the passenger that plays a central role in defining landside capacity, as other elements of landside (e.g., visitors, ground access, and parking facilities) are all dictated by the needs and requirements of passenger activities within and outside the terminal building and the pattern of this demand.

Level of service (LOS) is defined as the combined qualitative and quantitative assessment of the service conditions and operating characteristics of a terminal facility or subsystem at a particular demand level that reflects the dynamic aspects of the ability of supply to meet the demand (36). The IATA defines it simply as the assessment of the ability of supply to meet demand (37) and adds that the dynamic nature of demand affects the LOS that passengers experience.

IATA LOS Framework

This dual expression of capacity–LOS was not very well understood by airport planners until the early 1980s when Transport Canada defined it in a way similar to the highway capacity context and the IATA adopted and established it as its qualitative and quantitative LOS framework. The IATA framework has two elements: a six-level framework for LOS describing quality of service for each level and assigning quantitative ranges of space and time and simple equations to approximate their nominal capacity. The IATA definition of LOS (37) is "a range of values representing assessment of the ability of supply to meet demand." The qualitative description of LOS is presented in Table 7.5, with a comparative description of service quality among the various systems and subsystems of the airport. To reflect the dynamic nature of demand upon a facility, a range of LOS measures from A through to F is used, similar to highway capacity standards. The evaluation criteria and actual standards for each subsystem are developed separately. The IATA recommends that level C should be taken as the minimum design objective, as it denotes good service at a reasonable cost (37).

The primary input to terminal facility design is facilitation of passenger processing. All passengers on international and domestic flights are required to pass through certain processing facilities at the airport to conduct certain necessary transactions mandated by law. These transactions and the facilitation procedures are required by the ICAO Annex 9 (38) as the globally accepted international facilitation standard. The functional components in the passenger terminal to perform facilitation and accommodate passenger flows through the building are basically three: processing, holding, and transit. The

Table 7.5a IATA LOS Framework (37)

LOS	Description		
	Flow	Delay	Comfort
A. Excellent	Free	None	Excellent
B. High	Stable	Very Few	High
C. Good	Stable	Acceptable	Good
D. Adequate	Unstable	Acceptable for short time	Adequate
E. Inadequate	Unstable	Unacceptable	Inadequate
F. Unacceptable	Total system breakdown	Unacceptable	

Table 7.5b IATA LOS Congestion Standards (37[a])

Sub-system	LOS standards (square meters per occupants)					
	A	..B. .	..C. .	..D. .	E ..	..F..
Check-in queue area	1.8	1.6	1.4	1.2	1.0	*Total*
Wait/circulate	2.7	2.3	1.9	1.5	1.0	*System*
Hold room	1.4	1.2	1.0	0.8	0.6	*Breakdown*
Bag claim area	2.0	1.8	1.6	1.4	1.2	
Government inspection	1.4	1.2	1.0	0.8	0.6	

[a] As stated in another IATA document: *Guidelines for Airport Capacity/Demand Management*, AACC/IATA, IATA, Geneva, 1981.

characteristics and performance of each are operationally distinct and therefore their capacity–LOS relationships are also different.

For many years the IATA method was used to estimate airport landside capacity, but it provided only gross estimates of capacity that are mostly static and deterministic in nature and not suitable for the highly dynamic and stochastic operation influenced by highly behavioral aspects of passenger flows and processing. Several tools have been developed over the years to conduct the demand–capacity evaluation and assess LOS.

During these years, airport planners were using peak-period planning terms taken as capacity measures to design facilities. These terms include the FAA's typical peak-hour passengers (TPHP), the British Airports Authority's standard busy rate (SBR), and the IATA's busy hour rate (BHR, which is the busiest hour of the second busiest day of the average week of the busy month). These capacity descriptors are mostly static, rigid and are invariably approximations that could not address the mostly dynamic, stochastic, constantly varying, and entirely behavioral nature of passenger demand and service processing at airports. They do not present any realistic or representative outcome of capacity and LOS that airport planners could use to improve on facility design. Needed was an approach that could accurately represent this dynamic and stochastic situation. The tool that was globally accepted and commonly adopted for landside demand–capacity analysis is landside simulation.

A Passenger-Responsive Approach (39)

One of the first methods to use simulation with a passenger-responsive approach to service in the demand–capacity analysis for airport terminal facilities is described elsewhere (39). This research noted the degree of subjectivity of current practices of planning and designing terminal facilities, where no design procedure exists to prescribe the capacity–LOS paradigm. The research also pointed out that the peak-period criteria of design are grossly simplistic and do not reflect the dynamics of passenger flows and processing, are erroneous when tested, focus mostly on broad aggregated averages, do not distinguish between critical peak and off-peak periods, and do not even recognize the importance of the LOS concept during planning and operation. This research effort devised a framework to develop the capacity–LOS relationship for airport landside facilities.

The proposed framework is comprised of a two-pronged approach to address the problem—one derives the "capacity curve" or "performance model" of facilities, and the other develops an LOS model to assess quality of facility operation based on direct passenger evaluation of service they actually perceived. The "capacity procedure" uses simulation techniques (e.g., SLAM simulation language) to develop the capacity curve, or the performance model, by incrementally increasing demand to at or beyond capacity to reflect the entire range of demand level and pattern. Simulation inputs were obtained through observations and airport surveys. The "LOS procedure" uses a unique LOS concept, the "perception–response model," to establish a three-tier LOS model. Based on data derived directly from passenger perception of service at individual facilities collected from passenger surveys and interviews at the airport. Figure 7.14 depicts the perception–response concept, indicating the two service measure thresholds T1 and T2 that mark the thresholds of the three-tier service levels. The fundamentals and application of landside simulation to build the performance model are described in Chapter 15.

The perception–response model is two dimensional and captures the relationship between the service measure and passenger response to service one measure at a time; that is, it is two dimensional. However, researchers believe that a correlation may exist between the two primary measures of service in terminals: space and time (40). Therefore, the perception–response LOS model shown in Figure 7.14 may likely describe a

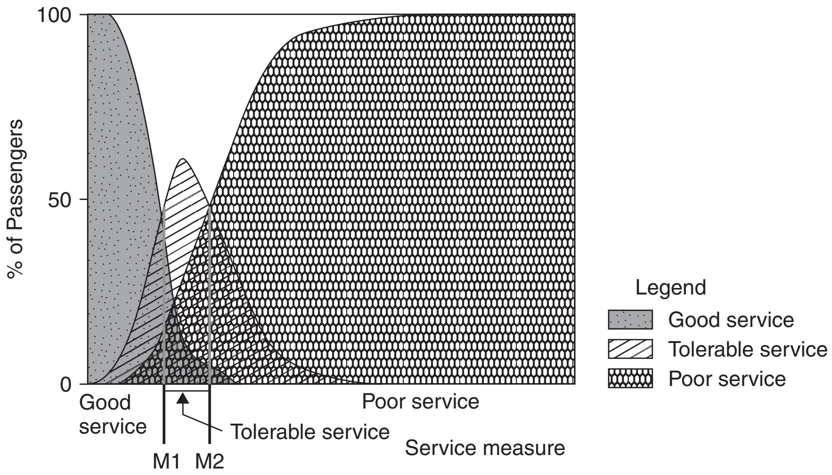


Figure 7.14 Perception–response model (39).

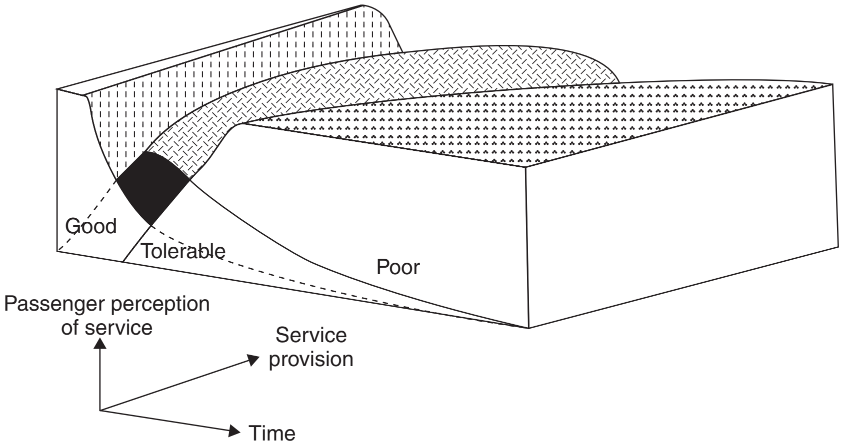


Figure 7.15 Three-dimensional perception–response model of time and space (40).

three-dimensional response surface with two independent variables—space provision and time spent in processing and holding facilities—as depicted in Figure 7.15.

Similar to the above perception–response three-tier concept, the IATA provides guidance on maximum queuing time in the terminal processing facilities. This queuing time standard augments the previous space standards indicated in Table 7.5b. Other references provide similar guidance on queuing time (35, 41). The IATA's maximum queuing guidelines are indicated in Table 7.6.

Functional Types of Landside Facilities

To understand the relationship that influences the capacity of landside facilities, description of the operational characteristics of these facilities and factors airport planners normally consider in designing them need to be well understood. As landside facilities and the entities using them are inherently different functionally, each would have a different set of capacity–LOS relationship.

Processing. The demand–capacity relationship of processing facilities generally follows the typical M/M/1queuing relationship (described earlier in this chapter). In evaluating the capacity of processing facilities in the terminal landside, the demand

Table 7.6 Maximum Queue Time LOS in Processing Facilities (37)

Processing facilities	Short to acceptable (min)[a]	Acceptable to long (min)
Check-in economy	0–12	12–30
Check-in business class	0–3	3–5
Passport control (arrival)	0–7	7–15
Passport control (departure)	0–5	5–10
Baggage claim	0–12	12–18
Security check	0–3	3–7

[a]When queue time = 0 min, there is no queue.

arrival rate and processing rate (as observed from processing time) are first defined, carefully measured, and used in the analysis as inputs.

Processing rate is defined as the number of entities (e.g., passengers, bags) processed by a single resource (e.g., metal detector, agent, X-ray machine) in a given unit of time (e.g., minutes and seconds). Processing rate can only be expressed from the perspective of a resource (36).

Processing time is defined as the duration of a transaction or other process for a particular entity and resource. Processing time can be expressed from the perspective of either the entity or the resource; these two times may or may not be equal. Average processing time is a summary statistic of the mean time required for all entities to be processed within a given time period. For processing rate analysis, *entities, resources,* and *processes* must be distinguished and clearly defined (36).

As stated earlier, measuring capacity is meaningless without reference to a LOS. In evaluating the capacity of a processing facility, a predefined LOS is established to monitor the performance of the facility and evaluate its capacity. A schematic representation of this relationship is depicted in Figure 7.16. In Figure 7.16(a), the building up of queues reflects the state where passenger arrival rate (or demand) exceeds the capability of the facility to serve arriving passengers (or capacity), and as shown in the shaded area, queues and delays increase. Important features of the typical facility capacity–demand and LOS relationship are as illustrated in Figure 7.16(b), where LOS indicators A, B, and C point to the status of the queue at different stages of operation (41).

Processing facilities of the terminal building are listed and described below. For each, factors influencing the operation and capacity–LOS demand relationship are indicated in their respective tables:.

1. *Passenger Baggage Check-in*. Operation of this processing facility to departing passengers is the start of the departure facilitation process in the terminal building. For international airports around the world, this facility may come after the passengers and their baggage are security screened at the entrance of the

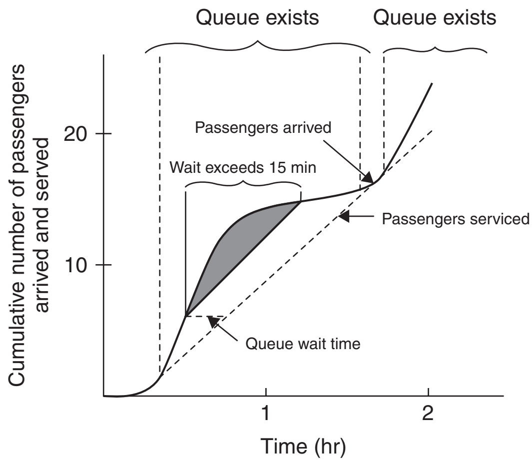


Figure 7.16(a) Demand–capacity relationship for processing facilities (41).

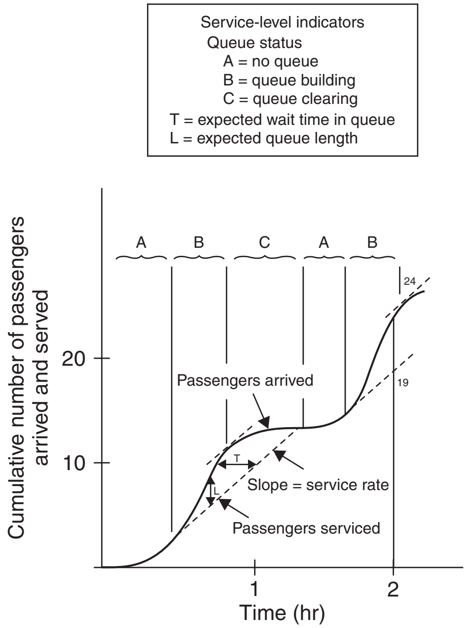


Figure 7.16(b) Graphical representation of capacity and level of service (41).

Table 7.7 Demand Factors Influencing Capacity–LOS of Passenger Check-in (41)

Factor	Description
Number and type of position	Average processing rates are a function of position type (baggage check only, ticket purchase, frequent or firstclass traveler, etc.)
Airline procedures and staffing	Number of positions manned and processing times
Passenger characteristics	Number preticketed or with boarding pass, amount of luggage, and distribution of arrival before scheduled departure influence demand loads, fraction of passengers by-passing check-in
Space and configuration	Available waiting area for queues approaching agent positions, banked or separate queues; conflict with circulation patterns
Flight type, schedule and load	Basic determinant of number of people arriving at this facility
Airline Lease agreement and airport management practices	Counter use policy, as formalized in lease agreements, similar to gate issues and options

terminal. Table 7.7 describes the operational and demand factors influencing the capacity–LOS of this facility.

The IATA *Airport Development Reference Manual* (37) focuses specifically on the area in front of the check-in counter as it is the first stop for departing passengers where they and their visitors assemble to check in their bags and be processed for flight. Therefore, a reasonably good LOS should be maintained, and this reflects on the design of space required for queuing and waiting. The IATA recommends using four different sets of space standards at check-in that includes use of carts and number of luggage per passenger, as indicated in Table 7.8. The IATA stresses other equally

Table 7.8 Check-in Queue Area LOS Standards (37)

	Level of service (space, in sq. meter/occupant)				
Service condition/space standards	A	B	C	D	E
1. Few carts and few passengers with check-in luggage (row width = 1.2 m)	1.7	1.4	1.2	1.1	0.9
2. Few carts and 1 or 2 pieces of luggage per passenger (row width = 1.2 m)	1.8	1.5	1.3	1.2	1.1
3. High percentage of passengers using carts (row width = 1.4 m)	2.3	1.9	1.7	1.6	1.5
4. Heavy flight load with 2 or more items per passenger and a high percentage of passengers using carts (row width = 1.4 m.)	2.6	2.3	2.0	1.9	1.8

important factors that may impact provision of service and influence capacity which airport planners should consider. These factors include passenger behavior patterns, cultural backgrounds, psychological considerations related to comfort and occupancy time, and passenger familiarity with airports and past experiences. Table 7.8 is part of Table 10.2 which sets the IATA LOS-based design standards discussed later in detail in Chapter 10, where the recommended dimension and space provision for specific facility plans is provided. The IATA also recommends a methodology to determine requirements for common-use check-in counters, as they are "*key facilities with huge footprint and significant impact on level of service*" (37).

In general terms, service standards for check-in processing follow industry standards set as part of the facilitation framework the airport and/or airlines adopt. Airlines normally assign facility check-in counters to serve the airline passenger classes (i.e., first, business, and economy) separately. Service rates for each class are expected to be different. Airlines also provide separate counters to serve other needs of passengers (i.e., baggage check in-only, ticket purchase, etc.) and the service rate for each is also different.

Passengers would queue for these facilities either separately and individually or as a pool of passenger queuing for a number of counters, which is used mostly for domestic flights at large airports. For the latter, the long winding queue of the pool is not an indication of capacity shortage. It is the average wait time per passenger in the queue that is the major criterion to assess the capacity–LOS relationship.

Distribution of passengers arriving to check in is the primary demand variable of the demand–capacity analysis. The distribution pattern is based on two factors: flight schedules and airport–airline directions to passengers for reporting prior to flight departure and the share of different airport access modes that passengers use. Airlines may use creative and effective service measures for passengers to bypass this facility entirely. These measures include online advance ticketing and seat assignment, curb or remote check-in, and automated check-in machines located in parts of the terminal more convenient to passengers (e.g., terminal entrance, airport train station, or car parking).

Average processing time (or passenger contact time per agent) at ticket counters varies widely. For demand–capacity analysis, surveys are normally conducted to provide accurate measurement of service times and their true distribution. The Transportation Research Board (TRB) (35) published a manual providing guidance to airport planners and operators in this field.

2. *Passenger Security Screening*. This facility is located before or after passenger check-in or at the entrance of the airside concourse, depending on the airport's facilitation and processing procedure. Timing of passengers' arrival demand for flight departure as per flight schedule determines the basic demand profile on the security screening facility. Operational characteristics and demand factors influencing capacity and LOS assessment are described in Table 7.9. As depicted in Figure 7.15(b), when passengers arrive at the security screening facility at rates exceeding its service rate, queues form and passenger wait and delay escalate. Delays associated with waiting queues are indicative of capacity shortage and form the principal measure of LOS.

The IATA (38) recommends that to ensure overall capacity balance, the centralized security check must be designed to process check-in maximum throughput. The design of this facility entails the following steps:

A. Calculate the peak 10-min check-in counters throughput (A) based on the check-in observed processing rate; that is,

$$A = B \times (600/C) + D \qquad (7.26)$$

where

A = peak 10-min demand
B = number of economy class check-in servers assuming common-use
C = average processing time at check-in (seconds)
D = percent of business class passengers

B. Calculate the number of security check units (E); that is,

$$E = A \times (F/600) \qquad (7.27)$$

where

E = number of security check units
F = average processing time at security check

Table 7.9 Demand Factors Influencing Capacity–LOS of Passenger Security Screening (41)

Factor	Description
Number of channels, space, and personnel	Influences number of passengers processed per unit time (magnetometer and X ray considered separately)
Type, equipment sensitivity, and airport/airline/agency policy and practice	Determine average service time per passenger and likelihood of close inspection
Passenger characteristics	Hand luggage, mobility, and patterns of arrival influence average service time as well as number of passengers
Building layout and passenger circulation patterns	Interference among pedestrian flows can influence flow rates and create congestion
Flight schedule and load	Basic determinants of number and direction of people in concourse

C. Calculate the maximum number of passenger queuing (Q_{max}); that is,

$$Q_{max} = (G \times H \times 60)/F \tag{7.28}$$

where

G = maximum queuing time in minutes
H = number of security check units

3. *Government Customs, Immigration, and Passport Control*. Passengers on international flights have to undergo government inspection in customs and passport/immigration control. In the United States, departing passengers do not pass through these facilities. Elsewhere, all departing international passengers are required to undergo passport control prior to proceeding to departure and gate lounges, as per ICAO facilitation standards. All arriving passengers (including in the United States) have to undergo immigration/passport inspection, customs, and at times medical and agricultural controls. The passenger arrival demand pattern and distribution to these facilities are primarily dictated by the arrival and departure flight schedules. For arriving passengers, passport/immigration is the first stop of passenger processing, after which passengers proceed to baggage claim and customs.

When two processing facilities are close-in-series and back-to-back, the differential processing (service) rates basically define the facilities' capacity–LOS status. It is therefore important that total capacity of both facilities (i.e., service rate per channel times number of channels) is matched; otherwise disparity results in excessive queuing and congestion. This was indicated in previous research (37) where one facility (security) manifested serious congestion with excessive delay, while the downstream facility (passports) exhibited no congestion. Operational and demand factors influencing capacity–LOS and operations of government inspection services are described in Table 7.10.

The IATA (37) recommends that the approach of peak 10-min demand similar to that used for security checks discussed above be used for these facilities to ensure proper capacity balance. In general, for queuing space required for outbound and inbound

Table 7.10 Demand Factors Influencing Capacity–LOS of Government Customs and Passport Control (41)

Factor	Description
Number of channels, space, and personnel	Inspector channels, U.S. citizen pass-through positions in immigration and passports, "red-green" channels use in customs
Inspector	Average processing time per passengers, efficiency rate of selection for close inspection policy
Passenger characteristics	Fraction of U.S. citizens, flight origin, citizenship of foreign nationals, baggage loads
Space configuration	Available queue space, access to and configuration of baggage display, use of carts
Flight schedule and load	Basic determinant of number of people arriving at this facility

passport control, the IATA recommends using 1.5 m^2 per passenger waiting to be served, with sufficient separation between start of queue and the desk.

The IATA specifies that for LOS the passport control space is as follows (37):

Level of service	A	B	C	D	E
Passport control area (m^2)	1.4	1.2	1.0	0.8	0.6

4. *Baggage Claim*. Terminating passengers end their arrival processing when they reclaim their checked baggage. The operational characteristics of this processing facility are more complex than other terminal facilities. Therefore the demand-capacity model would be more difficult to understand and to establish. Typically, this process involves several variables outside the airport planner's control, mainly related to airline baggage handling procedures and the airport and airline policies and operation characteristics on baggage facilitation. The principal demand and operating factors influencing the capacity–LOS of the baggage claim facility are described in Table 7.11.

This facility is where the two separate flows of passengers and baggage originating at the landed plane docked at the gate-stand converge, which adds to the complexity of the demand–capacity analysis. Passengers may have finished their arrival processing and wait to collect their baggage at this facility, or the baggage may have already been delivered to this facility awaiting pick-up by passengers. The arrival and service distributions are not as simple and straightforward to evaluate and use in the demand–capacity analysis.

Operationally, passengers typically form "layered queues" along the baggage claim device during peak periods to reclaim their baggage. Therefore, capacity and service standards have to consider two elements of the analysis: average time passengers must wait to pick up their baggage and the space (in terms of area of baggage claim hall and length of the belt available to the passenger) that passengers need to reclaim bags and leave the facility. Several industry, planning, and operating standards have been used to assess the capacity–LOS of this facility (34, 37, 42)

Table 7.11 Demand Factors Influencing Capacity–LOS of Baggage Claim (Reference 41)

Factor	Description
Equipment configuration and claim area	Type, layout, feed mechanism, and rate of baggage display; space available for waiting passengers; relation of wait area to display frontage; access to and amount of feed belt available
Staffing practices	Availability of porters and inspection of baggage at exit from claim area influence rates of exit; rate of baggage loading/unloading from cart to feed belt
Baggage load	Number of bags per passenger, fraction of passengers with baggage, time of baggage arrival from aircraft
Passenger characteristics	Rate of arrival from gate, ability to handle luggage, use of carts, number of visitors

The IATA previously recommended the following space provision for the retrieval and peripheral area of the baggage claim device (in square meters per occupant)*:

Level of service	A	B	C	D	E
Baggage claim space	2.0	1.8	1.6	1.4	1.4

In the ninth edition of the *Airport Development Reference Manual* (37), the IATA now assumes that 40% of passengers use carts in baggage claim, and thus a wider LOS range would be required. The IATA therefore recommends the following space provision for the retrieval and peripheral area of the baggage claim device (in square meters per occupant):

Level of service	A	B	C	D	E
Baggage claim space	2.6	2.0	1.7	1.3	1.0

In order to estimate the number of baggage claim units to provide adequate service, the IATA (37) recommends the following approach:

Wide-body aircraft:

$$\text{BC} = (\text{PHP} \ \times \text{PWB} \times \text{CDW})/(60 \times \text{NWB}) \tag{7.29}$$

Narrow-body aircraft:

$$\text{BC} = (\text{PHP} \ \times \text{PWB} \times \text{CDW})/(60 \times \text{NWB}) \tag{7.30}$$

where

PHP = peak-hour number of terminating passengers, international/domestic transfer passengers
PWB = proportion of passengers arriving by wide-body aircraft
PNB = proportion of passengers arriving by narrow-body aircraft
CDW = average claim device occupancy time per wide-body aircraft (in minutes), or assume 45 min
CDN = average claim device occupancy time per narrow-body aircraft (in minutes), or assume 20 min
NWB = number of passengers per wide-body aircraft at 80% load factor, or assume 320 passengers
NNB = number of passengers per narrow-body aircraft at 80% load factor, or assume 100 passengers

Holding/Waiting Facilities

The primary facilities under this category are the departure and gate lounges. Table 7.12 provides a summary of the operational and demand factors influencing the demand−capacity analysis and the LOS assessment. Major parameters for facility

*Stated only in the 8th edition of the IATA *Airport Development Reference Manual* (37).

Table 7.12 Demand Factors Influencing Capacity–LOS of Departure/Gate Lounges (41)

Factor	Description
Waiting and circulation area (lounge and accessible corridor)	Space available for people to move around and wait for departing flights; terminal configuration; shared or exclusive use of waiting area (shared by passengers on several departing flights or restricted to single gate)
Seating and waiting area geometry	Seated people may occupy more space but are accommodated at higher service levels
Flight schedule, aircraft type, passenger load, and gate utilization	Larger aircraft typically mean higher passenger loads; areas used jointly to serve simultaneous departures
Passenger boarding method	Availability and type of jet-ways, stairs, and doors from terminal to aircraft; rates at which passengers board aircraft; airline passenger handling procedures
Passenger behavioral characteristics and airline service characteristics	Passenger arrival to gates prior to scheduled time of departure; amount of carry-on baggage; passenger knowledge of and familiarity with system; percentage of special needs passengers (families with children, elderly, handicapped, first-class and business travelers); airline passenger service policy, seat assignment, and boarding pass practices

design and the evaluation of capacity–LOS include departure flight schedule, aircraft size per flight and assigned gate, average space available per passenger, seating capacity, and behavioral aspects that may influence utilization of space.

Another important factor for departure lounge lobbies is the average percent of connecting passengers, as this impacts the number of departing passengers occupying departure lounges and gates. Total passengers (both connecting and originating) have to spend a certain amount of time within this area and hold and wait until aircraft boarding. The general planning and design requirements for this type of facility generally follow architectural and interior space planning and design practices.

The IATA (37) recommends that for hold room and waiting areas (e.g., departure and gate lounges), a distinction should be made between areas for standing or seating of passengers. 1.7 m^2 per person is provided in facilities with seated passengers, and for standing passengers 1.2 m^2 per person is provided. The LOS is defined in terms of percent of space occupied. In general, the occupancy rate for LOS determination is:

Level of service	A	B	C	D	E
Maximum occupancy rate	40%	50%	65%	80%	95%

The IATA previously recommended the following space provision for the holding areas (in meters squared per occupant)*:

Level of service	A	B	C	D	E
Holding area space	1.4	1.2	1.0	0.8	0.6

According to the IATA (37), space at the hold room/waiting areas is based on passenger load and percentage of passengers seated and standing. A simple approach

*Stated only in the eight edition of the IATA *Airport Development Reference Manual* (37).

is to use aircraft capacity to estimate space for a gate lounge:

$$\text{Required gate hold space} = (80\% \text{ aircraftcapacity} \times 80\% \text{ seated pax} \times 1.7) + (80\% \text{ aircraft capacity} \times 20\% \text{ standing pax} \times 1.2)$$

For the airport arrival hall (lobby) where arriving passengers meet greeters (excluding concessions), the IATA recommends the following (37):

$$\text{Area} = \text{SPP} \times (\text{AOP} \times \text{PHP})/60 + [\text{SPP} \times (\text{AOV} \times \text{PHP} \times \text{VPP})/60] \quad (7.31)$$

where

PHP = peak-hour number of terminating passengers
AOP = average occupancy time per passenger (in minutes), or assume 5 min
AOV = average occupancy time per visitor (in minutes), or assume 30 min
SPP = space required per person (m^2) for LOS, or assume 2.0 m^2
VPP = number of visitors per passenger

Terminal Transit/Circulation Facilities

Capacity–LOS assessment for this type of facility in the terminal building is more related to average space per person available (width of corridors), length of passenger walk between facilities, provision and capacity of mechanical assistance mobility both horizontal and vertical, and the effective application of way-finding concepts.

Typical free-flow distribution of passenger walking speeds as well as processing facility output forming the passenger flow distribution through these facilities are important factors to include. In certain locations, circulation space is deliberately diffused with other space to increase contact exposure of passengers to amenities such as duty-free shops, restaurants, news stands, and toilets. Table 7.13 describes the demand factors influencing the capacity–LOS of the terminal circulation facilities.

The IATA recommends the following LOS standards for the circulation facilities and passageways at the terminal (37):

Circulation facility	Level of service standards					
	A	B	C	D	E	F
Corridor	**10.0**	**12.5**	**20.0**	**28.0**	**37.0**	> **38**
Stairs	**8.0**	**10.0**	**12.5**	**20.0**	**20.0**	> **20**

Table 7.13 Demand Factors Influencing Capacity–LOS of Terminal Circulation Areas (41)

Factor	Description
Terminal configuration	Space available for people to move freely without conflict of flows; availability of alternative paths; placement of seating, commercial activities, stairs, escalators
Passenger characteristics	Amount of hand luggage; mobility, rate of passenger arrival before scheduled time of flight departure; passenger demand load
Flight schedule, passenger load	Basic determinant of number and direction of people moving on concourse

The IATA recommends the following space provisions for the "wait and circulate" facilities according to location and availability of carts and speeds for the definition of LOS (37):

Location	Cart availability	Space available (m^2 per occupant)	Speed (m/sec)
Airside	None	1.5	1.3
After check-in	Few	1.8	1.1
Departure lounge	High availability	2.3	0.9

Terminal Curb Frontage

Terminal curb frontage is a special type of terminal facility that essentially processes passengers and visitors arriving in ground transport vehicles to enter the terminal, and vice versa. This facility has special requirements for demand–capacity analysis that is mostly related to these vehicles, not the persons entering and leaving the terminal. The primary determinant for curb frontage length required is dwell time, the length of time it takes for loading and unloading of passengers (41). The demand and operating factors influencing capacity–LOS are described in Table 7.14.

The two most important variables in the capacity determination of curb frontage are curb vehicle dwell time and the availability of terminal curb contact length. Vehicle dwell time depends largely on type of vehicle, persons in the vehicle, and baggage loads of passengers, but it varies with airport policies on terminal curbside management (41). Airport operators can influence curb frontage operation primarily through traffic management, development and enforcement of regulations on access to and use of terminal curbside, and minor modifications of the basic design of the terminal curb frontage.

The unique function of this facility implies a different capacity–LOS relationship vis-à-vis demand. This facility is unique in that it has an intermodal function where passengers interface between walking mode and ground vehicle mode. Therefore, the LOS framework established by the IATA (Table 7.5) does not truly apply for terminal curb frontage. In this aspect, this facility is closer to the highway capacity–LOS

Table 7.14 Demand Factors Influencing Capacity–LOS of Terminal Curb Frontage (41)

Factor	Description
Available frontage	Length of curb frontage modified by presence of obstructions and assigned uses (e.g., airport limousines only, taxi only); separation of departure and arrival curbs
Frontage roads and pedestrian paths	Number of traffic lanes feeding into and from frontage area; pedestrian crossing vehicle traffic lanes
Management policy	Stopping and dwell regulations, enforcement practices; commercial access control; public transport dispatching
Passenger characteristics and motor vehicle fleet mix	Passenger choices of ground transport mode; average occupancy of vehicles; dwell times at curb frontage; passenger patterns of arrival before scheduled flight departure; baggage loads
Flight schedule	Basic determinant of number of people arriving and departing at given time in a given area

framework that the IATA's airport landside framework, as directly applied for airport ground access. There have been efforts to devise a capacity–LOS concept for curb frontage. One relates vehicle traffic volumes at the curb and service levels to available curb length appropriately corrected for specific operational and physical characteristics of the airport (43). This approach is adapted from the LOS framework of the *Highway Capacity Manual* (44).

In this approach, service for different demand levels (traffic volumes that need to use the curb) is related to available curb length adjusted for specific operational and physical characteristics of the airport terminal. Expressed in terms of effective curb utilization, the LOS reflects drivers' ability to find and occupy a vacant curb space for short times, or otherwise have to double park, to load and unload passengers.

This effort pointed out that the probability that drivers can find an empty curb space or have to double park is typically used to describe the different levels of service. Figure 7.17 depicts the curb frontage capacity curves indicating peak-hour passenger arrival/departure demand with the corresponding LOS (from A to E), and the resulting curb lengths. Other parameters such as general traffic congestion and police enforcement may also be used as indicators of this probability (41). Also noted is that the capacity of the terminal curb lane is distinct from the capacity of the travel lanes adjacent to it. Travel lanes are part of the airport ground access discussed below.

Airport Parking

Airport parking facilities consist of surface and multilevel parking for short-term, long-term, and remote parking, where location and parking fees of each are different:

- Short-term parking is located closer to the terminal building and serves motorists dropping off or picking up travelers. Normally, passengers remain less than 3 hr, and it is has the highest parking fees.

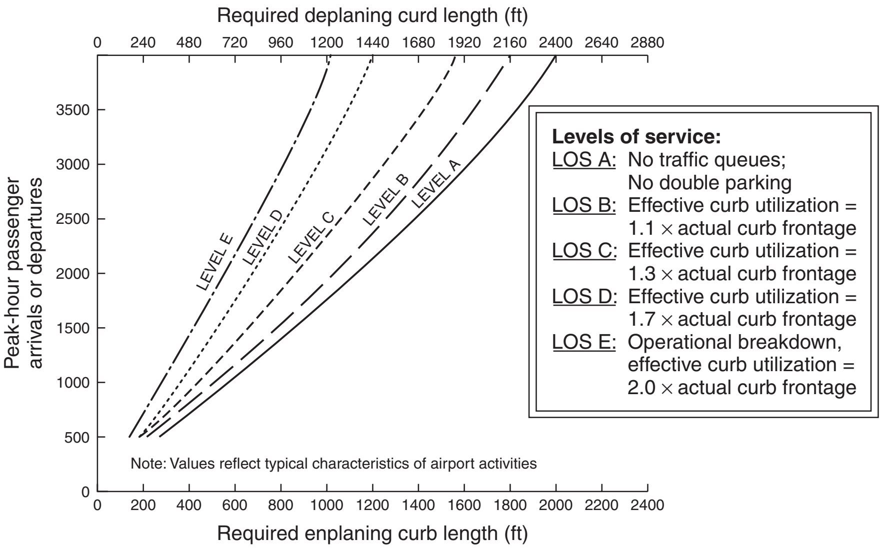


Figure 7.17 Capacity–LOS of terminal curbside frontage (43).

- Long-term parking serves passengers who leave their cars at the airport while traveling, and it accounts for the majority of parking spaces at airports.
- Remote parking is long-term parking located farthest from the terminal building, where the airport provides shuttle buses or people movers to transport passenger to/from the terminal. Parking rates for this facility are the lowest, and passengers usually leave their cars here for several days.

Factors that influence the capacity–LOS of the airport parking operation for access (flight enplaning) and egress (flight deplaning) are indicated and described in Table 7.15. These factors include flight characteristics and passenger loading; available space and proximity to the terminal; total access time for both directions; passenger characteristics related to the airport trip mode; and parking pricing.

In general, the pattern of parking demand is characterized by the accumulation of vehicles parked in certain parking facilities that is measured by both the length of time the vehicle is parked and the number of parking spaces occupied. This demand is directly influenced by passenger arrival times at the airport, passenger type, and purpose of trip. Parking demand is particularly sensitive to cost of parking and it is dependent on passenger type and trip purpose, as the behavior of business travelers vis-à-vis parking is different from vacation and leisure travelers (41). Effective parking capacity can therefore be managed by altering parking pricing for the different types of airport parking facilities and their location.

Parking space needs are determined primarily by long-term parking demand, as it has the highest level of space-hours, while short-term parking has higher turnover rates and would therefore has higher entry/exit movement counts. For capacity–LOS determination, usually required parking capacity to provide adequate service would normally be greater than total parking demand (41). A balance between providing short- and long-term parking is critical to capacity estimation and is influenced by

Table 7.15 Demand Factors Influencing Capacity–LOS of Airport Parking (41)

Factor	Description
Access (Enplaning) 1. Available space	A function of distance from terminal area; systems for reaching terminal; parking pricing structure; and availability of weather-protected waiting and walking areas
2. Access times	Total time, including search for space; wait; and travel from remote locations
3. Passenger characteristics	Percentage of people driving to airport; automobile occupancy; visitor–passenger ratio; length of stay in terminal
4. Pricing structure	Have to be well designed as higher fees may suppress demand or divert some to lower cost lots
5. Flight schedule	Basic determinant of people arriving at parking areas
Egress (Deplaning) 1. Access time	Total time, including search for space; wait; and travel from remote locations
2. Passenger characteristics	Percentage of people driving to airport; automobile occupancy; length of stay in terminal
3. Exit position and employee efficiency	Number and direction to exits; service times to exit
4. Flight schedule and load	Basic determinant of people arriving at parking areas

factors related to passenger characteristics (business vs. leisure), parking fees, and effective distance (and time) to get to the terminal.

According to the FAA, airport parking demand is most meaningful when based on originating passengers only as transfer passengers do not even leave the terminal building. Using mathematical modeling to develop a demand–capacity relationship, airport parking accumulation (capacity) curves were developed based on mathematical modeling using accurate observations of auto parking operation conducted in several U.S. airports, as depicted in Figure 7.18.

Airport Ground Access

Highway access to the airport terminal is through several airport ground access modes (e.g., rail, light rail, bus, and automobile), but highways and roads are the primary access facilities, and the automobile is the principal access mode. Beyond picking up and dropping off of passengers and their visitors, airport access is also used by airport employees, air cargo companies, express package and shipping, airport-aircraft service companies, concessionaires, and other airport service, maintenance, and supply requirements.

The principal demand and operating factors influencing capacity and LOS for ground access are summarized in Table 7.16. These factors focus only on the assessment of service provided between the terminal curbside or parking area and the interchange linking the airport with the regional transportation network.

Airport access demand is primarily determined by the travel modes passengers and visitors select as well as other members of the airport population and businesses. For passengers and visitors, ground access is driven primarily by the airline flight schedule, arrivals and departures simultaneously. Airport ground access is unrelated to intra-airport transport, whereby ground movement (whether on roads, people movers,

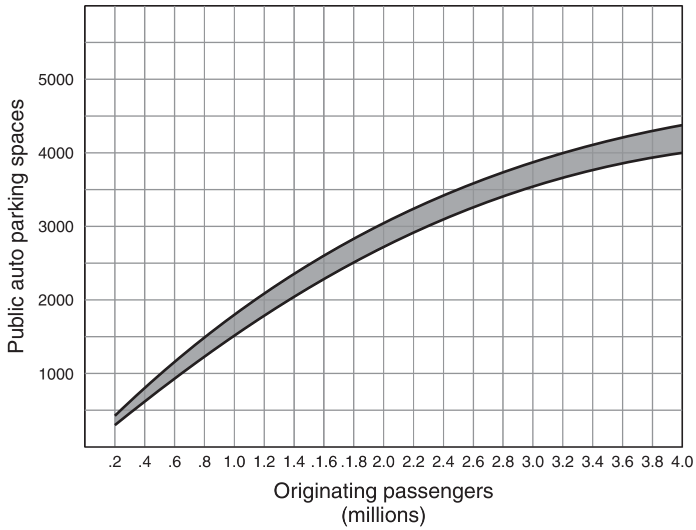


Figure 7.18 Capacity curve for airport public auto parking space requirements (42).

Table 7.16 Factors Influencing Capacity–LOS of Airport Ground Access (41)

Factor	Description
Available modes and prices	Connection from various parts of the metropolitan area served, considering prices, comfort, and convenience, particularly with respect to baggage and required vehicle changes
Access times	Total time, including wait for vehicles or access and travel from representative locations
Passenger characteristics	Fraction choosing each travel mode, vehicle occupancy, number of people accompanying passenger, other visitors, baggage loads, share of origin/destination passengers
Vehicle operator behavior	Fraction going directly to curb or to parking, weaving, curb dwell time, knowledge of traffic pattern
Flight schedule and load	Basic determinant of capacity, referring to the number of people using ground access modes and facilities
Facilities and background traffic conditions	Highway and transit routes, interchanges; levels of traffic on facility heading for destinations other than airport; availability of alternative check-in options including remote facilities

or buses) takes place for individuals and loads to travel between different on-airport locations. Important factors influencing demand for airport ground access include extent of provision and availability of public transport system, passenger trip purpose, availability of airport parking and cost, type of flight, and availability of alternatives for check-in (41).

Assessment of capacity and LOS for highways and roadways directly follows those of the *Highway Capacity Manual** (45), where a six-LOS framework is used. These levels of service are:

A. *Excellent*. Free-flow conditions where traffic operates at free-flow speeds. Individual users are virtually unaffected by the presence of others in the traffic stream. Freedom to select desired speeds and to maneuver within the traffic stream is extremely high. The general level of comfort and convenience provided to drivers is excellent.
B. *Very Good*. Reasonably free flow conditions that allow speeds at or near free-flow speeds, but the presence of other users in the traffic stream begins to be noticeable. Freedom to select desired speeds is relatively unaffected, but there is a slight decline in the freedom to maneuver within the traffic stream.
C. *Good*. Flow with speeds at or near free-flow speeds, but the freedom to maneuver is noticeably restricted (lane changes require careful attention on the part of drivers). The general level of comfort and convenience declines significantly at this level. Disruptions in the traffic stream can result in significant queue formation and vehicular delay.

*The *TRB Highway Capacity Manual* was first published in 1950, with progressively expanding updates: 2nd edition (1965), 3rd edition (1985, 1994, and 2000), and a metric edition in 2010. It was the first document to quantify the concept of capacity and service for transportation facilities and has become the standard reference on capacity and LOS procedures, relied on by transportation analysts around the world.

D. *Fair*. Flow conditions with speeds begin to decline slightly with increasing flow. The freedom to maneuver becomes more restricted and drivers experience reductions in physical and psychological comfort. Incidents can generate lengthy queues as higher density associated with this LOS provides little space to absorb disruption in the traffic flow.

E. *Poor*. Operating conditions at or near the roadway's capacity. Vehicles are closely spaced within traffic stream. Even minor disruptions to the traffic stream can cause delays as other vehicles give way to allow such maneuvers. Maneuverability is extremely limited and drivers experience considerable physical and psychological discomfort.

F. *System Breakdown*. Breakdown in vehicular flow, where queues form quickly behind points in the roadway where the arrival flow rate temporarily exceeds the departure rate determined by the roadway capacity. Vehicles typically operate at low speeds in these conditions and are often required to come to a complete stop, usually in a cyclic formation, and dissipation of queues is a key characterization of this LOS.

Adaptation of the capacity and LOS from the *Highway Capacity Manual* (44) is entirely adequate for average hourly volumes of service roadways. Demand analysis (for subsequent demand–capacity evaluation) on a typical airport access system is conducted by estimating (separately, through a different process) vehicle trips on each link associated with arriving/departing passengers/visitors, airport employees, airport service vehicles, taxi cabs (empty and full), limousines (empty and full), public transport vehicles, and air cargo trucks and combining these vehicular volumes on roads that each will actually use. This exercise should be conducted per period (1-hr or 15-min intervals) for regional traffic, as well as the airport traffic components, each conforming to its daily peaking pattern. These volumes are then compared against hourly volumes under the designated LOS to determine what LOS the airport access facilities are operating under. Again, for more details on these calculations, the reader is referenced to the *Highway Capacity Manual* (44).

The FAA and Federal Highway Administration published a guidance document for planning intermodal ground access to airports that uses the capacity–LOS of airport ground access facilities as a performance indicator for airport and transportation planners to assess operation and plan improvements and expansion when and where required (45). For example, average hourly volume [expressed as passenger car equivalent (PCE) vehicles per hour per lane] operating under LOS C/D is used for highway design and capacity assessment of the following facilities (41):

Roadway facility	Average hourly volume, (PCE/hr/lane)
Main-access and feeder freeways with controlled access and no signalization	1000–1600
Ramp to and from main-access freeways, single lane	900–1200
Principal network arterial with two-way traffic, some cross streets	900–1600
Main access road with signalized intersection	700–1000
Service road	600–1200

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8

Airside Configuration and Geometric Design of the Airside

8.1 INTRODUCTION

This chapter provides the airport designer with the fundamental principles of the geometric design of the airfield and the specific design standards and procedures required for the preparation of plans and specifications for the airport airside. The process to follow and topics to be covered include the following:

- Airfield configuration
- Runway orientation
- Runway length
- Taxiway system
- Longitudinal-grade design for runways and taxiways
- Geometric design of the runway and taxiway system.
- Design of obstruction-free surfaces

The design criteria presented here have been derived from the ICAO and the U.S. FAA. There is some variation in the rigidity of these criteria. Unless otherwise indicated, the ICAO criteria are *recommended practices*, as distinguished from compulsory standards. The ICAO Annexes are designated Standards and Recommended Practices. Standards include the word “shall”; for Recommended Practices it is “should”. Similarly, the FAA criteria are recommended standards rather than absolute requirements.

In some cases, because of local conditions, designers may find it necessary to deviate from a particular standard. Any decision to deviate from a particular standard should be discussed with the Licensing Authority and dispensation obtained before proceeding to final designs.

Chapter 1 describes how airports are grouped into classes according to the type of air service provided. Clearly, the design requirements for a given airport must reflect the numbers, types, and operating characteristics of the aircraft to be served.

The FAA (1–3) provides design criteria for six groups of transport airports, four classes of general aviation airports, and special criteria for heliports and short take off and landing (STOL) ports. Aircraft are grouped according to approach speed and wingspan width. Section 8.9 describes the FAA’s airplane design group concept.

The ICAO (4, 5) relates the recommended runway dimensions and clearances to an “airport reference code.” This code takes into account key lateral dimensions of the critical aircraft as well as the runway length requirements of the critical aircraft for sea-level and standard atmospheric conditions. Later in this chapter, the ICAO airport reference code is further described.

The primary determinants of airport geometric design are the overall layout and geometric characteristics of the airfield. Airfield configuration is the general arrangement of the various parts or components of the airport airside system.

8.2 PRINCIPLES OF AIRPORT LAYOUT

The layout of an airport must be suitable for the shape and acreage of available land, but most importantly it must satisfy fully the operational requirements of aircraft for landing and takeoff. The airfield, or runway–taxiway system, must contain enough runways to meet air traffic demand and be properly aligned with the optimum flow of aircraft, and the runways must have adequate separation to ensure safe air traffic movements. Runways must be oriented to take advantage of prevailing winds and should be directed away from fixed air navigation hazards. An airport layout should include suitable parking areas for aircraft and various airport ground service vehicles as well as space for freight processing and baggage handling and storage and for aircraft maintenance and service.

Therefore, airport configuration should facilitate safe and expeditious movements of aircraft and ground service vehicles. The following sections contain the process and information the airport designer needs to carry out the geometric design of the airfield.

8.3 AIRFIELD CONFIGURATION

A wide variety of runway configurations exist; however, most runway systems are arranged according to some combination of four basic configurations: (a) single runways, (b) parallel runways, (c) open-V runways, and (d) intersecting runways. Table 7.3 in the previous chapter depicts examples of these runway configurations (6, 7).

In determining the proper configuration for the airfield, the airport designer has to consider the following aspects: resultant capacity of the runway group layout, spatial relation between the airfield vis-à-vis the terminal area, and geometric features to enhance operation and increase resultant capacity.

Airfield Capacity Considerations

Since the primary determinant of airfield design is the resultant capacity of the runway group layout, the principals of runway capacity discussed in Chapter 7 would provide the input to the process. Table 7.3 provides the hourly capacity (VFR and IFR) and annual service volume (ASV) for common runway configurations and for different aircraft mix. The simplest runway configuration is a single runway system, illustrated as configuration A. Although capacity varies widely with aircraft mix, as described previously, the hourly capacity is 51–98 operations per hour under VFR conditions and 50–59 operations per hour under IFR conditions (7).

Since only one aircraft may occupy a runway at any time, it is frequently necessary for a departing airplane to wait for a landing airplane to clear the runway before beginning the takeoff maneuver. Significant increases in capacity could be utilized if departing airplanes were permitted to enter the runway by way of an acceleration ramp during the arrival rollout. However, such a procedure is not considered to be safe. A similar scheme has been recommended that would utilize a *dual-lane* runway, consisting of two parallel runways spaced at least 700 ft between centerlines. Such a scheme, shown as configuration B, would increase capacity without introducing undue hazard. But the resultant capacity of both runways is less than that of two parallel *independent* runways.

The attractiveness of the dual-lane approach stems from the fact that an over 50% increase in (saturation) capacity might be achieved without going to the construction of a fully separated independent parallel runway. In situations where land costs are very high (as at many major "landlocked" hub airports) or land is simply unavailable, there could be savings in land from an increase in capacity with a high benefit–cost ratio for the "dual-lane," or dependent, parallel configuration (8).

The dual-lane configuration would operate in the following way. One runway would have high-speed exits and would be used for arrivals. The other runway would then be used for departures, which would be released as arrivals touched down. Departing airplanes would taxi across the end of the arrival runway in groups interspersed between arrivals. For arrival rates greater than 60/hr, it would probably be necessary for controllers to open an arrival gap periodically to allow departing aircraft to taxi across. To achieve maximum-capacity capability, the FAA has suggested a minimum centerline spacing of 1000 ft for dual-lane runways (1).

Configuration B is an "IFR-dependent" configuration; that is, under IFRs, an operation on one runway is dependent on the operation on the other runway. In effect, simultaneous operations are permitted under VFR conditions, but not under IFR conditions. Therefore, this layout provides nearly twice the capacity of a single runway under VFR conditions but only a slight improvement over a single runway under IFR conditions.

In configuration C, a spacing of 4300 ft between runway centerlines would provide an independent IFR simultaneous approach capability. With this layout, simultaneous precision instrument approaches are permitted, and the resultant capacity is the total for two single runways.

A common approach to increasing airport capacity is to provide one or more additional parallel runways. The effect of an additional runway on capacity depends on the runway spacing, weather conditions (VFR or IFR), runway use, and type of air traffic control system. More detailed information on the required separation of parallel runways is discussed below.

Frequently, a second runway is added in a different direction to take advantage of a wider range of wind directions. The runways may or may not intersect. Configuration D illustrates dual parallel runways with an intersecting crosswind runway. An example of the nonintersecting configuration termed "open V" is shown as configuration F. Parallel runways plus a crosswind runway are illustrated as configuration G.

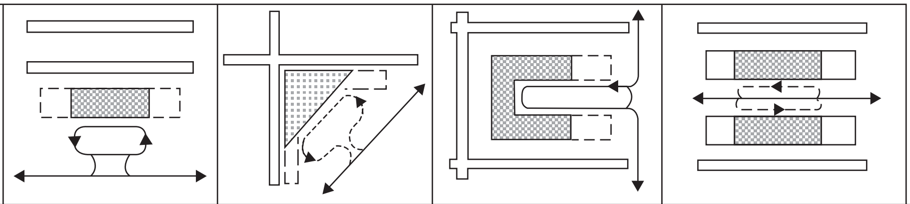
In considering the optimum runway configuration for the airport, the capacities of open-V and intersecting runway configurations depend to a great extent on the direction of operations as dictated by wind direction and speed. Both runways can be used simultaneously when winds are light. In conditions of high winds and poor visibility, these configurations operate as single-runway systems, and there is incremental increase in total runway capacity.

Large airports may require three or more runways to accommodate demand. The configuration that has been proven to provide higher resultant capacity and is more efficient operationally is the multiple-parallel-runway system. But this largely depends on the minimum centerline spacing required for safety, the prevailing wind directions, the topographic features of the airport site, the shape and amount of available space, and the space requirements for aprons, the terminal, and other buildings.

Airfield–Terminal Area Spatial Relation

An important issue for the designer to consider is the operational implications of the relative placement of the terminal area and the runway–taxiway system. The FAA identified four generic layouts for optimal placement of the terminal area vis-à-vis the airfield (8). Figure 8.1 illustrates the spatial airfield–terminal relation and the various possibilities of placement. The FAA variations of the parallel-runway configuration result from the different relative location of the terminal area to the runway–taxiway system. The designer must carefully consider the different features in light of the operational consideration prior to finalizing the location of the terminal area relative to the airfield.

A common arrangement is to place the terminal area and gate–apron facilities to one side of a pair of runways. This layout is somewhat inefficient operationally as



LAYOUT	(see diagrams above)			
APRON-TERMINAL RELATIONSHIPS	SINGLE OR CLOSELY PLACED PARALLEL RUNWAYS; LIMITED APRON TERMINAL ON ONE SIDE	RUNWAYS WITH INTERSECTING AXES; LIMITING APRON TERMINAL ON TWO SIDES	WIDELY SPACED PARALLEL RUNWAYS WITH INTERSECTING CROSSWIND RUNWAY OR TAXIWAY; LIMITING APRON TERMINAL ON THREE SIDES	WIDELY SPACED PARALLEL RUNWAYS WITH NO INTERSECTING CROSSWIND RUNWAY; LIMITING APRON TERMINAL ON TWO SIDES, EXCEPT AS LIMITED BY TAXIWAYS
GROUND-ACCESS CHARACTERISTICS	ACCESS FROM SINGLE POINT USING ONE-WAY LOOP ROAD	ACCESS FROM SINGLE POINT USING ONE-WAY LOOP ROAD	ACCESS FROM SINGLE POINT USING ONE-WAY LOOP ROAD	POSSIBLE ACCESS FROM TWO POINTS USING TWO-WAY LOOP AXIAL ROAD WITH ONE-WAY LOOP ROADS SERVING EACH APRON-TERMINAL AREA
APRON-TERMINAL EXPANSION	RUNWAY AND ROADWAY LIMIT EXPANSION TO TWO DIRECTIONS	RUNWAY AND ROADWAY LIMIT EXPANSION TO TWO DIRECTIONS	RUNWAY AND ROADWAY LIMIT EXPANSION TO TWO DIRECTIONS	RUNWAYS EXPANSION TO TWO DIRECTIONS
AIRCRAFT CAPACITY	USUALLY (BUT NOT LIMITED TO) SMALL OR MEDIUM VOLUMES	SMALL, MEDIUM, OR LARGE VOLUMES	MEDIUM OR LARGE VOLUMES	MEDIUM OR LARGE VOLUMES
	APRON TERMINAL	RUNWAYS	GROUND ACCESS	

Figure 8.1 Spatial relationship between the airfield and airport terminal area. (*Source*: FAA (8).)

aircraft would have to taxi across an active runway, hence reducing runway capacity in busy periods. This disadvantage is overcome by an *open parallel*-runway system in which the terminal building, apron, and taxiways are placed between the two runways.

Geometric Enhancement Features

Depending on operational factors, certain geometric features would provide desirable enhancements to airfield configuration. These include staggering of runway thresholds, displaced thresholds, and tandem placement of runways. Where prevailing winds are favorable, parallel runways may be staggered or placed in tandem, with the runway lengths overlapping. In the tandem–parallel configuration, the terminal facilities are located between the runways. This geometric enhancement makes it possible to reduce taxiing distances by using one runway exclusively for takeoff operations and the other runway for landings; however, disproportionately larger land would be required. In certain situations in existing airports, a runway threshold displacement may prove effective in enhancing aircraft operations or even increasing overall capacity.

8.4 RUNWAY ORIENTATION

Because of the obvious advantages of landing and taking off into the wind, runways are oriented in the direction of prevailing winds. Aircraft may not maneuver safely on a runway when the wind contains a large component at right angles to the direction of travel. The point at which this component (called the crosswind) becomes excessive will depend upon the size and operating characteristics of the aircraft.

In the wind analysis, determining allowable crosswind is critical, and it is the basis of the airport reference code (ARC), which is discussed later. In the FAA standards (1) the allowable crosswind speeds (in knots) are based on two parameters: allowable crosswind speed and to a lesser extent runway width, as given in Table 8.1. For the ICAO standards (4), the allowable crosswind (in kilometers per hour and knots) is based entirely on the airport reference field length (RFL), and the maximum permissible crosswind components are given in Table 8.2.

Standards of the ICAO and the FAA agree that runways should be oriented so that the usability factor of the airport is not less than 95%. (The usability factor is the percentage of time during which the use of the runway system is not restricted because of an excessive crosswind component.) Where a single runway or set of parallel runways cannot be oriented to provide a usability factor of at least 95%, one or more crosswind runways may need to be provided.

Table 8.1 FAA Maximum Permissible Crosswind Components (1)

Airport reference code[a]	Runway width (ft)	Allowable crosswind component (kt)
A-I and B-I	<75	10.5
A-II and B-II	75–100	13.0
A-III, B-III, and C-1 through D-III	100 to 150	16.0
A-IV through D-VI	>150	20.0

[a]Defined later in this chapter.

Table 8.2 ICAO Maximum Permissible Crosswind Components (4)

Reference field length	Max crosswind, km/hr (knots)
1500 m or more[a]	37 (20)
1200–1499 m	24 (13)
<1200 m	19 (10)

[a]For insufficient coefficient of friction, where poor runway braking action occurs frequently, a crosswind component not exceeding 24 km/hr (13 knots) should be assumed.

Genesis of Runway Orientation

Probably the oldest, most basic and fundamental features of an airport are its runway configuration and orientation. Orientation, the angle that the runway centerline makes with the azimuth, goes back to the infancy of airports when aircraft landed on dirt or grass strips with airmen guided primarily by wind direction as indicated by the wind sock. Because aircraft must take off and land into the wind and must minimize the adverse effects of crosswind, runway orientation is dependent on wind speed and direction. As airplanes became larger and heavier, they required stronger runway surfaces and pavements able to withstand increasingly heavy loads.

The building runways of stronger pavements that are aligned in the right wind direction became critical to airport planners. This was particularly true when aircraft engine technology was not sufficiently advanced to minimize the adverse effect of crosswinds on the aircraft landing maneuver. Cross-runways became popular during the period between the wars for both civil and military airports. As seen in Figure 8.2, this runway orientation signature is evident in the old interwar airports developed in those times; Chicago Midway Airport is one example of those that still exist.

World War II ended causing a huge subsequent increase in passenger and aircraft traffic, airport planners devised a concept to maximize runway use at varying directions of wind. This concept is basically a runway system of varying orientations that end and are tangential to a circumferential taxiway system around a central terminal area (9). These runways could accommodate aircraft landing in almost any wind direction. The tangential-runway system seemed attractive to increase capacity and was actually adopted in two airports developed immediately after the war—New York and Amsterdam airports. The New York Idlewild International Airport, renamed JFK in the 1960s, was built becoming one of the largest airports of its time.

On July 12, 1948, *Time* magazine reported: "The world's largest commercial airport opened last week. Its official name is New York International Airport, but known to millions of New Yorkers as 'Idlewild'. The 4,900-acre Idlewild has seven runways ranging in length between 7,800 and 10,000 feet with a total length of ten miles. This configuration would eventually handle upwards of 60 aircraft landings and take-offs an hour." New York Idlewild Airport was originally envisioned as a reliever for the congested LaGuardia Airport, and as the primary East Coast international gateway to the United States. However, this concept quickly died as aircraft technologies advanced, and the basic premise for such a concept became irrelevant. Figure 8.3 depicts the current configuration of the New York JFK International Airport.

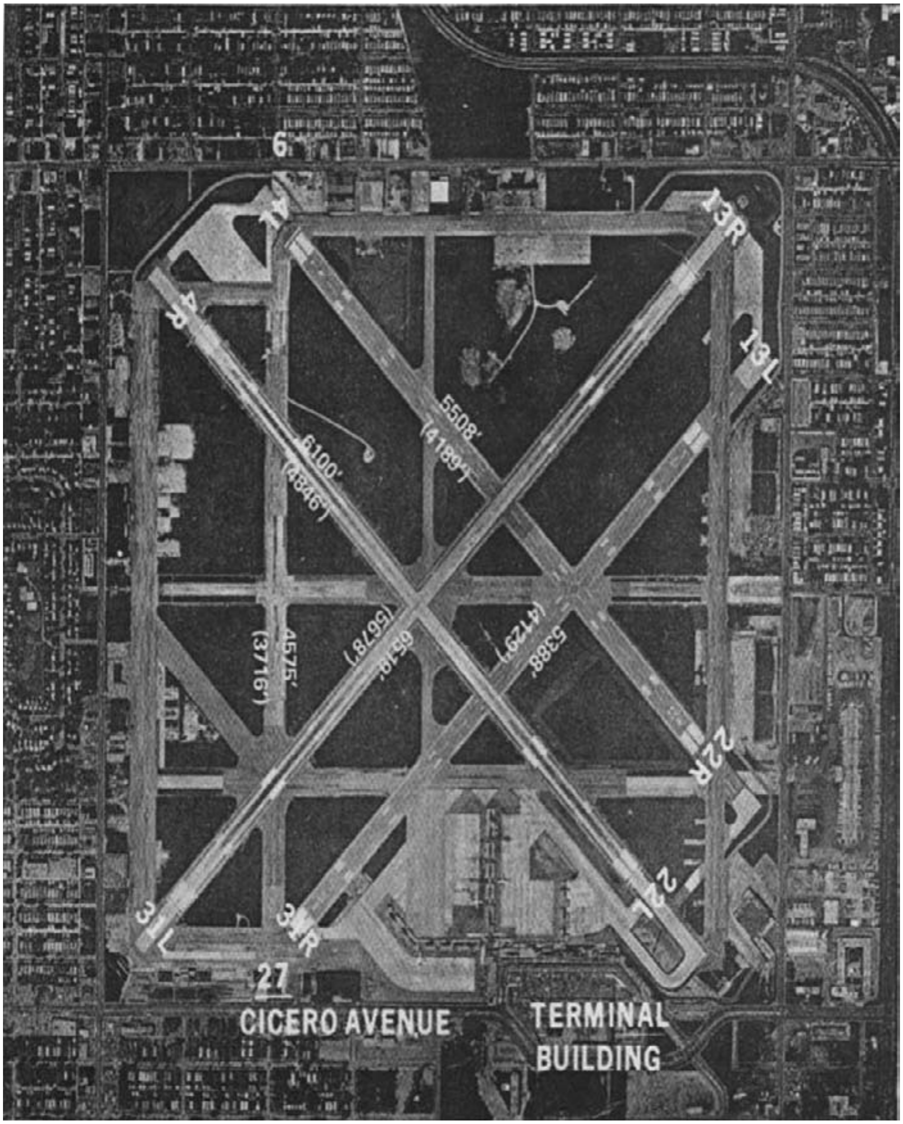


Figure 8.2 Chicago Midway Airport cross-runway configuration.

In the 1950s, aircraft became larger and needed longer runways and more widely spaced runway–taxiway separation. Moreover, with the high performance jet engines, crosswinds became more manageable for aircraft maneuvering to land. As a result, the seven-runway tangential layout at the New York Airport was gradually abandoned to adapt to the change in aircraft technology. JFK today has two sets of dual-parallel runways in two orientations (Figure 8.3). In JFK's current layout, some of the old tangential runways are actually used as taxiways. Amsterdam Schiphol was rebuilt after the war with the original plans indicating it shared the same concept with New York Airport. Schiphol's layout was also revised in the 1960s and the runway

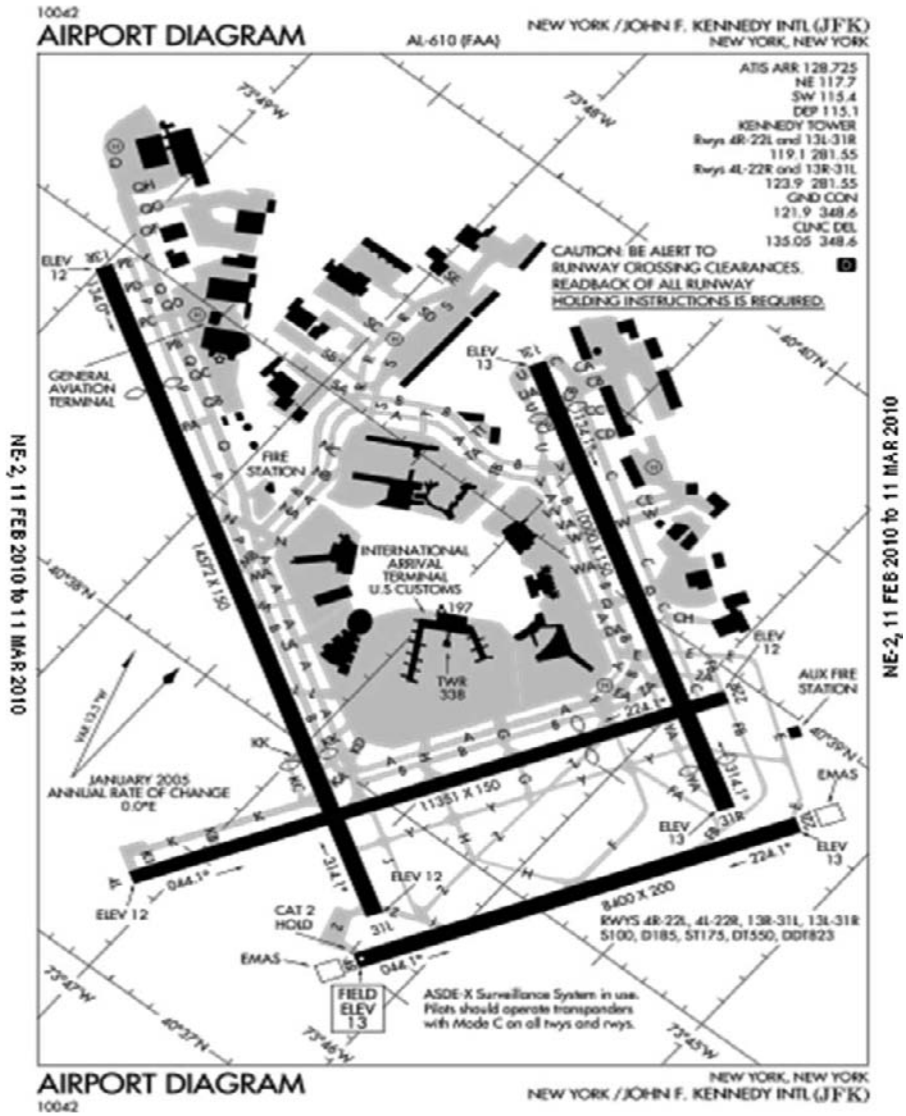


Figure 8.3 Configuration of the New York JFK International Airport.

orientation was transformed into a dual-orientation similar to New York, as shown in Figure 8.4.

As was shown in Table 7.3, airports developed since the 1960s have the following orientation signatures:

1. Single runway
2. Parallel runways (two or more dependent or independent simultaneous approach, staggered or even threshold)
3. Intersecting runway centerlines (runways intersecting at any angle, or open V)
4. Boxed runways (two or more sets of perpendicular runways)

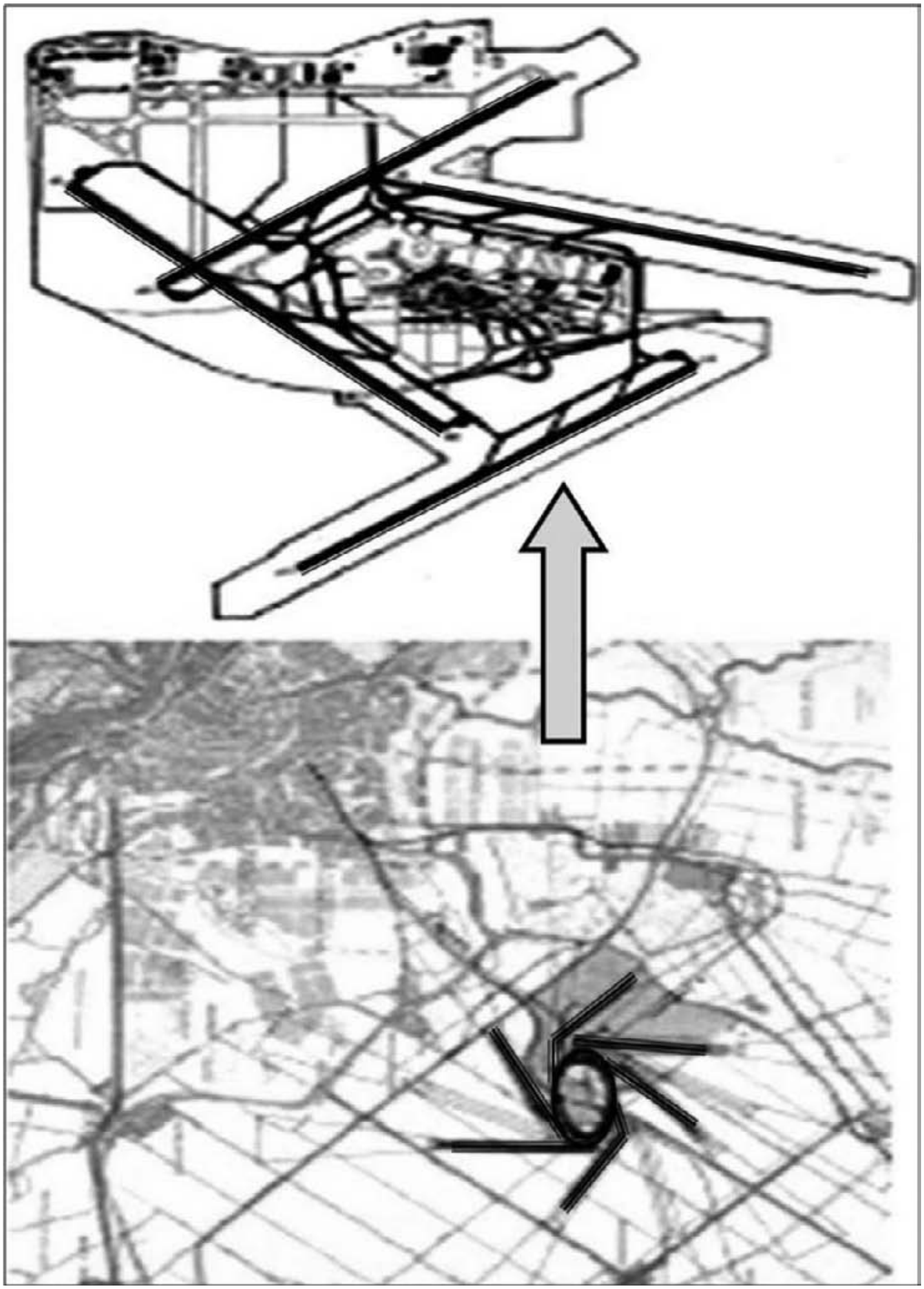
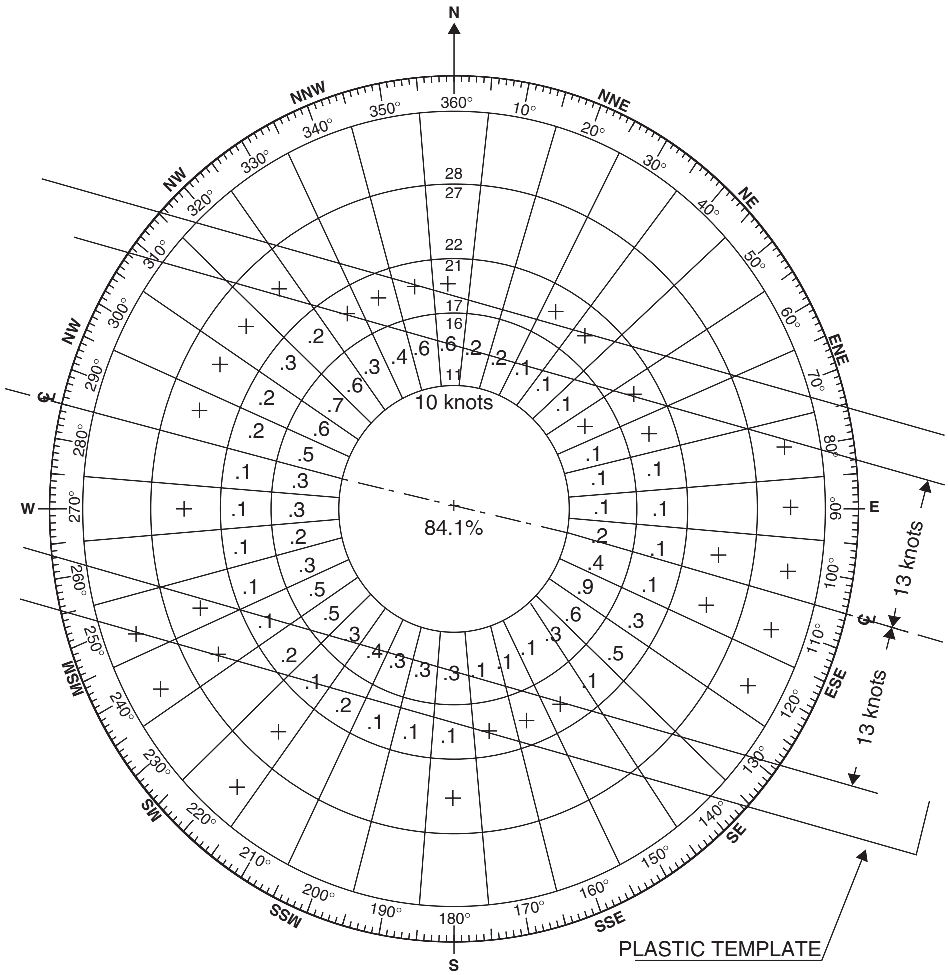


Figure 8.4 Transformation of Amsterdam Schiphol runway configuration.

It is important to note that for medium to large airports developed during the last three decades the airfield layout most widely adopted is the independent dual parallel runway (C in Table 7.3), with the terminal area optimally located midfield.

Wind Rose Analysis

The orientation of the runway is in part the result of the aircraft performance characteristics. On takeoff and landing, aircraft must fly into the wind. The convention for numbering runways is to provide a runway designation number which is the azimuth of the runway in degrees from magnetic north divided by ten. A graphical procedure utilizing the "wind rose" is typically used to determine the "best" runway orientation insofar as prevailing winds are concerned, as depicted in Figure 8.5. Wind roses are based on true north orientation.



A runway oriented 105°–285° (true) would have 2.72% of the winds exceeding the design crosswind/crosswind component of 13 knots.

Figure 8.5 A typical wind rose for an allowable crosswind of 13 kts.

A wind analysis should be based on reliable wind distribution statistics that extend over as long a period as possible, preferably at least five years. Suitable wind data are often available from the national weather agency. For example, in the United States, wind data are usually available from the National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Ashville, North Carolina.

If suitable weather records are not available, accurate wind data for the area should be collected. Another alternative would be to form a composite wind record from nearby wind-recording stations. The wind data are arranged according to velocity, direction, and frequency of occurrence, as shown by Table 8.3. This table indicates the percentage of time that wind velocities within a certain range and from a given direction can be expected. For example, the table indicates that, for the hypothetical site, northwesterly winds between 315 degrees and 325 degrees in the 10–17 kt range can be expected 0.6% of the time.

These data are plotted on a wind rose by placing the percentages in the appropriate segment of the graph. On the wind rose, the circles represent wind velocity in knots, and the radial lines indicate wind direction. The data from Table 8.4 have been plotted in Figure 8.5. The wind rose is essentially a compass representing wind conditions on polar coordinates: circumference with 36 segments representing all wind directions and radial with 5 wind speed ranges. Each cell represents percentage of direction and speed of wind.

The wind rose procedure makes use of a transparent template on which three parallel lines have been plotted. The middle line represents the runway centerline, and the distance between it and each of the outside lines is equal to the allowable crosswind component (e.g., 13 knots).

The following steps are taken to determine the "best" runway orientation and to determine the percentage of time that orientation conforms to the crosswind standards:

1. Place the template on the wind rose so that the middle line passes through the center of the wind rose.
2. Using the center of the wind rose as a pivot, rotate the template until the sum of the percentages between the outside lines is a maximum.
3. Read the true bearing for the runway on the outer scale of the wind rose beneath the centerline of the template. In the example, the best orientation is 105°–285° true.
4. The sum of percentages between the outside lines indicates the percentage of time that a runway with the proposed orientation will conform to crosswind standards.

It is noted that wind data are gathered and reported with true north as a reference, while runway orientation and numbering are based on the magnetic azimuth. The true azimuth obtained from the wind rose analysis should be adjusted to magnetic azimuth by taking into account the magnetic variation* for the airport location. An easterly variation is subtracted from the true azimuth, and a westerly variation is added to the true azimuth.

*The magnetic variation can be obtained from aeronautical charts.

Table 8.3 Typical Wind Data

Circle segment in degrees	Percentage of winds			
	10–16 knots	17–21 knots	22–27 knots	>28 knots
06 to 15	0.20	—	—	—
16 to 25	0.20	—	—	—
26 to 35	0.10	—	—	—
36 to 45	0.10	—	—	—
46 to 55	0.10	—	—	—
56 to 65	0.00	—	—	—
66 to 75	0.10	—	—	—
76 to 85	0.10	0.10	—	—
86 to 95	0.10	0.10	—	—
96 to 105	0.20	0.10	—	—
106 to 115	0.40	0.10	—	—
116 to 125	0.90	0.30	—	—
126 to 135	0.60	0.50	—	—
136 to 145	0.30	0.10	—	—
146 to 155	0.10	—	—	—
156 to 165	0.10	—	—	—
166 to 175	0.10	—	—	—
176 to 185	0.31	0.10	—	—
186 to 195	0.33	0.10	—	—
196 to 205	0.33	0.10	—	—
206 to 215	0.44	0.20	—	—
216 to 225	0.34	0.10	—	—
226 to 235	0.52	0.20	—	—
236 to 245	0.53	0.10	—	—
246 to 255	0.34	0.10	—	—
256 to 265	0.22	0.10	—	—
266 to 275	0.32	0.10	—	—
276 to 285	0.34	0.10	—	—
286 to 295	0.54	0.20	—	—
296 to 305	0.63	0.20	—	—
306 to 315	0.74	0.30	—	—
316 to 325	0.64	0.20	—	—
326 to 335	0.33	0.10	—	—
336 to 345	0.44	—	—	—
346 to 355	0.63	—	—	—
356 to 05	0.63	—	—	—

The FAA recommends that 36 wind directions and the standard speed groupings of the Environmental Data Service (EDS) are used (as in Table 8.3 and Figure 8.5). The standard wind speed groupings are 0–3, 4–6, 7–10, 11–16, 17–21, 22–27, 28–33, 34–40, and 41 and over. For more details on the FAA wind rose design method, refer to Appendix 1 of the FAA airport design circular (1).

A simple computer spreadsheet program has been prepared by the FAA for wind rose analysis (1). More advanced computer-based algorithms have been developed to provide more accurate results of wind rose analysis, including an AutoCad-based

Table 8.4 Dimensions of FAA Imaginary Surfaces (12)

		Dimensional standards (ft)					
				Nonprecision instrument runway			
		Visual runway			B		Precision instrument runway
Dimensions[a]	Item	A	B	A	C	D	
A	Width of primary surface and approach surface width at inner end	250	500	500	500	1,000	1,000
B	Radius of horizontal surface	5,000	5,000	5,000	10,000	10,000	10,000
				Nonprecision instrument approach			
		Visual approach			B		Precision instrument approach
	Item	A	B	A	C	D	
C	Approach surface width at end	1,250	1,500	2,000	3,500	4,000	16,000
D	Approach surface length	5,000	5,000	5,000	10,000	10,000	—[b]
E	Approach slope	20:1	20:1	20:1	34:1	34:1	—[b]

[a]Key to dimensions: A—utility runways; B—runways larger than utility; C—visibility minima greater than 3/4 mi; D—visibility minima as low as 3/4 mi.
[b]Precision instrument approach slope is 50:1 for inner 10,000 ft and 40:1 for an additional 40,000 ft.
Source: Objects Affecting Navigable Airspace, Federal Aviation Regulations, Part 77, January 1975.

algorithm to compute optimal wind coverage in the wind rose analysis based on a mathematical modeling procedure to optimize runway orientation with higher accuracy (10). Through a mathematical maximization process this method targets partial wind coverage areas in the wind rose cells and attempts to minimize left-out areas of the coverage.

More recently, a GIS-based wind rose model called airport runway optimization (ARO) model was developed that automates the determination of runway orientation and placement (11). The ARO model uses a set of user-defined ArcView GIS functions and database management tools to solve the partial coverage problem in the other wind rose analysis methods. This approach should improve earlier "trial-and-error" manual estimation and computation-intensive methods to determine runway alignment.

8.5 OBSTRUCTIONS TO AIRSPACE: FAA AND ICAO STANDARDS

Airports must be sited in areas where airspace is free from obstruction that could be hazardous to aircraft turning in the vicinity or on takeoff or approach paths. It is also necessary to maintain the surrounding airspace free from obstacles, preventing the development and growth of obstructions to airspace that could cause the airport to become unusable. The regulations on the protection of airspace in the vicinity of airports are laid down by the definition of a set of imaginary or obstacle limitation surfaces, penetration of which represents an obstacle to air navigation. In the United States, the layout of the imaginary surfaces is governed by the FAA regulations set out in FAR Part 77 (12). A somewhat similar set of international standards is promulgated by the ICAO in Annex 14 (4). In FAA terms, protected airspace around airports is made up of five principal imaginary surfaces. These are illustrated in Figure 8.6; Table 8.4 lists the dimensions corresponding to the drawings.

1. *Primary Surface.* A surface that is longitudinally centered on the runway, extending 200 ft beyond the threshold in each direction in the case of paved runways.

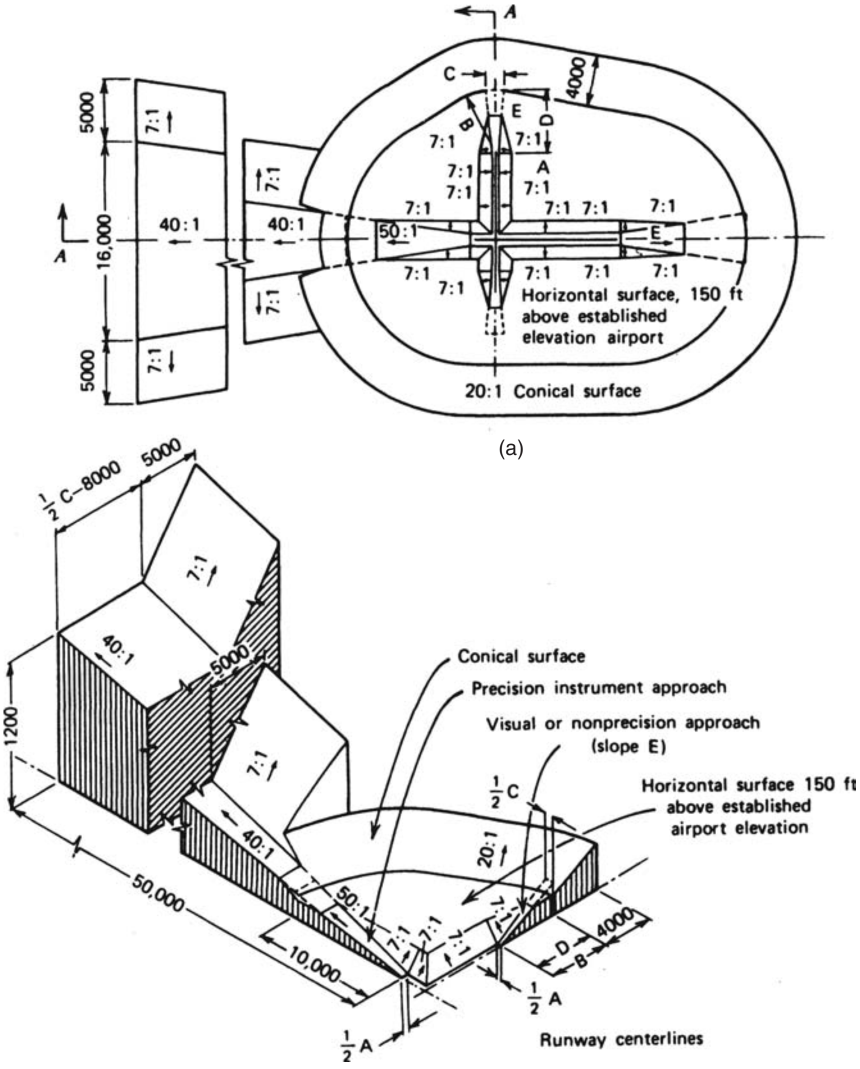


Figure 8.6 FAA imaginary surfaces for civil airports: (a) plan view; (b) isometric view of A–A (12).

2. *Approach Surface.* An inclined plane or combination of planes of varying width running from the ends of the primary surface.
3. *Horizontal Surface.* A horizontal plane 150 ft above the established airport elevation. As Figure 7.11 indicates, the plan dimensions of the horizontal surface are set by arcs of specified dimensions from the end of the primary surfaces, which are connected by tangents.
4. *Transition Surface.* An inclined plane with a slope of 7:1 extending upward and outward from the primary and approach surfaces, terminating at the horizontal surface where these planes meet.
5. *Conical Surface.* An inclined surface at a slope of 20:1 extending upward and outward from the periphery of the horizontal surface for a horizontal distance of 4000 ft.

The dimensional standards are determined by the runway classification (visual, non-precision instrument, or precision instrument runways). A *visual* runway is a facility designed for operation under conditions of visual approach only. A *non-precision instrument* runway has limited instrument guidance in the form of azimuth or area-wide navigation equipment. A *precision instrument* runway is fully equipped for instrument landing procedures with ILS (instrument landing system) or PAR (precision approach radar) equipment.

The federal government additionally requires the establishment of runway protection zones (RPZs) at the ends of runways when federal funds are to be expended on new or existing airports. Figure 8.7 is a schematic view of the runway protection zone; the dimensions appear in Table 8.5. The airport owner must have positive control over development within the zone by long-term easements or by ownership in fee simple; this gives long-term positive assurance that there will be no encroachment of airspace within the critical portions of the inner approach surface.

The international recommendations on obstacle limitation surfaces set by the ICAO are generally similar to those contained in FAR, Part 77; however, there are some significant differences:

1. The horizontal projection of the conical surfaces varies by runway type in the ICAO standards; it is fixed at 4000 ft by FAR Part 77.

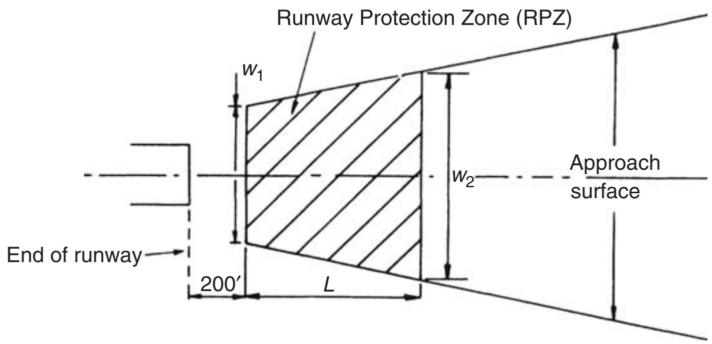


Figure 8.7 FAA runway protection zone layout.

Table 8.5 Runway Protection Zone Dimensions[a] (1)

	Runway end		Dimensions for approach end			
Facilities expected to serve	Approach end	Opposite end	Length L, ft	Inner width W_1, ft	Outer width W_2, ft	RPZ, acres
Only small airplanes	V	V	1000	250	450	8.035
		NP	1000	500	650	13.200
		NP 3/4 P	1000	1000	1050	23.542
	NP	V NP	1000	500	800	14.922
		NP 3/4 P	1000	1000	1200	25.252
Large airplanes	V	V NP	1000	500	700	13.770
		NP 3/4 P	1000	1000	1100	24.105
	NP	V NP	1700	500	1010	29.465
		NP 3/4 P	1700	1000	1425	47.320
Large or only small airplanes	NP 3/4	V NP NP 3/4 P	1700	1000	1510	48.978
	P	V NP NP 3/4 P	2500	1000	1750	78.914

[a] 1 ft = 0.3048 m.
V = visual approach.
NP = non-precision instrument approach with visibility minimums more than 3/4 statute mi.
NP 3/4 = non-precision instrument approach with visibility minimums as low as 3/4 statute mi.
P = precision instrument approach.

2. The slope of the transition surface varies by runway type in Annex 14; it is fixed at 7:1 by FAR, Part 77.
3. For all but Category 1 Precision Approach Runways of Code Numbers 1 and 2, the approach surface is horizontal beyond the point where the 2.5% slope intersects the horizontal plan 150 m above the threshold elevation.
4. The ICAO takeoff and approach surfaces are different; the FAA surfaces are the same.

The ICAO standards for the obstacle limitation surfaces (OLSs) are stated in Tables 8.6 and 8.7, which show the dimensions and slopes for the OLS for approach and takeoff runways (4).

8.6 RUNWAY LENGTH

Selecting a design runway length is one of the most important decisions an airport designer makes. To a large degree, the runway length determines the size and cost of the airport and controls the type of aircraft it will serve. Furthermore, it may limit the payload of the critical aircraft and the range available for its flight.

The runway must be long enough to allow safe landings and takeoffs by current equipment and by aircraft expected to use the airport in future operations. Runways must accommodate differences in pilot skill and a variety of aircraft types and operational requirements.

The following factors most strongly influence required runway length (2):

1. Performance characteristics of aircraft using the airport (see Chapter 3)
2. Landing and takeoff gross weights of the aircraft

Table 8.6 Takeoff Runways: Dimensions and Slopes of OLSs (4)

Surface and dimensions[a] (1)	Code number 1 (2)	2 (3)	3 or 4 (4)
Takeoff climb			
Length of inner edge	60 m	80 m	180 m
Distance from runway end[b]	30 m	60 m	60 m
Divergence (each side)	10%	10%	12.5%
Final width	380 m	580 m	1,200 m 1,800 m[c]
Length	1,600 m	2,500 m	15,000 m
Slope	5%	4%	2%

[a] All dimensions are measured horizontally unless specified otherwise.
[b] The takeoff climb surface starts at the end of the clearway if the clearway length exceeds the specified distance.
[c] 1800 m when the intended track includes changes of heading greater than 15° for operations conducted in instrument meteorological conditions (IMC), visual meteorological conditions (VMC) by night.
Source: Aerodromes, Annex 14 to the Convention on International Civil Aviation, Vol. I, 4th ed., Montreal: International Civil Aviation Organization, 2004.

3. Elevation of the airport
4. Average maximum air temperature at the airport
5. Runway gradient

Other factors causing variations in required runway length are humidity, winds, and the nature and condition of the runway surface.

Aircraft performance curves of individual airplanes have been developed and published by the FAA (2) and by the aircraft manufacturers as a design and planning tool. These curves, which are based on actual flight test and operational data, make it possible to determine precisely required landing and takeoff runway lengths for almost all the civilian aircraft in common use, both large and small. The curves vary in format and complexity.

The manufacturer's performance curves appearing in Figures 8.8(a) and 8.8(b) indicate the required runway lengths for the Boeing 737-900.

Performance curves for takeoff are based on an *effective runway gradient* of 0%. Effective runway gradient is the maximum difference in runway centerline elevations divided by the runway length. The FAA specifies that the runway lengths for takeoff be increased by the following rates for each 1% of effective runway gradient:

1. For piston and turboprop airplanes, 20%
2. For turbojet airplanes, 10%

In the case of turbojet aircraft landing on wet or slippery runways, it may be necessary to increase the required dry-landing length from 5.0 to 9.5%, depending on aircraft series (2). No correction is required for piston or turboprop airplanes.

Example 8.1 demonstrates the use of Figure 8.8.

Table 8.7 Approach Runways: Dimensions and Slopes of OLSs

Runway classification	Non-instrument Code number				Non-precision approach Code number			Precision approach: Category I Code number		Precision approach: Category II or III Code number
Surface and dimensions[a]	1	2	3	4	1,2	3	4	1,2	3,4	3,4
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Conical										
Slope	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Height	35 m	55 m	75 m	100 m	60 m	75 m	100 m	60 m	100 m	100 m
Inner Horizontal										
Height	45 m	45 m	45 m	45 m	45 m	45 m	45 m	45 m	45 m	45 m
Radius	2,000 m	2,500 m	4,000 m	4,000 m	3,500 m	4,000 m	4,000 m	3,500 m	4,000 m	4,000 m
Inner Approach										
Width								90 m	120 m	120 m
Distance from threshold								60 m	60 m	60 m
Length								900 m	900 m	900 m
Slope								2.5%	2%	2%
Approach										
Length of inner edge	60 m	80 m	150 m	150 m	150 m	300 m	300 m	150 m	300 m	300 m
Distance from threshold	30 m	60 m	60 m	60 m	60 m	60 m	60 m	60 m	60 m	60 m
Divergence (each side)	10%	10%	10%	10%	15%	15%	15%	15%	15%	15%

First section										
Length	1,600 m	2,500 m	3,000 m	3,000 m	2,500 m	3,000 m	3,000 m	3,000 m	3,000 m	3,000 m
Slope	5%	4%	3.33%	2.5%	3.33%	2%	2%	2.5%	2%	2%
Second section										
Length						3,600 m[b]	3,600 m[b]	12,000 m	3,600 m[b]	3,600 m[b]
Slope						2.5%	2.5%	3%	2.5%	2.5%
Horizontal section										
Length						8,400 m[b]	8,400 m[b]		8,400 m[b]	8,400 m[b]
Total length						15,000 m	15,000 m	15,000 m	15,000 m	15,000 m
Transitional										
Slope	20%	20%	14.3%	14.3%	20%	14.3%	14.3%	14.3%	14.3%	14.3%
Inner Transitional										
Slope								40%	33.3%	33.3%
Balked landing surface										
Length of inner edge								90 m	120 m	120 m
Distance from threshold								[d]	1,800 m[c]	1,800 m[c]
Divergence (each side)								10%	10%	10%
Slope								4%	3.33%	3.33%

[a] All dimensions are measured horizontally unless specified otherwise.
[b] Variable length.
[c] Or end of runway, whichever is less.
[d] Distance to the end of strip.
Source: Aerodromes, Annex 14 to the Convention on International Civil Aviation, Vol. I, 4th ed., Montreal: International Civil Aviation Organization, 2004.

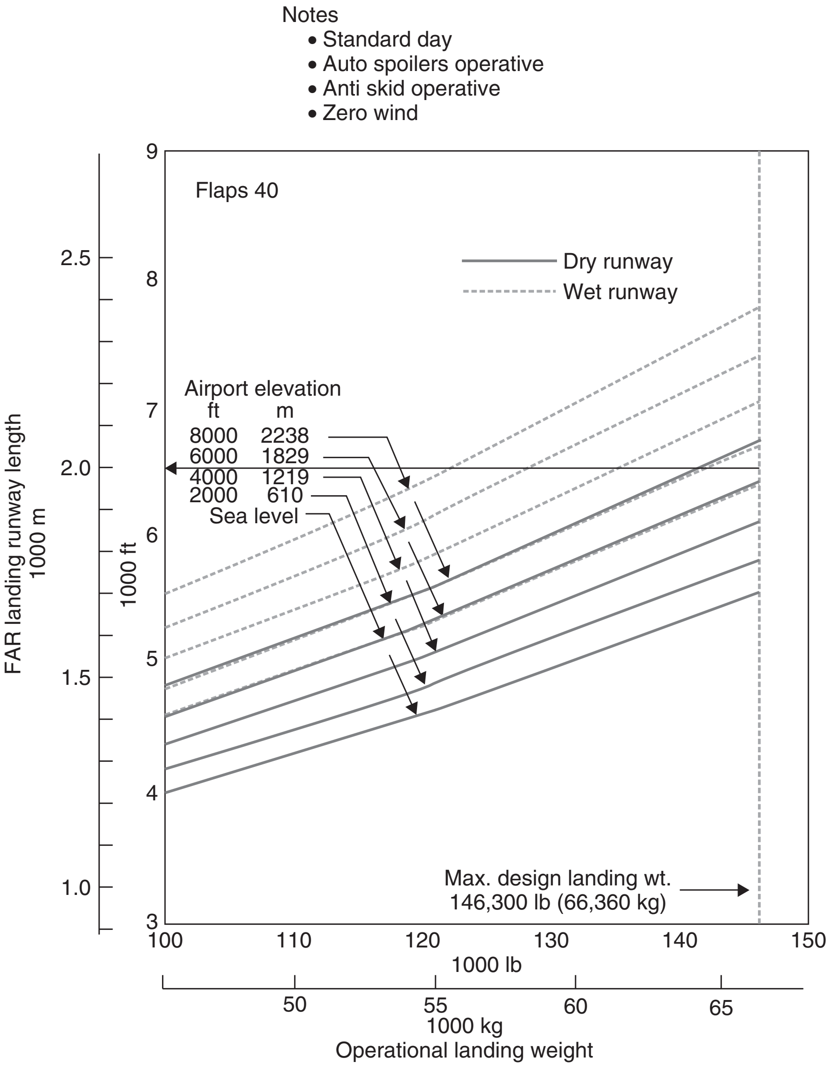


Figure 8.8(a) Aircraft performance landing curve for B737-900. (Courtesy of Boeing Airplane Company.)

Example 8.1 Runway Length Requirement for a Boeing 737-900 Series Aircraft What length of runway is required for a Boeing 737-900 series aircraft, given the following conditions?

1. Maximum landing weight, 146,300 lb
2. Normal maximum temperature, 84°F (28°C)
3. Airport elevation, 1000 ft
4. Takeoff weight, 174,200 lb
5. Maximum difference in runway centerline elevations, 20 ft

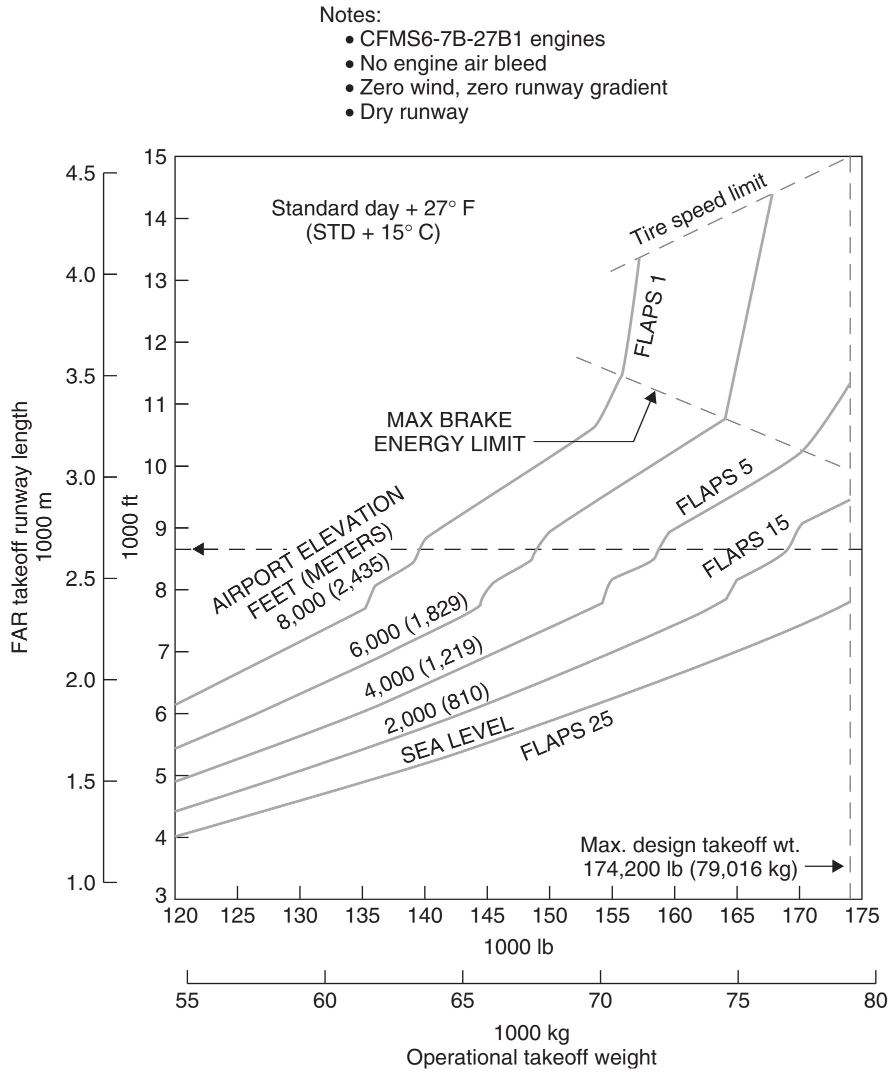


Figure 8.8(b) Aircraft performance takeoff curve for B737-900. (Courtesy of Boeing Airplane Company.)

Runway Length Required for Landing

The aircraft manufacturers supply graphs for calculating required landing lengths. There are different graphs for the various flap settings. In the landing case, the graph for the maximum flap setting, 40°, is selected because this will give the lowest runway length. Enter Figure 8.8(a) on the abscissa axis at the maximum landing weight (146,300 lb), and project this point vertically to intersect with the interpolated 1000-ft airport elevation line. Use the wet curves because the aircraft is a turbo-jet powered airplane. Extend this point of intersection horizontally to the left ordinate scale, where a runway length of 6550 ft is read. Do not adjust the length for wet conditions because the wet curves were used. Lengths of 30 ft and over are rounded up to the next 100-ft interval. The landing length required is 6600 ft.

Runway Length Required for Takeoff

The Boeing B737 Airport Planning Manual contains the takeoff requirement chart for a dry runway at standard daily temperature (SDT) and SDT+15°C. Use the latter chart, which is for airports where the mean daily temperature of the hottest month is equal to or less than STD + 15°C (86°F). The following steps are required to determine the runway length required for takeoff from Figure 8.8(b):

Enter the horizontal weight axis at the maximum design takeoff weight of 174,200 lb, (79,016 kg).

Draw a line vertically and interpolate where the line would intersect the 1000-ft elevation curve.

Read off on the vertical axis the intersection of the horizontal line from this point of intersection, 8750 ft.

This is rounded up to 8800 ft.

The effective slope is the maximum difference in runway elevations divided by the runway length:

$$20/8800 = 0.23\%$$

Adjust runway length for a nonzero effective runway gradient:

$$\text{Runway length} = 8800(1 + 0.1 \times 0.23) = 9002\,\text{ft}$$

The design runway length is 9000 ft.

In Appendix 11, "Airport Design for Microcomputers (AD42D.EXE)," of AC 150/5300-13 (1), the FAA publishes software that was developed for airport planners to facilitate in the planning of airport layouts. This computer program only provides estimates instead of actual runway length requirements. The design software is available online at: http://www.faa.gov/airports_airtraffic/airports/construction/.

8.7 CLEARWAYS AND STOPWAYS

In certain instances, it is possible to substitute clearways and stopways for a portion of the full-depth pavement structure. A clearway is a defined area connected to and extending beyond the end of a runway available for the completion of the takeoff operation of turbine-powered airplanes (see Figure 8.9). It increases the allowable airplane operating takeoff weight without increasing runway length (1).

A stopway is an area beyond the runway designated by the airport authority for use in decelerating an aircraft in case of an aborted takeoff (see Figure 8.10). It must be at least as wide as the runway and must be capable of supporting an airplane without causing structural damage to it. Because stopways are seldom used, it is often more cost effective to construct a full-strength runway that would be useful in both directions rather than a stopway.

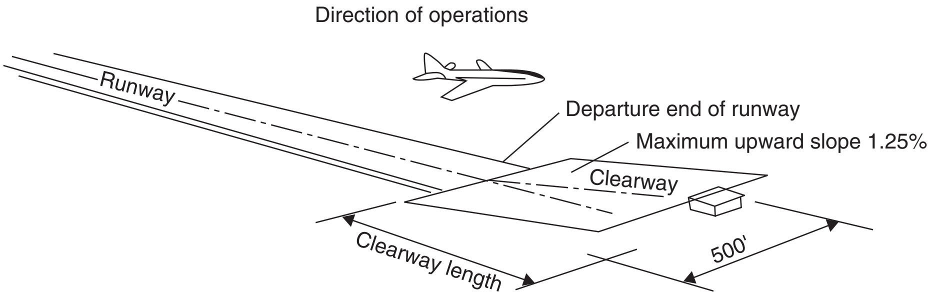


Figure 8.9 Clearway (1).

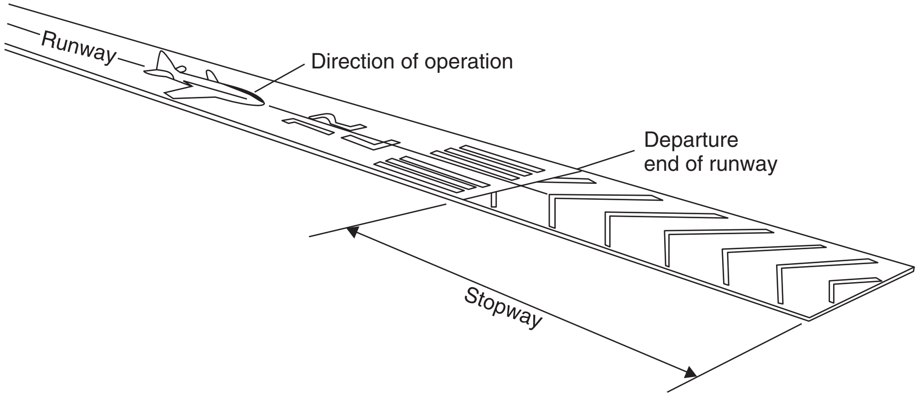


Figure 8.10 Stopway (1).

The decision to provide a stopway and/or a clearway as an alternative to an increased length of runway will depend on the nature of the area beyond the end of the runway. It also depends on the operating characteristics of airplanes expected to use it. Effects of aircraft characteristics on stopway, clearway, and runway lengths are discussed in Chapter 3.

8.8 ICAO REFERENCE CODE (4)

Runway length, being the most important airside design feature, should logically be linked to other physical characteristics of the airport. Like runway length, the physical dimensions, clearances, and separations are a function of the size and operating characteristics of the critical aircraft. We have seen, however, that large differences in required runway length may be caused by local factors that influence the performance of airplanes. Thus, to provide a meaningful relationship between field length* and other physical characteristics of the air side, the actual runway length must be converted to standard sea-level conditions by removing the local effects of elevation, temperature, and gradient. When these local effects are removed, the airplane reference field length remains.

*The field length includes the runway length plus the stopway and/or clearway lengths, if provided.

Table 8.8 ICAO Reference Code (4)

Code element 1		Code element 2		
Code number (1)	Aeroplane reference field length (2)	Code letter (3)	Wing span (4)	Outer main gear wheel span[a] (5)
1	Less than 800 m[b]	A	Up to but not including 15 m	Up to but not including 4.5 m
2	800 m up to but not including 1200 m	B	15 m up to but not including 24 m	4.5 m up to but not including 6 m
3	1200 m up to but not including 1800 m	C	24 m up to but not including 36 m	6 m up to but not including 9 m
4	1800 m and over	D	36 m up to but not including 52 m	9 m up to but not including 14 m
		E	52 m up to but not including 65 m	9 m up to but not including 14 m
		F	65 m up but not including 80 m	14 m up but not including 16 m

[a]Distance between the outside edges of the main gear wheels.
[b]1 m = 3.2808 ft.

To facilitate the publication of quantitative specifications for the physical characteristics of airports, the ICAO employs an aerodrome reference code consisting of two elements. As indicated in Table 8.8, the first element is a number based on the aerodrome reference field length, and the second element is a letter based on the aircraft wingspan and outer main gear wheel span. The code number or letter selected for design purposes is related to the critical airplane characteristics for which the facility is provided. For a given airplane, the reference field length can be determined from the flight manual provided by the manufacturer. It is noted that the airplane reference field length is used only for the selection of a code number. It is not intended to influence the actual runway length provided.

In certain instances, it may be desirable to convert an existing or planned field length to the reference field length. The reference field length is computed by dividing the planned or existing length by the product of three factors representing local elevation F_e, temperature F_t, and gradient F_g conditions:

$$\text{Reference field length} = \frac{\text{planned or existing field length}}{F_e \times F_t \times F_g} \tag{8.1}$$

The required field length increases at a rate of 7% per 1000 ft elevation above mean sea level. Thus, the elevation factor F_e can be computed by the following equation:

$$F_e = 0.07 \times E + 1 \tag{8.2}$$

where

E = airport elevation (in thousands of feet)

The field length that has been corrected for elevation should be further increased at a rate of 1% for every 1°C by which the airport reference temperature exceeds the temperature in the standard atmosphere for that elevation. The airport reference temperature T is defined as the monthly mean of the daily maximum temperatures (24 hr) for the hottest month of the year. It is recommended that the airport reference temperature be averaged over a period of years. The temperature in the standard atmosphere is 15°C at sea level, and it decreases approximately 1.981 degrees for each 1000-ft increase in elevation. The equation for the temperature correction factor becomes

$$F_t = 0.01\left[T\left({}^{\circ}\mathrm{C}\right) - (15 - 1.981E)\right] + 1 \tag{8.3}$$

It is recommended that the runway length that has been corrected for elevation and temperature be further increased at a rate of 10% for each 1% of effective runway gradient G. This recommendation is applicable for takeoff conditions when the runway code number is 2, 3, or 4. Thus, for takeoff conditions for runway code numbers 2, 3, or 4, the gradient factor is

$$F_g = (0.10G + 1) \tag{8.4}$$

8.9 FAA AIRPORT REFERENCE CODE (1)

In 1983, the FAA introduced a new concept for airport classification and design. With this system, airports are grouped into 2 broad categories and 10 design groups.* According to the FAA concept, there are two broad airport classes: utility airports and transport airports. Utility airports serve the general aviation community and commonly accommodate small aircraft (i.e., those with maximum certified takeoff weights of 12,500 lb or less). Transport airports can accommodate the smaller airplanes but are designed to serve the larger ones.

The FAA defines five aircraft approach categories. These categories group airplanes on the basis of an approach speed of $1.3V_{\mathrm{so}}$ (where V_{so} is the aircraft stall speed at the maximum certified landing weight); see Table 8.9. Utility airports serve the less demanding approach category A and B airplanes, that is, those with approach speeds of less than 121 knots. Transport airports are usually designed, constructed, and maintained to serve airplanes with approach speeds of 121 knots or greater.

FAA geometric design standards are linked to the wingspan of the critical aircraft. Definitions of each airplane design group are given in Table 8.10, along with a list of typical aircraft for each group. The chart shown in Figure 8.11 provides guidance in selecting the proper airplane design group and airport dimensional standards.

Table 8.9 FAA Aircraft Approach Category Classification (1)

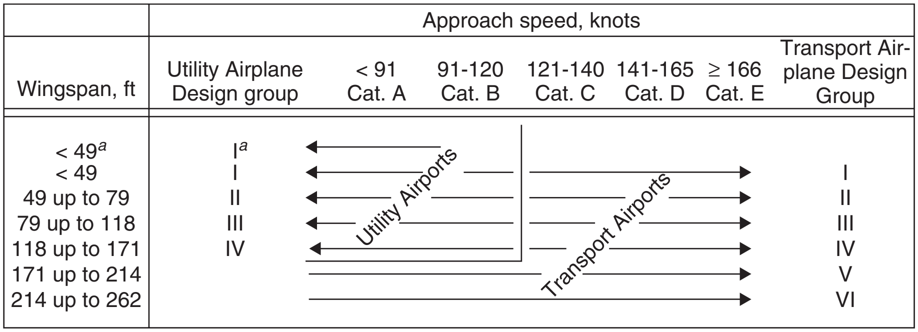
Approach category	Approach speed, knots	Airport category
A	<91	Utility airport
B	91–120	Utility airport
C	121–140	Transport airport
D	141–165	Transport airport
E	166 or greater	Transport airport

*In the design of utility airports, subgroups are used to account for differences in airplane weight (i.e., small airplanes only) and air traffic control procedures (visual, non-precision, and precision instrument runways).

Table 8.10 FAA Airplane Design Groups for Geometric Design of Airports (1)

Airplane design group	Wingspan ft	Wingspan m	Tail height ft	Tail height m	Typical aircraft
I	<49	<14.9	<20	<6.1	Citation CJ1+, Cessna Mustang
II	49–<79	14.9–<24.1	20–<30	6.1–<9.1	CRJ 200, Jetstream 41
III	79–<118	24.1–<36.0	30–<45	9.1–<13.7	B737, A321
IV	118–<171	36.0–<52.1	45–<60	13.7–<18.3	B757, A300-600
V	171–<214	52.1–<65.2	60–<66	18.3–<20.1	B747, A340-600, B777-300
VI	214–<262	65.2–<79.9	66–<80	20.1–<24.4	A380

[a]Original dimensions of this table were given only infeet and inches.



[a]Applies to airports that are to serve only small airplanes.

Figure 8.11 FAA airplane design group concept.

8.10 SEPARATION OF PARALLEL RUNWAYS

The overriding consideration in the determination of parallel-runway separation is safety. Where simultaneous operations will be permitted to occur under favorable weather conditions (VFR operations), the ICAO recommends different separation for different ARCs. For code number 1, parallel-runway centerlines to be placed as close as 120 m (4), and further specifies a minimum separation for simultaneous visual operations of 150 m for code 2 and 210 m for code 3 and code 4.

For simultaneous landings and takeoffs under visual flight rules, the FAA specifies a minimum separation between centerlines of parallel runways of 700 ft (214 m) for airplane design groups I–IV (1). However, the minimum centerline separation distance for design groups V and VI is 1200 ft (366 m).

The rules for instrument runways for IFR operations are more complicated. The ICAO recommends that for parallel instrument runways intended for simultaneous use, the following minimum separations are used:

Independent parallel approaches: 1035 m

Independent parallel departures: 760 m

These distances may be decreased or increased, depending on the staggering of runways and the position of the approach threshold relative to that being used for takeoffs.

The FAA has carried out considerable research in developing criteria for minimum separation of parallel instrument runways, which are now based on empirical data from special flight tests and studies of ground track recordings for actual flights. Such studies have provided data on lateral deviations from the ILS centerline and the effect of speed and intercept angle. Research in the 1960s indicated that a minimum separation of parallel runways of 5000 ft was required for simultaneous instrument approaches, and this is still the FAA's recommended minimum separation. However, the FAA (1) now specifies a minimum separation of 4300 ft (1310 m) for simultaneous precision instrument approaches, provided specific electronic navigational aids and monitoring equipment and air traffic control and approach procedures are used. Where normal separations are not possible, the FAA will consider separations down to 3000 ft (915 m). However, the FAA (1) notes that for modern designs of large airports with terminals positioned between the main parallel runways, separations of greater than 5000 ft are found to be necessary for terminal and apron layout requirements.

A minimum separation of 3500 ft (1067 m) is required for simultaneous non-radar departures; this can be reduced to 2500 ft (762 m) for simultaneous radar-controlled departures. This dimension is also recommended for simultaneous radar-controlled arrivals and departures, provided the thresholds are not staggered (1). When the thresholds are staggered, the 2500-ft separation may be reduced if the approach is to the nearer threshold but be increased if the approach is to the farther threshold. Specific recommendations with respect to the effect of staggered thresholds are given in reference 3. It will be necessary to observe wake turbulence avoidance procedures when runway centerline spacing below 2500 ft is used.

8.11 RUNWAY AND TAXIWAY CROSS SECTION

In the early days of aviation, all aircraft operated from relatively unimproved landing fields, maneuvering along unpaved paths called *landing strips.* Later, to meet the requirements of more advanced aircraft, it became necessary to improve or pave the center portion of the landing strip. The term "landing strip" came to refer to the graded area on which the load-bearing surface was placed. The function of the landing strip changed to that of a safety area bordering the runway. The FAA (1) now refers to the entire graded area between the side slopes as the *runway safety area,* as Figures 8.12 and 8.13 illustrate. In its literature, the ICAO (4) refers to a comparable area as the *runway strip.*

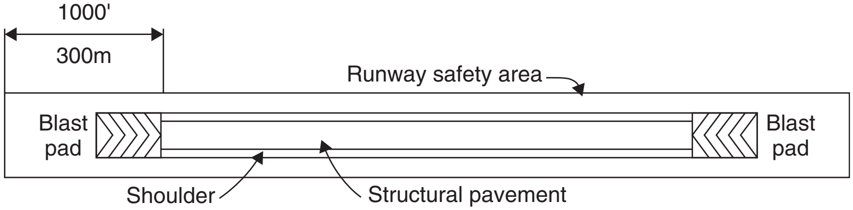


Figure 8.12 Plan view of runway element (1).

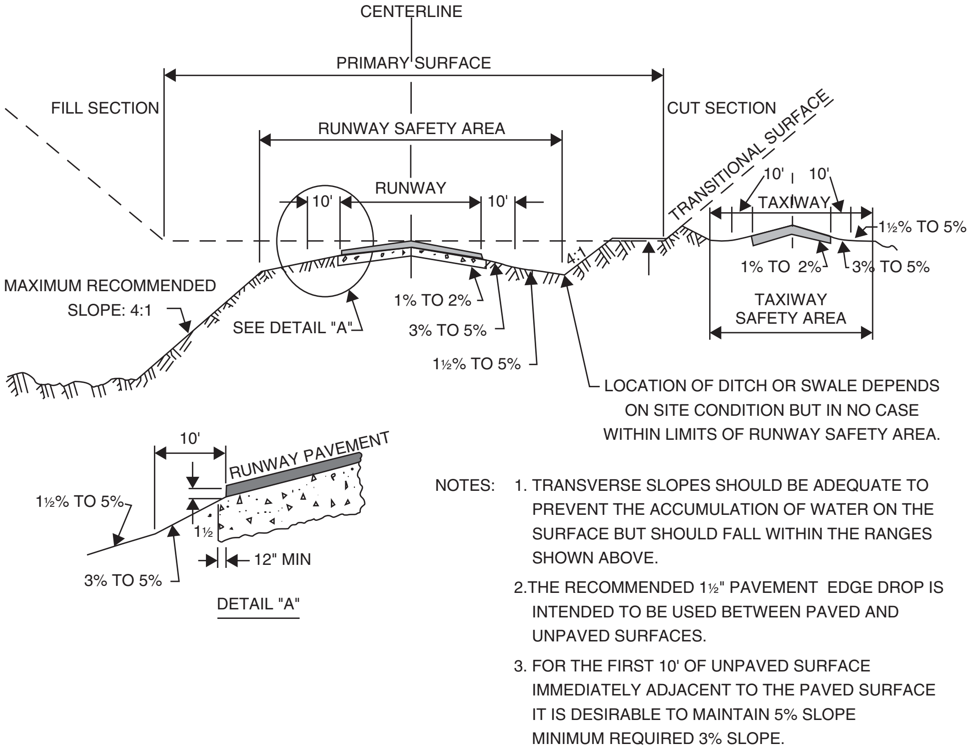


Figure 8.13 Transverse-grade limitations for utility airports. (*Source:* Adapted from ref. 1.)

The border areas immediately adjacent to the runway pavement are referred to as *shoulders.* Shoulders are usually paved or otherwise stabilized in order to resist jet blast erosion and/or to accommodate maintenance equipment. The portion of the runway safety area abutting the edges of the shoulders is cleared, drained, graded, and usually turfed. At airports serving small aircraft, the entire border area abutting the paved runway may be a natural surface, such as turf.

Runway safety areas range in width from 300 ft (90 m) at the smallest utility airports to 500 ft (150 m) or wider for all categories of transport airports (1). Similar widths of runway strips are recommended by the ICAO (4).

Runways and Shoulders

The runway is a paved load-bearing area that varies in width from about 75 ft (23 m) at the smallest general aviation airports to 200 ft (60 m) or more at the largest air carrier airports. Studies have shown that the distribution of wheel load applications occurring during landings and takeoffs approximates a normal distribution centered about the runway centerline. Virtually all the load applications are concentrated in a central width of about 100 ft (30 m). The additional 50 ft (15 m) of width on major runways protects jet aircraft engines from ingestion of loose material and also provides an added measure of safety for errant aircraft.

The FAA recommends shoulder widths ranging from 10 ft (3 m) to 40 ft (12 m) for transport airports (1). The ICAO recommends that the overall width of the runway plus its shoulders be not less than 60 m for code letters D and E or 75 m where the code letter is F (4).

Shoulders are not designed for frequent applications of aircraft or vehicular loads. Rather, they are intended to minimize the probability of serious damage to aircraft or injury to the crew or passengers in the event that an aircraft suddenly veers from the runway. At smaller civilian airports, shoulders are sometimes constructed of stabilized earth with a turf cover. At larger facilities, the shoulders are paved. Consideration should be given to constructing runway blast pads at the ends of runways that accommodate frequent jet operations. These pads should extend across the full width of the runway plus shoulders and should be marked as non-movement areas. Blast pads vary in length from 60 ft (18 m) to 400 ft (120 m), depending on the airplane group served.

Taxiways

In cross section, a taxiway is similar in appearance to a runway. The dimensions are, of course, much smaller. The taxiway structural pavement is typically 25–75 ft wide at general aviation airports and 50–100 ft wide at air carrier airports.

In the interests of safety and good aircraft maneuverability, the ICAO states that adequate separations must be provided between runways and taxiways, along with ample clearances to buildings and other obstacles. Tables 8.11a–8.11d summarize these and other minimum dimensional standards. To use the ICAO dimensional standards, first determine the reference field length, the wingspan, and the outer main gear wheel span for the critical aircraft. The standards are keyed to the reference code defined in Table 8.8.

The FAA's dimensional standards for runways and taxiways at transport airports are given in Tables 8.12 and 8.13, respectively. These standards are given by airplane

Table 8.11a ICAO Minimum Dimensional Recommended Practices (4): Width of Runway Strips and Cleared & Graded Areas

	ICAO code number			
	1	2	3	4
Width of runway strips				
Precision approach runway (m)[a]	75	75	150	150
Nonprecision approach runway (m)	75	75	150	150
Noninstrument runway (m)	30	40	75	75
Width of cleared and graded area				
Instrument runway (m)	40	40	75	75
Noninstrument runway (m)	30	40	75	75

[a] 1 m = 3.2808 ft.

Note: Distances shown extend laterally on each side of the center line of the runway and its extended centerline throughout the length of the strip.

Table 8.11b ICAO Recommended Practices—Width of Runways (4)

Code Number	A	B	C	D	E	F
1[a]	18 m[b]	18 m	23 m			
2[a]	23 m	23 m	30 m			
3	30 m	30 m	30 m	45 m		
4	—	—	45 m	45 m	45 m	60 m

[a]The width of a precision approach runway should be not less than 30 m where the code number is 1 or 2.
[b]1 m = 3.2808 ft.

Table 8.11c ICAO Recommended Practices—Width of Taxiways (4)

Code letter	Taxiway width
A	7.5 m[a]
B	10.5 m
C	15 m if the taxiway is intended to be used by airplanes with a wheel base less than 18 m
	18 m if the taxiway is intended to be used by airplanes with a wheel base equal to or greater than 18 m
D	18 m if the taxiway is intended to be used by airplanes with an outer main gear wheel span of less than 9 m
	23 m if the taxiway is intended to be used by airplanes with an outer main gear wheel span equal to or greater than 9 m.
E	23 m
F	25 m

[a]1 m = 3.2808 ft.

design group. (Refer to Table 8.10 and Figure 8.11.) Similar standards are given in Tables 8.14a and 8.14b for utility airports.

Transverse Grades

As shown in the typical section (Figure 8.13), runways are crowned or sloped away from the centerline to facilitate drainage. As a general rule, transverse runway slopes should be kept to a minimum consistent with drainage requirements. Normally, to prevent the accumulation of water on the surface, transverse grades of at least 1.0% are required. Maximum transverse slopes are specified to facilitate operational safety. Slopes up to 2.0% are permitted for runways that serve the smaller classes of aircraft (utility runways, and for ICAO code letters A and B). For all other runways, the maximum grade is 1.5%.

Beyond the runway edge, steeper slopes are employed to expedite the removal of surface water. Most agencies permit shoulder slopes up to 5.0% for the first 10 ft beyond the pavement edge. Beyond this point, slopes of 1.5–3.0% are commonly used, depending on the type of shoulder surface. The FAA further recommends a 1.5-in. drop from the paved surface to the graded shoulder surface. For taxiways, most agencies specify the same transverse gradient criteria recommended for runways.

Table 8.11d ICAO Recommended Practices—Taxiway Minimum Separation Distances (4)

	Distance between taxiway center line and runway center line (m)[a]										
	Instrument runways Code number				NonInstrument runways Code number				Taxiway center line to taxiway center line (m)	Taxiway, other than aircraft stand taxilane, center line to object (m)	Aircraft stand taxilane center line to object (m)
Code letter	1	2	3	4	1	2	3	4			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
A	82.5	82.5			37.5	47.5			23.75	16.25	12
B	87	87			42	52			33.5	21.5	16.5
C			168				93		44	26	24.5
D			176	176			101	101	66.5	40.5	36
E				182.5				107.5	80	47.5	42.5
F				190				115	97.5	57.5	50.5

[a] 1 m = 3.2808 ft.

Note 1: The separation distances shown in columns 2–9 represent ordinary combinations of runways and taxiways. The basis for development of these distances is given in the *Aerodrome Design Manual*, Part 2 (13).

Note 2: The distances in columns 2–9 do not guarantee sufficient clearance behind a holding aeroplane to permit the passing of another aeroplane on a parallel taxiway, see *Aerodrome Design Manual*, Part 2 (13).

Table 8.12 FAA Runway Dimensional Standards for Transport Airports (Aircraft Approach Categories C and D) (1)

Design item	Airplane design group					
	I	II	III	IV	V	VI
Runway safety area width (ft)[a,b]	500 (150 m)	500 (150 m)	500 (150 m)	500 (150 m)	500 (150 m)	500 (150 m)
Runway safety area length prior to landing threshold	600 (180 m)	600 (180 m)	600 (180 m)	600 (180 m)	600 (180 m)	600 (180 m)
Runway safety area length beyond runway end (ft)	1000 (300 m)	1000 (300 m)	1000 (300 m)	1000 (300 m)	1000 (300 m)	1000 (300 m)
Runway width (ft)	100 (30 m)	100 (30 m)	100[c] (30 m)	150 (45 m)	150 (45 m)	200 (60 m)
Runway shoulder width (ft)	10 (3 m)	10 (3 m)	20[c] (6 m)	25 (7.5 m)	35 (10.5 m)	40 (12 m)
Runway blast pad width (ft)	120 (36 m)	120 (36 m)	140[c] (42 m)	200 (60 m)	220 (66 m)	280 (84 m)
Runway blast pad length (ft)	100 (30 m)	150 (45 m)	200 (60 m)	200 (60 m)	400 (120 m)	400 (120 m)
Runway object-free area width (ft)	800 (240 m)	800 (240 m)	800 (240 m)	800 (240 m)	800 (240 m)	800 (240 m)
Runway object-free area length beyond runway end (ft)	1000 (300 m)	1000 (300 m)	1000 (300 m)	1000 (300 m)	1000 (300 m)	1000 (300 m)
Visual runways and runways with not lower than 3/4 mile (1200 m) approach visibility minima:						
Runway centerline to:						
Taxiway/taxilane centerline (ft)	300 (90 m)	300 (90 m)	400 (120 m)	400 (120 m)	Varies[e]	500 (150 m)
Aircraft parking area (ft)	400 (120 m)	400 (120 m)	500 (150 m)	500 (150 m)	500 (150 m)	500 (150 m)
Runways with lower than 3/4 statute mi (1200 m) approach minima:						
Runway centerline to:						
Taxiway/taxilane centerline (ft)	400 (120 m)	400 (120 m)	400 (120 m)	400 (120 m)	Varies[f]	550[d]
Aircraft parking area (ft)	500 (150 m)	500 (150 m)	500 (150 m)	500 (150 m)	500 (150 m)	500

[a] 1 ft = 0.3048 m.
[b] For runways designed to serve Aircraft Approach Category D, the runway safety area width increases 20 ft for each 1000 ft of airport elevation above mean sea level.
[c] For Airplane Design Group III serving airplanes with maximum certificated weight greater than 150,000 lb, the standard runway width is 150 ft, the shoulder width is 25 ft, and the runway blast pad width is 200 ft.
For approaches with visibility down to 1/2 statute miles, the separation distance increases to 500 ft (150 m) plus elevation adjustment. For approaches with visibility of less than 1/2 statute mile, the separation distance increases to 550 ft (168 m) plus required OFZ elevation adjustment.
[e] Varies with elevation. See Reference 3
[f] Varies with elevation and approach minimum. See Reference 3

Table 8.13 FAA Taxiway Dimensional Standards (1)

Design item	Airplane design group					
	I	II	III	IV	V	VI
Taxiway safety area width (ft)[a]	49 (14.9)	79 (24.1)	118 (36.0)	171 (52.1)	214 (65.2)	262 (79.9)
Taxiway width (ft)	25 (7.6)	35 (10.7)	50[b] (15.2)	75 (22.9)	75 (22.9)	100 (30.5)
Taxiway edge safety margin (ft)[c]	5 (1.5)	7.5 (2.3)	10[d] (3.0)	15 (4.6)	15 (4.6)	20 (6.1)
Taxiway shoulder width (ft)	10 (3.0)	10 (3.0)	20 (6.1)	25 (7.6)	35 (910.7)	40 (12.2)
Taxiway object-free area width (ft)	89 (27.1)	131 (39.9)	186 (56.7)	259 (78.9)	320 (97.5)	386 (117.7)
Taxilane object-free area width (ft)	79 (24.1)	115 (35.1)	162 (49.4)	225 (68.6)	276 (84.1)	334 (101.8)
Taxiway centerline to:						
Parallel taxiway/taxilane centerline (ft)	69 (21.0)	105 (32.0)	152 (46.3)	215 (65.5)	267 (81.4)	324 (98.8)
Fixed or movable object (ft)	44.5 (13.6)	65.5 (20.0)	93 (28.3)	129.5 (39.5)	160 (48.8)	193 (58.8)
Taxilane centerline to:						
Parallel taxilane centerline (ft)	64 (19.5)	97 (29.6)	140 (42.7)	198 (112.5)	245 (74.7)	298 (90.8)
Fixed or movable object (ft)	39.5 (12.0)	57.5 (17.5)	81 (24.7)	112.5 (34.3)	138 (42.1)	167 (50.9)

[a] 1 ft = 0.3048 m.
[b] For airplane design group III taxiways intended to be used by airplanes with a wheelbase equal to or greater than 60 ft, the standard taxiway width is 60 ft (18 m).
[c] The taxiway edge safety margin is the minimum acceptable distance between the outside of the airplane wheels and the pavement edge.
[d] For airplanes in design group III with a wheelbase equal to or greater than 60 ft, the taxiway edge safety margin is 15 ft (4.5 m).

Table 8.14a FAA Runway Design Standards for Aircraft Approach Category A and B Visual Runways and Runways with Not Lower than 3/4-statute-mi (1200-m) Approach Visibility Minima (1)

Design item	Airplane design group				
	I[b]	I	II	III	IV
Runway width in ft[a]	60 (18 m)	60 (18 m)	75 (23 m)	100 (30 m)	150 (45 m)
Runway shoulder width in ft	10 (3 m)	10 (3 m)	10 (3 m)	20 (6 m)	25 (7.5 m)
Runway blast pad width in ft	80 (24 m)	80 (24 m)	95 (29 m)	140 (42 m)	200 (60 m)
Runway blast pad length in ft	60 (18 m)	100 (30 m)	150 (45 m)	200 (60 m)	200 (60 m)
Runway Safety Area Width in ft	120 (36 m)	120 (36 m)	150 (45 m)	300 (90 m)	500 (150 m)
Runway Safety Area Length Prior to Landing Threshold in ft	240 (72 m)	240 (72 m)	300 (90 m)	600 (180 m)	600 (180 m)
Runway Safety Area Length beyond Runway End in ft	240 (72 m)	240 (72 m)	300 (90 m)	600 (180 m)	1000 (300 m)
Runway Object Free Area Width in ft	250 (75 m)	400 (120 m)	500 (150 m)	800 (240 m)	800 (240 m)
Runway object free area length beyond runway end in ft	240 (72 m)	240 (72 m)	300 (90 m)	600 (180 m)	1000 (300 m)
Runway centerline to:					
Hold line in ft	125 (38 m)	200 (60 m)	200 (60 m)	200 (60 m)	250 (76 m)
Taxiway/taxilane centerline in ft	150 (45 m)	225 (69 m)	240 (73 m)	300 (90 m)	400 (120 m)
Aircraft parking area in ft	125 (38 m)	200 (60 m)	250 (76 m)	400 (120 m)	500 (150 m)

[a] 1 ft = 0.3048 m.
[b] These dimensional standards are for facilities expected to serve only small airplanes.

Table 8.14b FAA Runway Design Standards for Aircraft Approach Category A and B Runways with Lower Than 3/4-statute mi (1200-m) Approach Visibility Minima[a]

Design item	Airplane design group				
	I[b]	I	II	III	IV
Runway width (ft)	75 (23 m)	100 (30 m)	100 (30 m)	100 (30 m)	150 (45 m)
Runway shoulder width (ft)	10 (3 m)	10 (3 m)	10 (3 m)	20 (6 m)	25 (7.5 m)
Runway blast pad width (ft)	95 (29 m)	120 (36 m)	120 (36 m)	140 (42 m)	200 (60 m)
Runway blast pad length (ft)	60 (18 m)	100 (30 m)	150 (45 m)	200 (60 m)	200 (60 m)
Runway safety area width (ft)[a]	300 (90 m)	300 (90 m)	300 (90 m)	400 (120 m)	500 (150 m)
Runway safety area length prior to landing threshold (ft)	600 (180 m)	180 (180 m)	180 (180 m)	180 (180 m)	180 (180 m)
Runway safety area length beyond runway end (ft)	600 (180 m)	600 (180 m)	600 (180 m)	800 (240 m)	1000 (300 m)
Obstacle-free zone width and length					
Runway object-free area width (ft)	800 (180 m)	800 (180 m)	800 (180 m)	800 (180 m)	800 (180 m)
Runway object-free area length beyond runway end (ft)	600 (180 m)	600 (180 m)	600 (180 m)	800 (180 m)	1000 (300 m)

[a]For other table footnotes see Ref. 1.
[b]These dimensional standards pertain to facilities for small airplanes exclusively

8.12 OBJECT-CLEARING CRITERIA

To ensure safe and efficient airport operations, the FAA requires that certain areas at or near airports be free of objects or else restricted to objects with a specific function and design. The agency's object clearance requirements are set forth as clearly defined areas or zones, which are described below.

Runway and Taxiway Safety Areas

Runway and taxiway safety areas are prepared, graded areas that are suitable for reducing the risk of damage to airplanes in the event of an undershoot, overshoot, or deviations from the runway or taxiway. Such areas must be clear of objects except for lights, signs, and other objects whose locations are fixed by function. Dimensions for runway and taxiway safety areas are given in Tables 8.12, 8.13, and 8.14.

Object-Free Area

An object-free area is defined as a two-dimensional ground area surrounding runways, taxiways, and taxilanes that is clear of objects, except for those objects whose locations are fixed by function (1). Dimensions of object-free areas are set forth in Tables 8.12, 8.13, and 8.14.

Obstacle-Free Zone

The FAA also provides standards for an obstacle-free zone (OFZ), defined as airspace that must be clear of object penetrations except for frangible navigation aids. The OFZ may include three subzones: the runway OFZ, the inner approach OFZ, and the inner transitional surface OFZ. These zones are depicted in Figure 8.14.

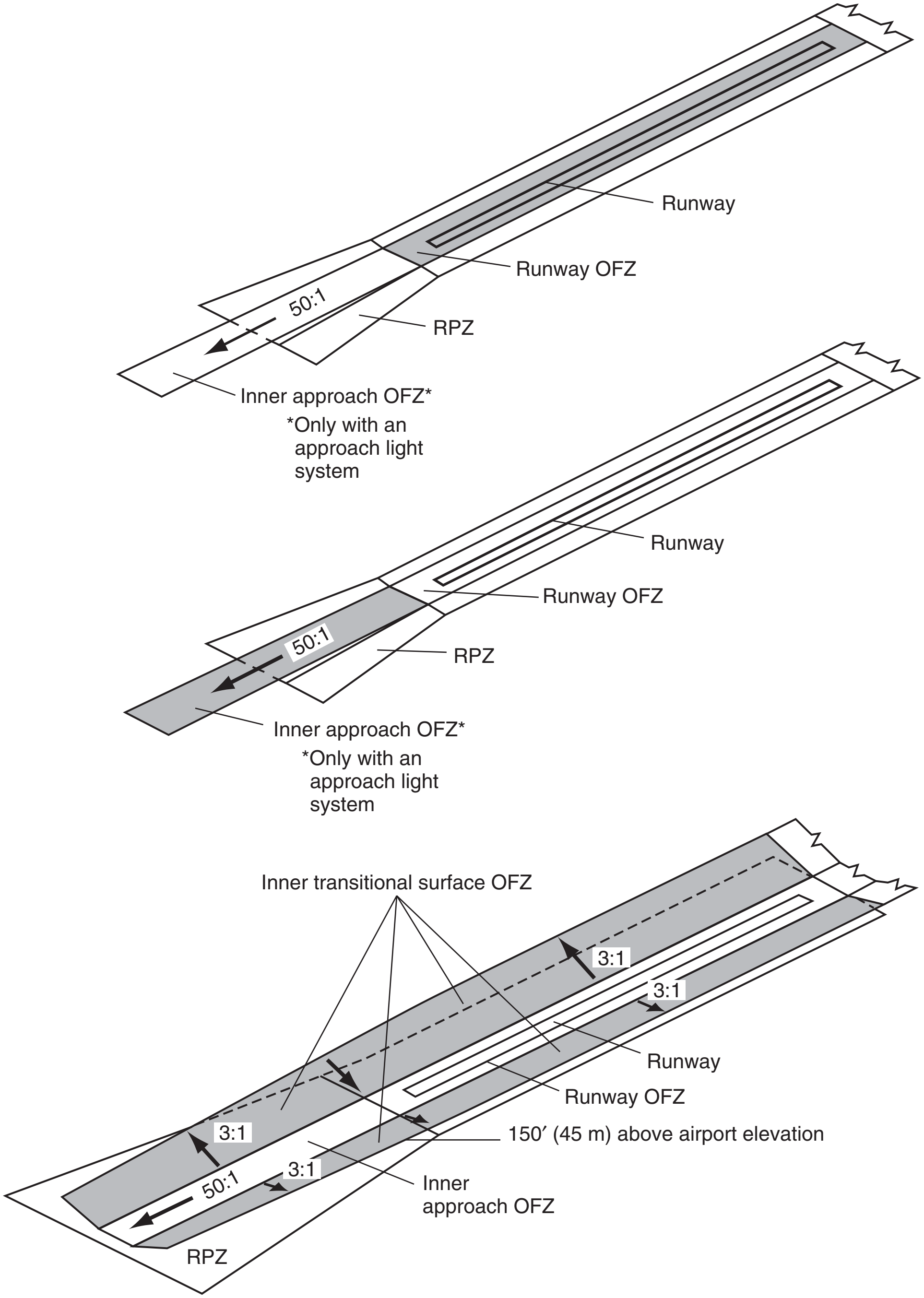


Figure 8.14 FAA components of OFZ.

Centered above the runway, the runway OFZ is the airspace "above a surface whose elevation at any point is the same as the elevation of the nearest point on the runway centerline" (1). It extends 200 ft beyond each end of the runway, and its width varies from 120 to 400 ft, depending on the size of airplanes served and the class of runway.

The inner approach OFZ is a defined volume of airspace centered on the approach area, and it applies only to runways with an approach lighting system. It begins 200 ft from the runway threshold and at the same elevation as the runway threshold and extends 200 ft beyond the last light unit in the approach lighting system.

The inner transitional OFZ applies only to precision instrument runways. As Figure 8.14 illustrates, this zone is a 3 (horizontal) to 1 (vertical) sloped surface that extends out from the edges of the runway OFZ and the inner approach OFZ to a height of 150 ft above the established airport elevation.

8.13 LONGITUDINAL-GRADE DESIGN FOR RUNWAYS AND STOPWAYS

From the standpoint of aircraft operational efficiency and safety, a level runway is ideal. However, this ideal is seldom achievable in practice. A runway safety area encompasses a vast expanse, and its preparation may involve the excavation and movement of great quantities of earth. The cost of such earth moving will generally rule out the attainment of a totally level runway gradient. Nevertheless, to facilitate smooth, comfortable, and safe landings and takeoffs, longitudinal runway grades should be as level as is practicable, and grade changes should be avoided. It should also be remembered that needless gradients have the effect of increasing the required runway length, thereby raising the construction costs.

As Table 8.15 and Figure 8.15 indicate, a maximum longitudinal grade of 1.25–1.50% is generally specified for runways that serve the largest classes of aircraft. Much flatter slopes should be used in the first and last quarters of such runways. Maximum grades of 2.0% are permitted at utility airports. The FAA (1) recommends that longitudinal-grade changes be not greater than 1.5% at air carrier airports and no more than 2.0% at general aviation airports. Similar criteria have been given by the ICAO (4).

Note from Table 8.15 that the FAA specifies the minimum distance between the points of intersection of two successive grade changes. This distance is based on the sum of the absolute values of corresponding grade changes.

Example 8.2 A −0.5% runway longitudinal grade intersects a −1.2% grade, which in turn intersects a +0.3% grade. Based on the specification for ICAO code number 3, what minimum distance should be used between the points of intersection for these grades?

Solution

The absolute value of the grade change for the first point of intersection is given by

$$A = -0.5\% - (-1.2\%) = 0.7\%$$

Table 8.15 Runway Longitudinal-grade Design Criteria[a] (1, 4)

	Maximum longitudinal grade (%)	Maximum grade, first and last quarter (%)	Maximum effective grade (%)	Maximum change (%)	Distance between points of intersection[b]	Length of vertical curve[c]/1% grade change)	
FAA					(ft) (m)	(ft)	(m)
Approach categories C and D	1.5	0.8	1.0	1.5	1000(A + B)[d]	1000	
Approach categories A and B	2.0	—	—	2.0	250(A + B)	300	
ICAO							
Code number 4	1.25	0.8	1.0	1.5	300(A + B) or 45 m		300
Code number 3	1.5	0.8[c]	1.0	1.5	150(A + B) or 45 m		150
Code number 2	2.0	—	2.0	2.0	50(A + B) or 45 m	75	
Code number 1	2.0	—	2.0	2.0	50(A + B) or 45 m	75	

[a]Runway grade changes shall also conform to sight distance criteria described in Section 8.10.

[b]1 ft = 0.3048 m.

[c]In the case of runways designed to serve aircraft approach categories A and B, no vertical curve is required when grade change is less than 0.4%.

[d]A and B are the intersecting slopes (%).

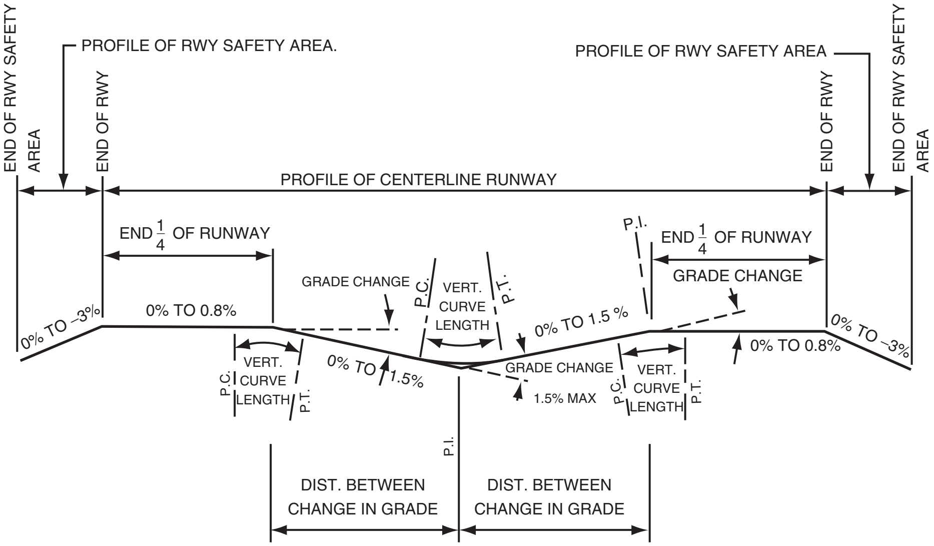


Figure 8.15 Longitudinal-grade criteria for transport airports: PI = point of intersection; PC = point of curvature; PT = point of tangency (1).

Table 8.16 Runway Sight Distance Requirements (1, 4)

Runway grade changes shall be such that any two points Y ft above the runway centerline will be mutually visible for a minimum distance of X ft.		
Airport category	Y^a	X (ft)
FAA Airports—All	5 ft	Entire runway length[b]
ICAO code letter A	1.5 m	Half runway length
ICAO code letter B	2 m	Half runway length
ICAO code letter C, D, E, and F	3 m	Half runway length

[a] 1 ft = 0.3046 m.
[b] If full-length parallel taxiway is provided, X = half the runway length.

Similarly, the absolute value of the grade change for the second point of intersection is given by

$$B = -1.2\% - (+0.3\%) = 1.5\%$$

The minimum distance between points of intersection is

$$D = 492(A + B) = 492(0.7 + 1.5) = 1082\,\text{ft}$$

When there is a change in grade as great as 0.4%, a transition from one slope to another should be provided. The FAA recommends that the length of the transition curve be at least 300 ft for each 1% grade change at utility airports and 1000 ft for each 1% grade change at transport airports. Similar criteria for minimum lengths of vertical curves for the ICAO and the FAA are given in Tables 8.15.

Sight distance along runways should be as unrestrictive as possible and must adhere to the applicable requirements given in Table 8.16. The FAA (1) has also published special visibility criteria between intersecting runways.

Longitudinal-grade design criteria for that part of the runway safety area between the runway ends are generally the same as the comparable standards for the runway. Some deviations may be required because of taxiways or other runways in the area. In such cases, the longitudinal grades of the runway safety area should be modified to the extent feasible by the use of smooth curves.

For the first 200 ft of the runway safety area beyond the runway ends, the FAA (1) recommends that the slope be downward from the ends and not steeper than 3%. For the remainder of the safety area, the longitudinal slope should be such that no part of the runway safety area penetrates the approach surface or clearway plane. The maximum negative grade is 5% for that part of the safety area. A maximum grade change of ±2% is specified for points of intersection, and vertical curves are recommended where practical (1).

8.14 LONGITUDINAL-GRADE DESIGN FOR TAXIWAYS

Since aircraft movements along taxiways are relatively slow, longitudinal-grade design standards for taxiways are not as rigorous as for runways. Operationally, level taxiways are preferred. But there is also a need for taxiway gradients to harmonize with associated parallel-runway gradients.

At the highest functional airport classes, the maximum taxiway gradient of 1.5% is generally specified. This includes taxiways for all FAA air carrier airports and for ICAO code letters C, D, E, and F. The FAA specifies a maximum taxiway gradient of 2.0% for utility airports. Maximum longitudinal taxiway gradients of 3.0% are permitted for ICAO code letters A and B.

Agencies generally agree that taxiway vertical curves should be at least 30 m (100 ft) long for each 1% grade change. The ICAO permits taxiway vertical curves as short as 25 m (83 ft) for each 1% grade change where the code letter of the longest runway served is A or B. The FAA further recommends that, at transport airports, the distance between points of intersection of vertical curves be kept to a minimum of 100 times the sum of the grade changes (in percentages) associated with the two vertical curves; that is, using the terminology of the previous section, the minimum distance between vertical points of intersection should be $100(A + B)$.

The FAA has no specific line-of-sight requirements for taxiways but recommends that special analyses be made of sight distance where taxiways and runways intersect. The ICAO recommendations (4) are as follows:

> Where slope changes on taxiways cannot be avoided, they should be such that, from any point:
>
> **1.** Three meters above the taxiway, it will be possible to see the whole surface of the taxiway for a distance of 300 m from that point, where the code letter is C, D, E, or F.

2. Two meters above the taxiway, it will be possible to see the whole surface of the taxiway for a distance of 200 m from that point, where the code letter is B.
3. One and a half meters above the taxiway, it will be possible to see the whole surface of the taxiway for a distance of 150 m from that point, where the code letter is A.

8.15 TAXIWAY DESIGN

The design of the taxiway system is determined by the volume of air traffic, the runway configuration, and the location of the terminal building and other ground facilities. The ICAO (1, 13) and the FAA (1) have published general guidelines for taxiway layout and design, which are summarized below.

Taxiway routes should be direct, straight, and uncomplicated. Where curves cannot be avoided, their radii should be large enough to permit taxiing speeds on the order of 20–30 mph. Radii corresponding to taxiing speeds of 20, 30, and 40 mph are, respectively, 200, 450, and 800 ft. The taxiway pavement should be widened on curves and at intersections to lessen the likelihood of an aircraft's wheels dropping off the pavement. Table 8.13 shows recommended taxiway edge safety margins, the minimum distance between the outside of the airplane wheels and the pavement edge. The dimensions given in Table 8.17 are suitable for the design of taxiway fillets at intersections, entrance taxiways, and other areas where low-speed movements are anticipated. These standards should give adequate taxiway edge safety margins for the aircraft in each design group. The symbols for these dimensions are keyed to those shown in Figure 8.16. Where these standard fillet designs are not appropriate (e.g., because of space limitations or because a particular type of airplane does not have the minimum taxiway edge safety margin), the pavement fillet may be custom designed using equations given in reference 1.

The minimum separations between centerlines of parallel taxiways are based on a minimum wing tip clearance of 0.2 times the wingspan of the most demanding airplane plus a 10-ft (3-m) margin of safety (1). The same wing tip clearance is recommended for taxiway-to-obstacle separation (13). In the immediate terminal area where taxiing is

Table 8.17 Taxiway Fillet Dimensions

		Airplane design group					
Design item	Dimension[a]	I	II	III[b]	IV	V	VI
Radius of taxiway turn (ft)[c]	R	75	75	100	150	150	170
Length of lead-in to fillet (ft)	L	50	50	150	250	250	250
Fillet radius for judgmental oversteering symmetrical widening (ft)	F	62.5	57.5	68	105	105	110
Fillet radius for judgmental oversteering one side widening (ft)	F	62.5	57.5	60	97	97	100
Fillet radius for tracking centerline (ft)	F	60	55	55	85	85	85

[a]Letters are keyed to those shown as dimension on Figure 8.9.
[b]Airplane design group III with a wheelbase equal to or greater than 60 ft, should use a fillet radius of 50 ft.
[c]ft = 0.3048 m.

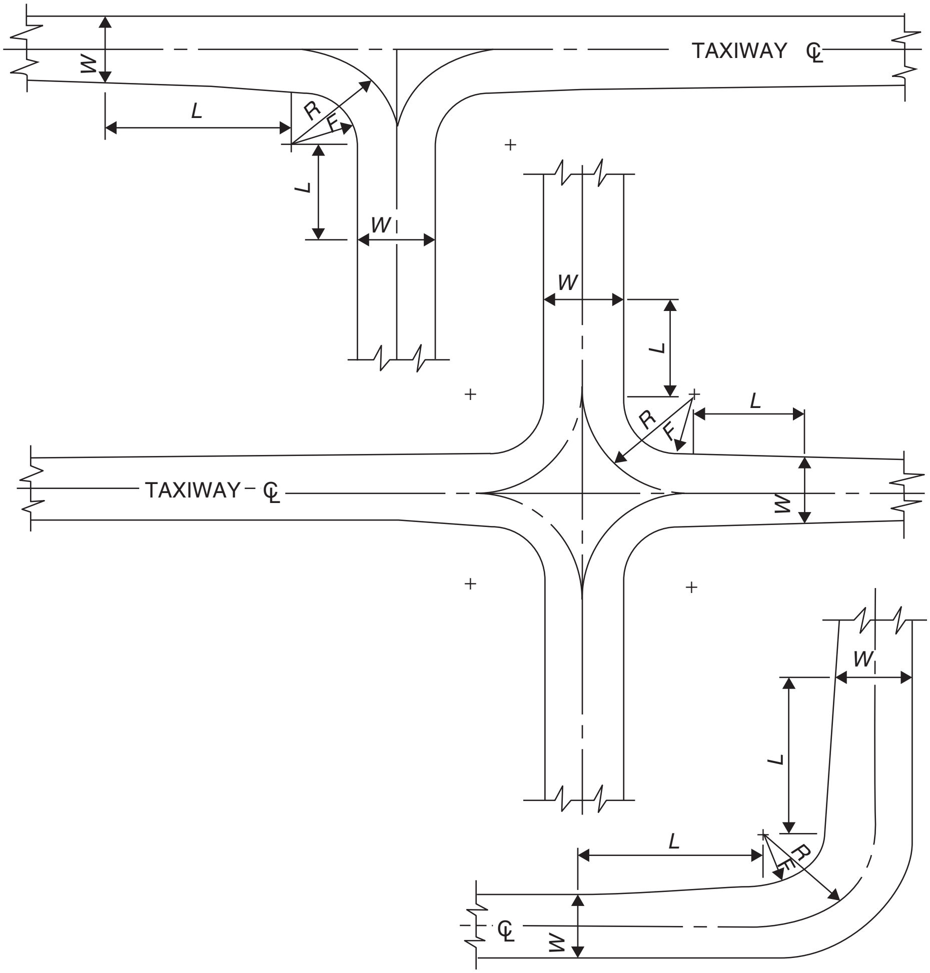


Figure 8.16 Typical taxiway intersection details (1).

accomplished at slow speeds and with special guidance procedures and devices, a wing tip clearance of 0.1 times the wingspan plus the margin of safety is recommended. Assuming these wing tip clearances, the required separations, expressed in feet, for taxiway design become:

Taxiway centerline to taxiway centerline: $1.2W + 10$

Taxiway centerline to obstacle: $0.7W + 10$

Taxiway centerline to obstacle in terminal area: $0.6W + 10$

where W = wingspan of the most demanding aircraft, ft

In most instances, the clearance and separation distances given in Table 8.13 will satisfy the minimum wing tip clearances. However, at high-density airports where higher taxiing speeds are desired, larger clearances and separations should be used.

At large and busy airports, the time an average aircraft occupies the runway frequently determines the capacity of the runway system and the airport as a whole. This indicates that exit taxiways should be conveniently located so that landing aircraft can vacate the runway as soon as possible.

Figure 8.17 illustrates three common types of exit taxiways. Perpendicular exit taxiways may be used when the design peak-hour traffic is less than 30 operations per hour. To expedite the movement of landing aircraft from the runway, most modern air carrier airports provide exit taxiways that are oriented at an angle to the runway centerline. The exit taxiway angled 45° to the runway centerline is recommended for small aircraft. It will accommodate an exit speed of 40 mph. The exit configuration in Figure 8.17 (30° angle of intersection) permits runway turnoff speeds up to 60 mph.

The number and location of exit taxiways depend on the type and mix of aircraft using the runway. At utility airports, three exit taxiways are generally sufficient: one at the center and one at each end of the runway. A modern air carrier runway may have three angled exit taxiways for each landing direction plus several 90° exit taxiways.

For a given class of aircraft, the desired location of a high-speed exit taxiway can be calculated based on the following design factors:

1. Distance from the threshold to touchdown
2. Touchdown speed
3. Initial exit speed (turnoff speed at the point of curvature) (PC)
4. Rate of deceleration

Other planning factors include location of the terminal/apron area, location of other runways and their exits, optimization of traffic flow in the operational area, and avoidance of unnecessary taxi detours (1).

The distance from the threshold to touchdown averages about 1500 ft for turbojet aircraft (categories C and D)* and approximately 1000 ft for other aircraft (category B). Typical touchdown speeds are 164, 202, and 237 ft/sec, respectively, for category B, C, and D aircraft.

Initial exit speeds are generally taken to be 40 mph (59 ft/sec) for small aircraft and 60 mph (88 ft/sec) for large aircraft with a deceleration rate of 5 ft/sec^2 (1). The ICAO recommends a deceleration rate of 1.25 m/sec^2 (4.1 ft/sec^2) for computing the location of exit taxiways (13).

Using its own classification, the ICAO groups aircraft according to their threshold speeds:

Group A	Less than 169 km/hr (91 knots)
Group B	Between 169 km/hr (91 knots) and 222 km/hr (120 knots)
Group C	Between 223 km/hr (121 knots) and 259 km/hr (140 knots)
Group D	Between 261 km/hr (141 knots) and 306 km/hr (165 knots)

*The categories here refer to groupings of airplanes in U.S. Standard for Terminal Instrument Procedures (TERPS). These categories, which are made on the basis of approach speed and maximum landing weight, should not be confused with those mentioned in Section 6-4 for the ICAO categories designated by the same letters.

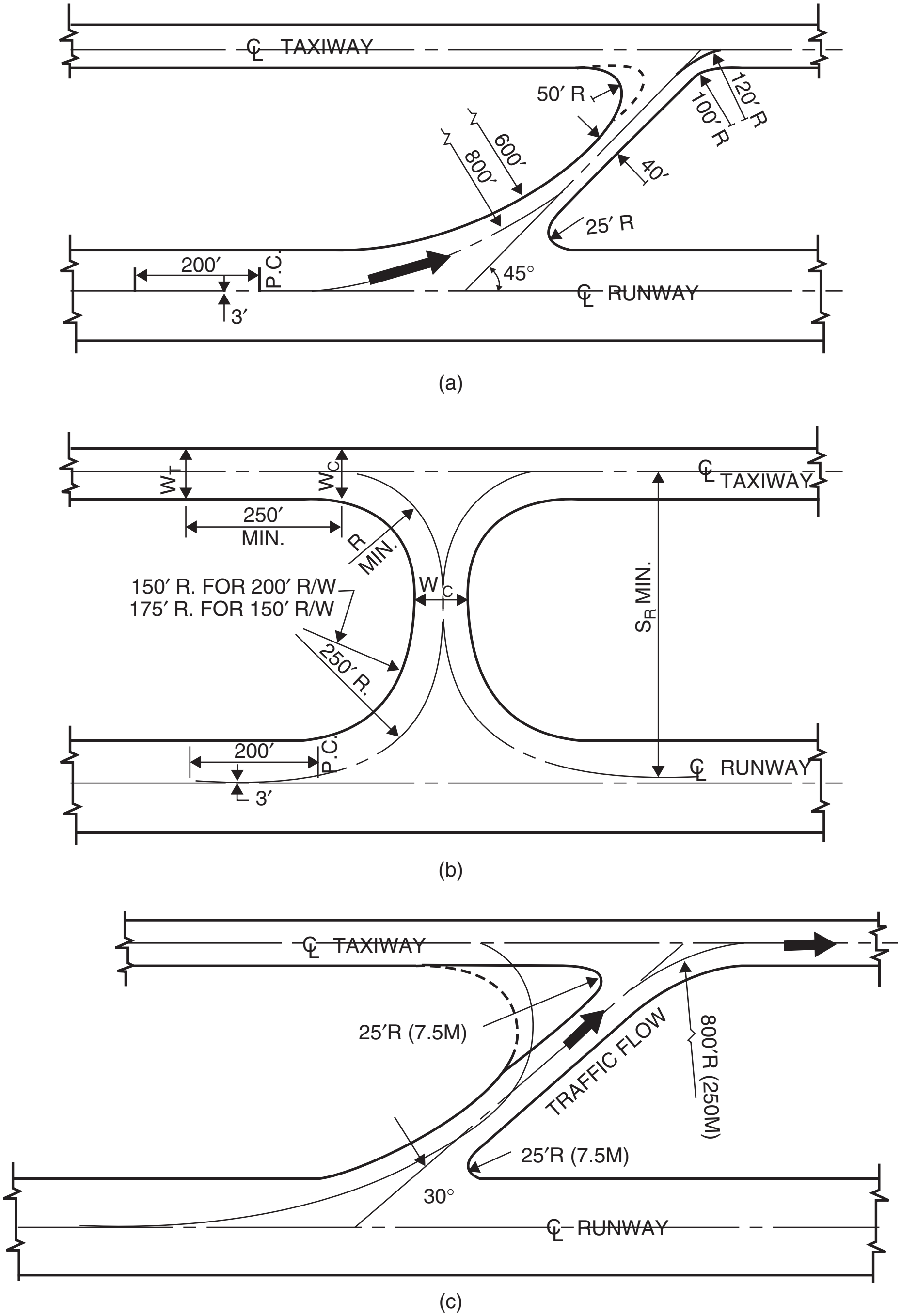


Figure 8.17 Common types of exit taxiways: (a) angled exit taxiway for small airplanes; (b) 90° exit taxiway; (c) angled exit taxiway for large airplanes (13).

The distance from touchdown to ideal exit location can be determined by the following formula:

$$D = \frac{(S_1)^2 - (S_2)^2}{2a} \tag{8.5}$$

where

S_1 = runway touchdown speed (ft/sec)
S_2 = runway initial exit speed (ft/sec)
a = deceleration (ft/sec^2)

The distance from the threshold to the PC of the exit curve is determined by adding to D a distance of 1000 or 1500 ft, as appropriate. Normally, it is necessary, however, to correct this distance for local altitude and temperature conditions. It is suggested that exit taxiway distances from the threshold be increased 3% per 1000 ft of altitude over that required for standard sea level and 1.5% per 10°F above 59°F.

8.16 HOLDING APRONS

A holding apron is an area contiguous to the taxiway, near the runway entrance, where aircraft park briefly before taking off while cockpit checks and engine runups are made. The use of holding aprons reduces interference between departing aircraft and minimizes delays at this portion of the runway system.

In the case of utility airports, the FAA (1) recommends the installation of holding aprons when air activity reaches 30 operations per normal peak hour. Space to accommodate at least two, but not more than four, is recommended for small airports (14):

> General space requirements may be approximated by applying factors to the wingspan of the aircraft that will be using the facility. These factors will provide a guide for space requirements for maneuvering and wingtip clearance. Studies of aircraft equipped with *dual-wheel undercarriages* reveal that the diameter of the space required to maneuver and hold such aircraft may be closely approximated by multiplying the wingspan by factors varying between 1.35 and 1.50. Similar investigations for dual-tandem gear aircraft reveal that factors of between 1.60 and 1.75 will suffice. This factor for small aircraft with a conventional single-wheel gear varies between 1.50 and 1.65.

8.17 TERMINAL APRONS

Airport designers must provide paved areas where aircraft may be parked while fueling, light maintenance, loading and unloading of passengers and cargo, and similar operations are performed. Perhaps the most important of such areas is the terminal apron, which is located adjacent to the terminal building. Individual loading positions along the terminal apron are known as "gate positions" or "stands." This section discusses approaches to determining the size and design of gate positions and of determining the total area of the terminal apron.

The design of the airport apron area depends on four factors:

1. The configuration of the terminal (linear, inboard pier, satellite, etc.) and the clearances required for safety and the protection of passengers from propeller wash, blast, heat, noise, and fumes

2. The movement characteristics of the aircraft to be served (e.g., turning radius), whether it moves into and out of the apron under its own power, and the angle at which it parks with respect to the building
3. The physical characteristics of the aircraft (i.e., its dimensions and service points and their relationship to the terminal and its appendages)
4. The types and sizes of ground service equipment and the maneuvering, staging, and operational practices employed in their use

Aircraft usually taxi into the terminal apron area, but they either taxi out or are pushed from the apron area by a tractor. The taxi-out arrangement is normally employed at low-volume locations where smaller aircraft may maneuver with few restrictions on space of operation, but the push-out procedure is often used for large jet aircraft.

The FAA (15) has published guidelines for the sizing and clearances required for aircraft gate design in terms of five aircraft gate types:

Gate type A serves aircraft in airplane design group III, which have a wingspan of between 79 and 118 ft. Route structures of these aircraft vary from short range/low density to medium range/high density.

Gate type B serves aircraft in airplane design group IV, with wingspans between 118 and 171 ft and a fuselage length less than 160 ft. These aircraft have passenger demands similar to those aircraft using gate type A but usually serve longer range routes.

Gate type C serves aircraft in airplane design group IV, which have a fuselage length greater than 160 ft. These aircraft typically have a route structure similar to the aircraft using gate type B but serve a higher passenger volume.

Gate type D serves aircraft in airplane design group V, which have wingspans between 171 and 196 ft. These aircraft operate over long-range routes and carry a high volume of passengers.

Gate type E serves aircraft in airplane design group VI, which have wingspans between 214 ft up to 262 ft. These aircraft also operate over long-range, high passenger volume routes.

Because of differences in type of terminal configuration, types of aircraft and service equipment, and airline policies and procedures, the sizing and clearances for the design of gate positions can vary considerably. The FAA has published the following clearance recommendations for planning purposes (9).

Nose-to-Building Clearances

These clearances may vary from 8 ft to more than 30 ft, depending on the method of push-out used, the aircraft's nose gear position relative to its nose, the length of tug, and maneuvering and parking requirements. For planning purposes, the FAA recommends the following:

For gate type A	30 ft	9 m
For gate types B, C	20 ft	6 m
For gate types D and E	15 ft	4.5 m

Wing-Tip-to-Wing-Tip Clearances

In the aircraft gate area, the following wing tip clearances are recommended:

FAA Gate Type		ICAO	
Code Letter	Clearance	Code Letter	Clearance
A	15 ft	A	3 m
B	25 ft	B	3 m
C	25 ft	C	4.5 m
D	25 ft	D	7.5 m
E	25 ft	E	7.5 m
		F	7.5 m

Where transporters are used to ferry passengers between the terminal building and remotely parked aircraft, a wing-tip-to-wing-tip clearance of at least 45 ft (13.7 m) should be allowed.

Aircraft Extremity to Building Clearances

As indicated in Figure 8.18, the FAA (8) recommends a 45-ft clearance from aircraft extremity to building for what it designates as an inboard pier gate and otherwise at least a 20-ft clearance. Many designers would increase that dimension to 20–25 m, especially when an airside road is positioned next to the terminal building.

Effect of Aircraft Parking Orientation on Apron Requirements

The overall area of the apron is greatly affected by the designer's choice of aircraft parking procedure. The minimum area of the apron is achieved where aircraft are parked nose-in to the terminal or pier and taxi-in push-out procedures are used. This however requires the use of apron tugs to push the parked aircraft out, involving additional capital expenditure and the use of ground handling apron staff. Therefore, sometimes there is a trade-off to be made between the provision of additional apron space and the savings from the use of less ground handling equipment and lower handling staff costs. At larger airports, providing larger aprons cannot be considered as an option, because the size of the terminal required would involve unacceptable internal walking distances.

The area required for an airplane negotiating a turn is governed by the size of the nose wheel angle that is used. Thus, under taxi-in and taxi-out conditions, the minimum size of the gate position is determined by the maximum nose wheel angle, which is defined by the manufacturer. The geometry of minimum aircraft parking turns is illustrated by Figure 8.19. To locate an aircraft's turning center, a line is extended at right angles to the nose wheel axle to intersect a line drawn through the center of the aircraft undercarriage. This point of intersection is the turning center about which the aircraft rotates in a turn.

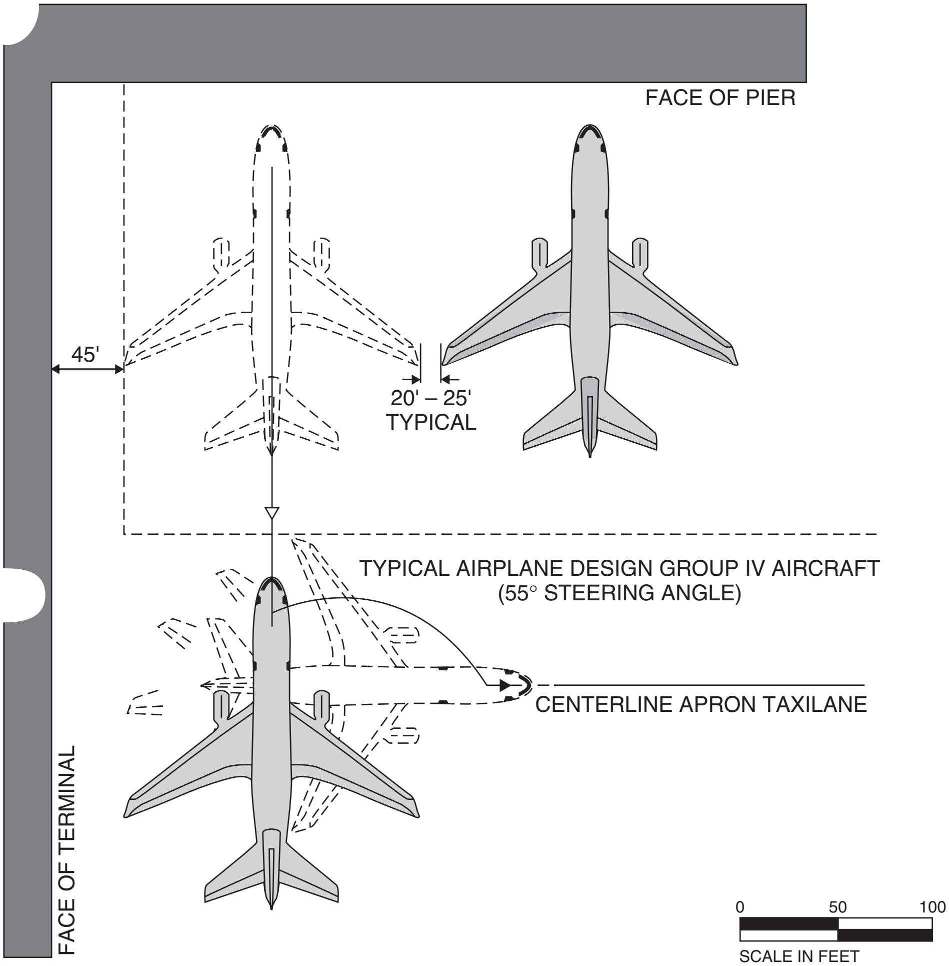


Figure 8.18 Recommended clearances for inboard pier gates (15).

Figure 8.20 indicates the dimensions that determine the requirements of a Boeing 737-900 making a 180° turn. When an aircraft maneuvers into and out of a parking position on the apron, the FAA recommends that clearances allow 10 ft forward roll for nose wheel alignment roll prior to stopping and another 10 ft forward roll prior to turn for taxiing out.

The FAA has also published graphs and equations that may be used to determine clearances for aircraft turning and taxiing out of a parking position for parking angle values ranging from 40 to 90°. Furthermore, a design procedure for determining the separation of aircraft parking stands that utilizes polar coordinate graph paper has been described by the ICAO (13).

Manufacturers now publish manuals for airport planning for each aircraft series, such as references 16 and 17. Among the data provided are those that describe aircraft

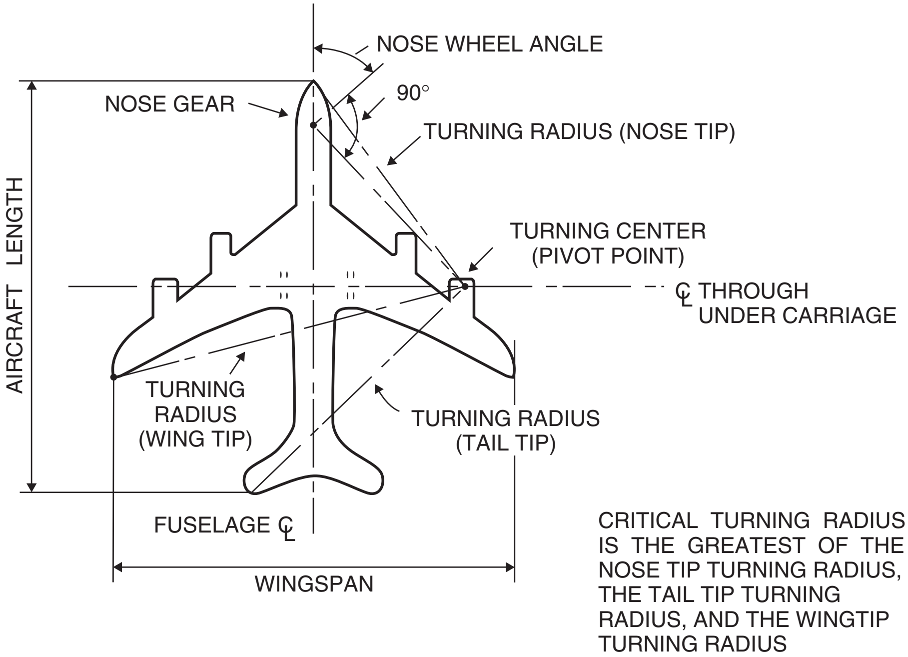
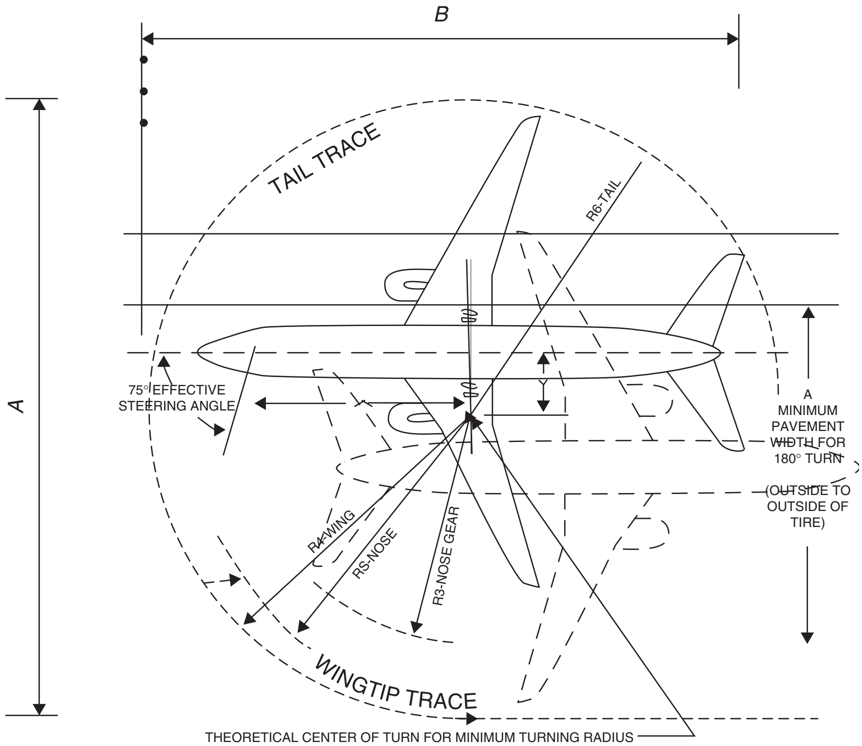


Figure 8.19 Geometry of minimum aircraft parking turns.

dimensions and ground maneuvering requirements including the location of the turning point and the radii of the traces of the nose, wing tip, and tail under various effective steering angles. Because the taxi-in push-out system of maneuvering is so common, when a taxi-in, taxi-out design must be used, it is suggested that the following design procedure is followed using these manufacturers' data:

1. Determine the number of required stands in each ICAO category A–F or FAA design groups I–VI
2. Choose the critical design aircraft for each stand category. (The critical aircraft chosen may not be the largest in the airplane categories, if smaller aircraft are to be used in service and aircraft of the maximum dimensions are never to be used.)
3. Determine the parking configuration to be used: nose-in, angled nose-in, nose-out, angled nose-out, nose-out, or parallel.
4. Compute the critical apron width and depth dimensions from manufacturers' planning manuals.
5. Compute the overall apron area from a composite apron layout plan.

In practice, aprons are now planned using software that is an application of computer-aided design (CAD). Various software systems are in use, all of which contain a library of aircraft types with accurate dimensions and pertinent steering geometry.



AIRPLANE MODEL	EFFECTIVE TURNING ANGLE (DEG)	X		Y		A		R3		R4		R5		R6	
		FT	M	FT	M	FT	M	FT	M	FT	M	FT	M	FT	M
737-600	75	36.8	11.2	9.9	3.0	60.8	18.5	39.3	12.0	68.5	20.9	51.5	15.7	61.9	18.9
737-700	75	41.3	12.6	11.1	3.4	66.4	20.3	43.8	13.3	69.6	21.2	55.9	17.0	65.5	20.0
737-800	75	51.2	15.6	13.7	4.2	79.1	24.1	53.8	16.4	72.1	22.0	65.9	20.1	74.9	22.8
737-900, -900ER	75	56.3	17.2	15.0	4.6	85.9	26.2	59.2	18.1	73.5	22.4	71.3	21.7	78.0	23.8

Figure 8.20 Dimensions of 180° turn for Boeing 737-900 (Boeing Airplane Company).

This enables the designer to superimpose a stand mix on the apron area in a particular planning scenario, and the software output gives overall and detailed dimensions of the final design, with all required minimum or required clearances in-built in the computed solution.

Figure 8.21 is an illustration of the output of one such program which can be directly used for apron dimensioning. Scaled sketches of the requirements of 180° turns are also available in reference 6.

An apron and terminal planning report (9) prepared for the FAA provides scaled outlines for six groups of aircraft that comprise the bulk of the U.S. fleet. The report gives general guidance for planning airport apron-terminal complexes. It includes scaled

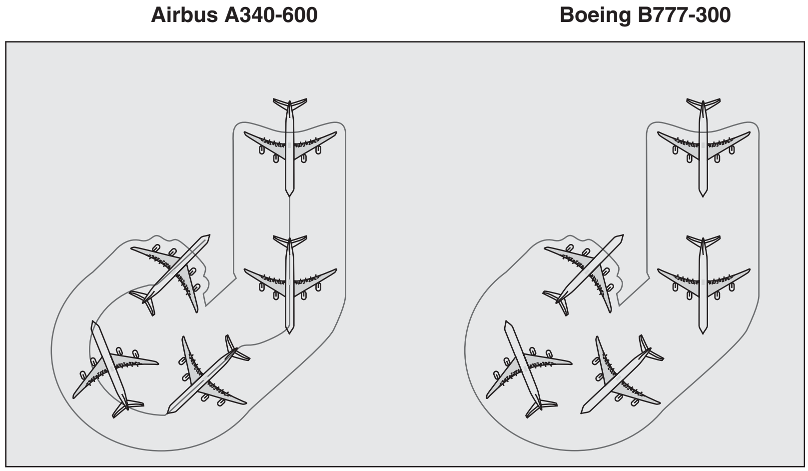


Figure 8.21 CAD simulations of taxi-in/taxi-out parking turns for an Airbus A340-6000 and a B777-300. (Courtesty of PathPlanner, Simtra AeroTech AB.)

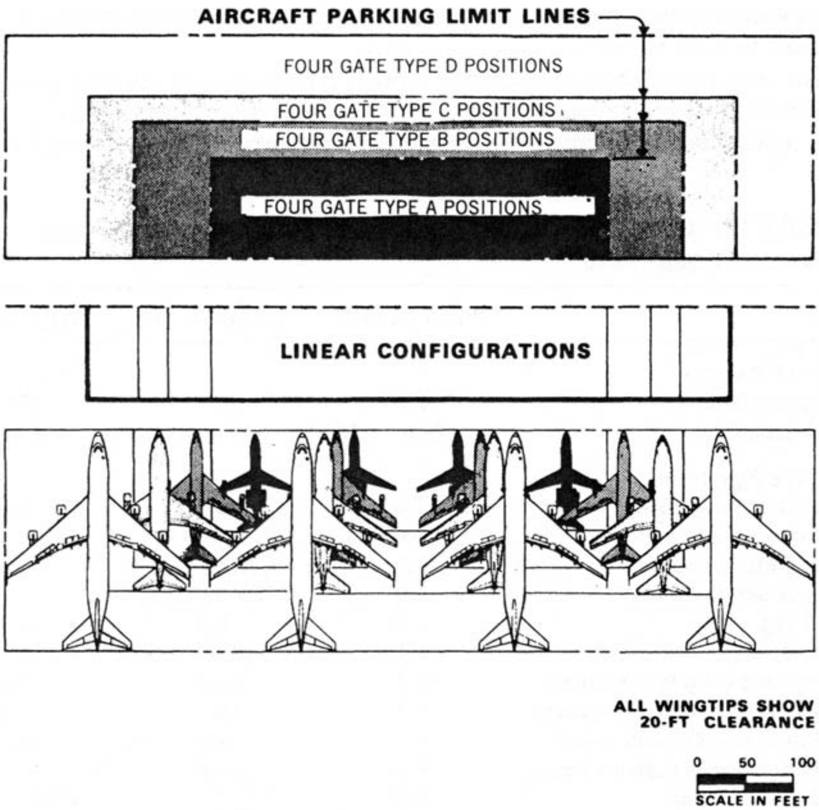


Figure 8.22 Scaled sketches showing apron space requirements for six groups of aircraft. (*Source*: Adapted from ref. 9.)

sketches showing apron space requirements for various combinations of aircraft groups, terminal configuration, parking arrangement, and operational procedures (taxi-out, push-out). Similar sketches have been published by the FAA showing scaled typical gate position layouts for selected aircraft and gate types. Figure 8.22 gives an example.

The designer of terminal aprons must also consider the need for apron space and vertical clearances for service equipment. A wide variety of equipment is required to service modern aircraft, as Figure 8.23 illustrates. Table 8.18 lists the dimensions of various pieces of ground service equipment. Generally, a minimum of 10 ft should be added to the depth of the apron to permit service access to the aircraft. When nose-in parking is used, as much as 30 ft additional depth may be required for operation of the push-out tractor.

A service road, typically 20 to 30 ft wide, must be provided either adjacent to the terminal or on the airside of the gate positions. If the road is placed next to the terminal

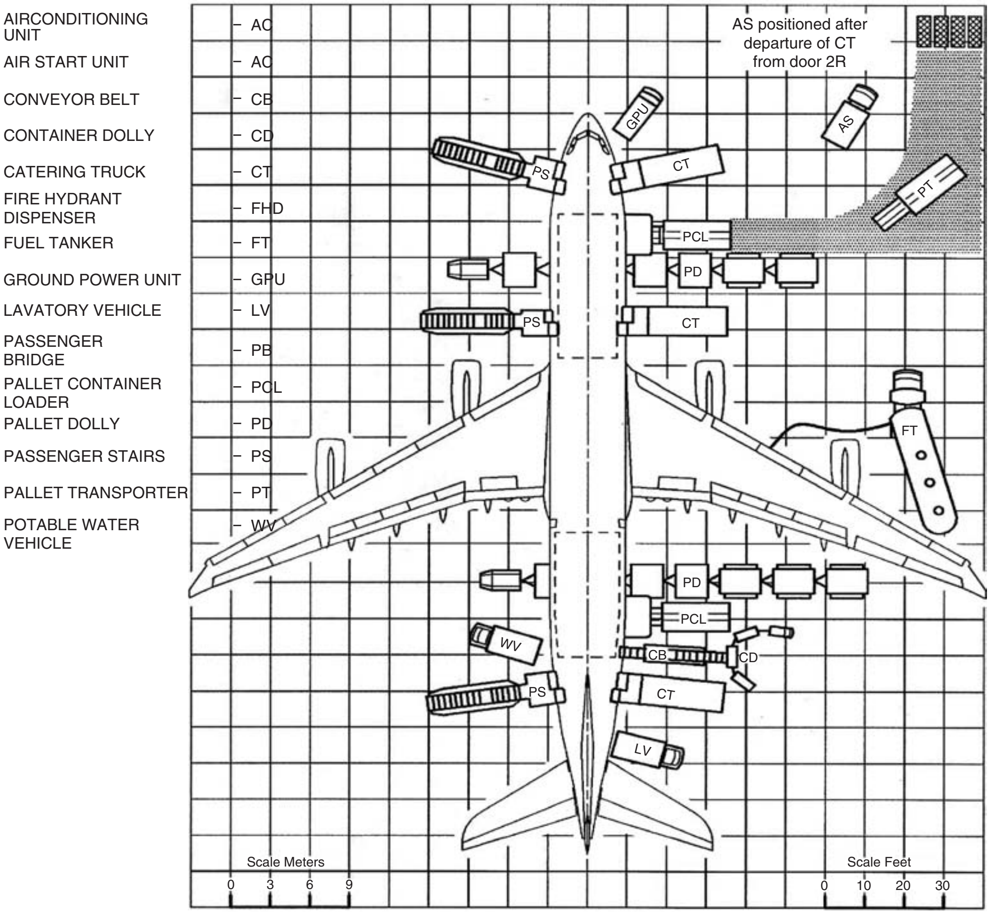


Figure 8.23 Ground servicing arrangement for A340-200/300 series aircraft. (*Source*: Manufacturer's data.)

Table 8.18 Ground Servicing Equipment Summary: Dimensions of Ground Equipment

Equipment	L (ft)	L (m)	W (ft)	W (m)
Passengers				
Passenger stairs	25.7	7.8	9.6	2.9
Baggage				
Cart, large	14.9	4.5	5.6	1.7
Cart, small	11.0	3.4	5.7	1.7
Baggage tug, large	12.7	3.9	5.4	1.6
Baggage tug, small	6.7	2.0	3.3	1.0
Conveyor belt	27.9	8.5	7.4	2.6
Cargo				
Pallet trailer	26.6	8.1	8.9	2.7
Container loader	30.2	9.2	11.8	3.6
Cabin service				
Catering vehicle	32.2	9.8	8.4	2.6
Vehicles				
Airside bus, standard	53.3	16.2	15.7	4.8
Airside bus, articulated	58.9	18.0	8.2	2.5
Firefighting unit	51.3	15.6	11.0	3.4
Snow sweeper	31.8	11.6	14.9	4.5
Ground support				
Hydrant vehicle	Up to 30.8	Up to 9.4	Up to 10.1	Up to 3.1
Fuel tanker	63.4	19.3	10.8	3.3
Deicing	35.6	10.8	10.2	3.1
Glycol recovery	26.6	8.1	9.2	2.8
Lavatory	19.8	6.0	7.4	2.3
Potable water	17.6	5.4	8.6	2.6
Tow bar	Up to 23.5	Up to 7.2		
Aircraft tugs				
Conventional	19.8	6.0	7.9	2.4

Source: Simtra AeroTech AB and Manufacturers' data.

building, it may be necessary to segregate passengers and service vehicles by use of nose-loading bridges. This calls for a clearance under the bridges of about 15 ft. If the service road is located on the airside of the parked aircraft, special precautions may need to be taken to minimize conflicts between ground vehicles and aircraft and to prevent collisions.

The effects of jet blast should also be considered in determining gate position size and location (1, 5). It is sometimes necessary to install jet blast deflector screens or fences to protect workers and possibly passengers.

The CAD apron design programs discussed above also contain data of ground servicing vehicles and other equipment that will need to be accommodated on the apron. Such software permits the siting of the ground servicing equipment and also is able to show areas affected by jet blast during the ground maneuvering operation.

Finally, to facilitate taxiing, towing, and servicing activities, apron slopes should be kept to a minimum, consistent with the need for good drainage. Apron slopes should not exceed 1.0%, and in aircraft fueling areas, a maximum slope of 0.5% is preferred. The apron should slope downward from the face of the terminal for proper drainage and safety in case of fuel spillage.

8.18 SUMMARY

What is referred to in this chapter with respect to terminal aprons relates to the most complicated area of a large airport. Simple terminals at small airports constitute the situations of the vast majority of existing airports. The large airports, however, carry the majority of all air passenger traffic, and the terminal–apron complexes of these airports are not simple. For large airports, the apron–terminal complex constitutes the majority of construction and investment. The reader is referred to reference 18 for further reading.

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9

Safeguarding the Airport

As the primary transport infrastructure assets in their respective regions, airports must be designed, managed, and operated with maximum protection against diverse and unforeseen hazard emergency circumstances. While it may be impossible to plan for total inclusion of all these emergency situations, as they may not be known ahead of their occurrence, an effective safeguarding framework for the airport must at least provide the basic requirements to minimize disruption to operation, damage and destruction to infrastructure and property, and harm to people. Therefore, essentially, there is no perfect plan to safeguard the airport against all kinds of emergencies.

A well-planned and designed airport may be subjected to exogenous factors that engineers would never anticipate. Airport developers and engineers could prepare a certain situational awareness framework that could be useful in minimizing adverse effects on the airport of such unforeseen situations—it would provide the first line of defense to safeguard the airport. So, what are the elements of this safeguarding framework?

Three major parts to an airport safeguarding framework come to the forefront: safeguarding the airport airspace and airfield and enabling optimal safety awareness, securing the airport's public areas against unlawful interference, and responding to emergencies of all kinds.

In recognition of the crucial importance of airports and the variety of unforeseen emergency conditions that may potentially occur, governments have set certain policies to prepare for and adapt to such adverse eventualities if and when they do occur. To ensure their timely implementation, governments enacted laws and regulations to implement these policies. Examples of government policies on airport emergency planning are discussed later.

In this chapter the context, purpose, framework and structure, implementation, and relevant underlying factors to the airport safeguarding framework are described.

9.1 AIRPORT SAFETY

The first line of defense for safeguarding the airport is providing a comprehensive plan for airport safety, including one for airport safety management.

In spite of the best efforts of pilots, air traffic controllers, aircraft manufacturers, airport designers, and best practices of airport operations, aircraft accidents and other airport mishaps continue to occur. Humans and machines are not entirely perfect—It is not surprising, therefore, that even with advances in modern technology accidents and mishaps still happen in airports. It is therefore necessary that more emphasis is placed on minimizing the occurrence of accidents and incidents in the airport as much as possible, minimizing harm to people and damage to the airport and aircraft, and avoiding interruption to normal operation at the airport. It is in this particular area that airport design can play a very important role. The following sections discuss different measures and practices to supplement the recognized international regulations and recommended airport design standards.

Nature of Aircraft Accidents

It is helpful for airport engineers to know where, when, and how aircraft accidents occur. Aircraft accident statistics indicate that only 5% of accidents occur en route. These are caused typically by structural fatigue, electromechanical failure, violent weather, hitting the ground (controlled flight into terrain, CFIT), or hitting obstructions close to the airport. Another 15% of accidents occur in the proximity (within 15 miles) of the airport arrival or departure areas. These accidents may be caused by weather, engine failure, or collision with another plane. These accidents are of primary concern to community emergency services around airports, and emergency response to these accidents are typically done with airports' emergency services under a mutual aid agreements as discussed later for airport emergency plans.

The remaining 80% of recent accidents occur within the airport active movement areas (i.e., runways, taxiways, and aircraft parking areas), an area 500 ft of the active runway centerline and 3000 ft of its threshold—the critical rescue and fire-fighting response area. It is where human lives get lost or aircraft are damaged in accidents due to unnecessary obstructions and unfortunate crashes. It is here where airport design could be improved and can be more safety conscious and most effective. Measures related to removing any obstruction hazards from runway approach areas would prevent potential damage to aircraft in runway incursion incidents.

Airport emergency managers categorize aircraft incidents on airports into:

- *Undershoots*. Constituting 40% of all incidents, where landing aircraft contact the ground or some elevated obstructions prior to the runway threshold. Due to the relatively high speed of the approach, the aircraft frequently continues its momentum and comes to rest near the runway, with severe structural damage usually occurring to the aircraft. Such accidents are typical of bad weather influence on the pilot's bad judgment of approach and touch-down area or wind shear and microburst.
- *Runway Veer-Off*. Constituting 35% of all incidents where the aircraft pilot loses directional control on either landing or takeoff caused by tire or break failure, skidding on a wet or icy runway during strong crosswind conditions.
- *Runway Overrun*. Constituting 25% of incidents and it occurs on landing caused by hydroplaning on an excessively wet runway, skidding on ice or snow, or excessive landing speed due to pilot error or misjudgment. A rejected takeoff would cause overruns caused by mechanical failure prior to liftoff, excessive aircraft weight, or a blown tire.

In terms of type of obstruction related to the above accident types and frequency of occurrence, the NTSB has identified the following: lighting structures (22%);

embankments and dikes (15%); fences and related structures (13%); ditches (13%); trees (10%); and hills, mounds, and boulders (10%).

Airport Safety Zones

Since 80% of aircraft accidents occur within the critical rescue and fire-fighting response area defined above, airport design standards specify "safety zones" around airports, mainly for runways within and outside the airport boundary.

Runway End Safety Zone. The FAA requires 1000 ft of potential overrun area as the runway end safety area. It is in this area where the majority of serious and fatal aircraft crashes occur. This area should be completely cleared of any obstructions. However, present airport standards do not go far enough to ensure smooth transition of the terrain between the overrun area and the runway clear zone. In fact, many runway end safety areas terminate with a steep embankment, ditch, river, railroad tracks, highway, or other obstructions that are impossible to negotiate by either the aircraft or emergency vehicles.

Public Safety Zones. Public safety zones (PSZs) are areas of land at the ends of runways where development is restricted in order to limit exposure to human fatality or injury from an aircraft crash on takeoff or landing. Public zones with an expected high density or that would attract masses of people include, shopping malls, industrial areas, stadiums, and other sports facilities should be considered as PSZs. Another risk is the unintended and uncontrolled release of potentially hazardous material, endangering the health and safety of the public and the environment. Such materials include flammable, explosive, and toxic substances such as from gas stations, chemical plants, and fuel tanks. An aircraft accident after landing or takeoff poses the biggest risk in the near vicinity of an airport (missed approach, skidding off a runway, engine failure, etc.) and may result in the uncontrolled release of hazardous material into the environment. To minimize environmental, health, and safety risks, it is recommended to restrict the land use for certain sensitive activities within a specified buffer zone, PSZs, which is defined as an area of 4 km^2 (36 million ft^2) extending laterally to a distance from the center of each runway of 0.5 km (1640 ft) in both directions and longitudinally 4.0 km (13,120 ft) measured from the end of each paved runway surface. Note that the dimensions of these areas may change in response to traffic growth at the airport and the risk analysis conducted.

Measures to Enhance Safety. An airport may adopt additional measures to enhance safety in and around the airport, including:

Avoiding Nonionizing Radiation. Nonionizing radiation is normally emitted by electromagnetic installations like radar, communication towers or repeaters, power cables, transformer substations, and other installations and devices. Based on the planned land use, a potential clearance zone in the proximity of airport-related emitters will be determined in which no permanent public land use (residential areas, hospitals, schools, business centers, etc.) is permitted.

Frangible-Mounted Wind Socks. Wind socks may be installed near the approach end of runways opposite the 1000-ft mark and 150 ft off the left side of the runway using frangible-mounted structures to minimize structural damage to aircraft if they crash into them.

Emergency Access and Egress. In order to respond to aircraft incidents and accidents outside the airport boundary fence, airport rescue and fire-fighting (ARFF) units have to be able to leave the fenced area from their station. Given the dimensions and weights of the larger intervention vehicles, they should be moving on paved surfaces rather than off-road. Emergency crash gates are designed for quick and easy exit and the roads leading to those gates have to be connected to a road network outside the fence. Conversely, in case of an aircraft accident within the airport boundary, mutual aid units for support and relief are summoned from various areas nearby and could enter the airport through specified emergency gates.

Landscaping. In and around runway safety and clear zones, trees should not be planted. Instead, small bushes and shrubs would provide the green surface but will minimize damage to a veering aircraft. However, bushes should be carefully selected so as not to attract birds; otherwise it would probably pose a more dangerous hazard to the aircraft.

In order to provide more airport safety enhancement, certain airport design measures are implemented, including:

1. Roadways of various types, from small airport service roads to six-lane expressways adjacent to the airport, are common obstructions in the runway clear zone. In the effort to comply with the FAA approach slope clearance requirements, roads and highways adjacent to the runway end are depressed to avoid potential interference with landing aircraft. While this may be taken to improve safety, it is actually a serious hazard for overrunning and undershooting aircraft if they are outside the airport boundary or beyond 3000 ft of the runway clear zone.

2. Airport service roads and emergency vehicle access roads should be all-weather construction, be level with surrounding terrain, and have no features (e.g., drainage depressions, structures, and gullies) that may damage an errant aircraft landing gear.

3. Steep embankments should be avoided and replaced by gradual gentle slopes, and all surface obstructions, such as light poles, signage trees, or any other object that may damage veering aircraft, must be removed.

4. Railroads through the extended runway safety area must also be treated carefully. Railroad tracks would cause major aircraft damage and would result in serious injuries or fatalities. Track embankments could be graded more gently and tracks paved the width of the safety area to make crossing the railroad tracks safer for an overshooting aircraft and for emergency vehicles responding to an aircraft accident directly and without taking circuitous routes.

5. Aircraft accidents occurring off the end of the runway but outside the airport perimeter should not be a major access problem for the emergency vehicles. Roads and emergency gates must be available at the end of aircraft overrun areas. Gates must be crashable with frangible mounting and provide quick response and access for emergency vehicles.

Airport Safety Management System (SMS)

The SMS provides the airport with a proactive, systematic, and integrated method for enhancing and managing safety. It is therefore essential to airports to have a SMS beyond safety design standards. The ICAO (1) has established international SMS standards for airports to adopt. The SMS provides a systems approach to develop safety policies, procedures, and practices to allow airports to achieve their safety objectives. The SMS would therefore enhance airport safety through planning, organizing, communicating, and providing direction.

Effective airport safety requires more than establishing appropriate organizational structures and rules and procedures to be followed. While being safety conscious during airport design will pay dividends later in terms of enhanced safety at the airport, having a strong commitment to safety by airport management is always required. Attitudes, decisions, provisions of safety measures and safety training, and methods of operation at the policy-making level demonstrate the priority given to airport safety. A key indicator of commitment to safety is the adequacy of resources, establishing management structure, assigning responsibility and accountability, and allocating appropriate resources consistent with the organization's stated safety objectives.

In effective safety cultures, there are clear reporting lines, clearly defined duties, and well-understood procedures. Airport personnel would fully understand their responsibilities and know what safety issues to report and to whom and when to enhance airport safety performance—in essence, a safety culture is both attitudinal and structural, relating to individuals and organizations. It may be difficult at times to measure airport safety, especially when the principal criterion for measuring safety is the absence of accidents and incidents. But it is important to observe and project unsafe operational conditions that are the precursors to accidents and incidents, and therefore, a safety culture may affect airport safety either negatively or positively. One positive effect is to engage in the "operational readiness and testing," or ORAT for a new airport during the engineering design phase to ensure that the facility design is synchronized with safety management during operation.

FAA Airport SMS (2). The ICAO provided the SMS standards for the airport industry based on generally accepted industry standards. The FAA has established an SMS guidance similar to the ICAO to describe airport SMSs and the preparation of the airport SMS. FAA Advisory Circular 150/5200-37 provides guidance to develop and implement the airport SMS, is applicable to all airports that have certificates issued under 14 Code of Federal Regulations (CFR) Part 139 "Certification of Airports," and considers the variations in operations and other complexities at these airports.

The basic structure and life-cycle flow of the SMS is depicted in Figure 9.1. In general, the SMS has four distinct elements: (a) safety policy and objectives, (b) safety risk management, (c) safety assurance, and (d) safety promotion.

The SMS deals with the entire airport as a system—the integrated set of elements constituting an airport which are combined in an operational, structural, and support environment to accomplish its defined objective. The airport system includes subsystems with people, hardware, software, firmware, information, procedures, facilities, services, and the environment.

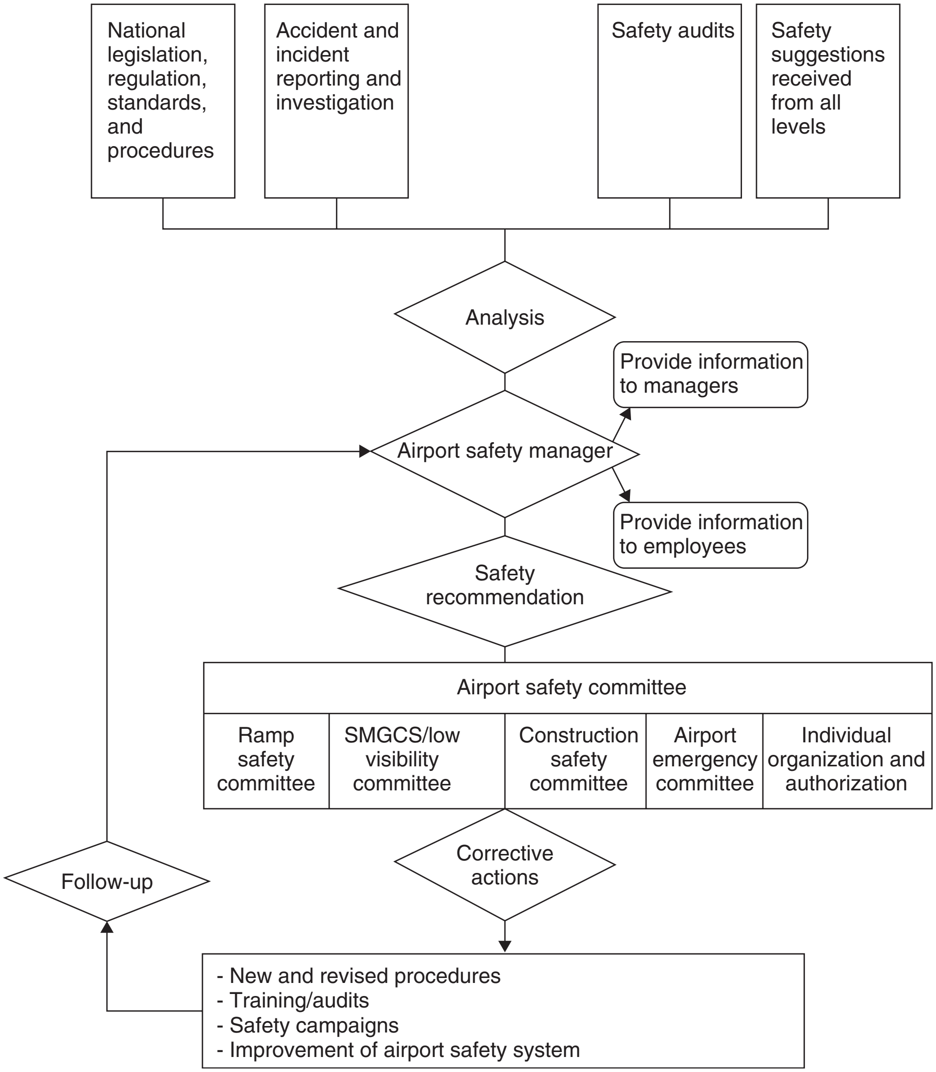


Figure 9.1 SMS process. (*Source*: FAA. (2).)

The main parts of a typical SMS analysis include:

- *Safety Management System.* Formal, top-down business-like approach to managing safety risk. It includes systematic procedures, practices, and policies for the management of safety (including safety risk management, safety policy, safety assurance, and safety promotion).
- *Safety Assessment and Assurance*. Conducting a systematic, comprehensive evaluation of an implemented SMS and systematically providing confidence that organizational products/services meet or exceed safety requirements.
- *Risk Assessment*. Assessment of the system or component to compare the achieved risk level with the tolerable risk level.

- *Gap Analysis*. Analysis conducted to identify existing safety components, compared to the SMS requirement as directed, and provides an initial SMS development plan and roadmap for compliance.
- *Safety Risk Management (SRM).* A formal process within the SMS composed of describing the system, identifying the hazards, assessing the risk, analyzing the risk, and controlling the risk. This process is embedded in the operational system; it is not a separate/distinct process.
- *Safety Risk*. The composite of the likelihood (i.e., risk) of the potential effect of a hazard and predicted severity of that effect. In this context:
    - *Hazard* is a condition that is a prerequisite to an accident or incident, and it is defined by any existing or potential condition that can lead to injury, illness, or death to people; damage to or loss of a system, equipment, or property; or damage to the environment.
    - *Severity* is the consequence or impact of a hazard in terms of degree of loss or harm.
- *Safety Policy*. Defines the fundamental approach to managing safety that is to be adopted within an organization. Safety policy further defines the organization's commitment to safety and overall safety vision.
- *Safety Promotion*. Composed of a combination of safety culture, training, and data-sharing activities that support the implementation and operation of an SMS in an organization.
- *Safety Risk Control*. Systematic mitigation of the safety risk of a hazard, and it should be mandatory, measurable, and monitored for effectiveness.

Based on the FAA guidance, there are five phases to the SRM process:

Phase 1. *Describe the system,* considering the environment of the entire airport as a system, with all of the safety-related functions that should steer the focus of the risk management analysis and assist in determining potential mitigation strategies.

Phase 2. *Identify the hazards* to the system (i.e., operation, equipment, people, and procedures) in a systematic, disciplined way. Hazard identification considers all possible sources of system failure, including equipment, operating environment, human element, operational procedures, maintenance procedures, and external services.

Phase 3. *Determine the risk* associated with each hazard in its system context to identify what risks exist, if any, that may be related to the hazard.

Phase 4. *Assess and analyze the risk*. This phase requires careful assessment and extensive analysis to estimate the level of risk using the predictive risk matrix in Figure 9.2. Risk is the composite of the predicted severity and likelihood of the outcome or effect (harm and damage) of the hazard in the worst credible system state. In order to assess the risk of an accident or incident occurring, severity and likelihood are first determined.

Determination of severity is independent of likelihood, and likelihood should not be considered when determining severity. Over time, quantitative data may

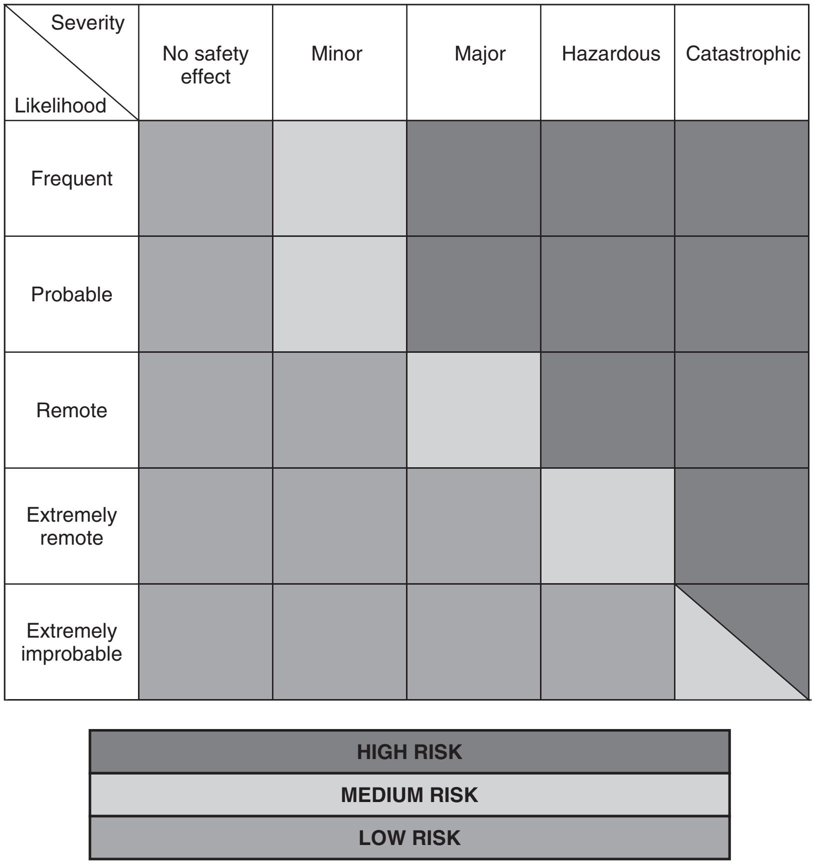


Figure 9.2 Risk assessment matrix. (*Source*: FAA.(2).)

support or alter the determination of severity and probability, but the initial risk determination will most likely be qualitative in nature, based more on experience and judgment than data. Risk levels used in the matrix are:

- *High Risk*. Unacceptable level of risk, covers catastrophic hazards that are caused by (a) single-point events or failures, (b) common-cause events or failures, and (c) undetectable latent events in combination with single-point or common-cause events; all are considered high risk even if extremely remote.
- *Medium Risk.* Acceptable level of risk representing the minimum acceptable safety objective where the activity can continue but tracking and management are required.
- *Low Risk*. Target level of risk that is acceptable without restriction or limitation, where hazards identified are not required to be actively managed but only need to be documented.

Phase 5. *Treat the risk*. Options to mitigate the risk are developed, monitored, and tracked. Alternative strategies for managing a hazard's risk(s) are also developed to reduce the hazard's effects on the airport. The majority of risk management strategies address medium- and high-risk hazards. Low-risk hazards may be accepted after considering risk. The risk management activity would also identify feasible options to control or mitigate risk, which includes (a) avoidance, (b) assumption and accepting likelihood, (c) control, and (d) transfer.

TRB Airport SMS (3). As airport SMSs provide a systematic, proactive approach to reducing the risk and severity of aircraft accidents/incidents on the airfield, they should always be adopted. The TRB has recently released an SMS *Guidebook* (3) that follows the ICAO standards for SMS applicable to international airports since November 2005. It also follows the FAA guidance on SMS implementation in the United States as stated in FAA Advisory Circular 150/5200-37.

Airport operators in the United States have safety programs in place that have resulted in today's high level of aviation safety. These programs can form the basis of a more comprehensive SMS. The SMS will supplement these programs by providing a systematic, proactive approach that includes (a) documenting identified hazards and their mitigation; (b) monitoring and measuring the ongoing safety experience of the airport; (c) establishing a voluntary nonpunitive safety reporting system that can be used by employees of the airport operator, airlines, and tenants; and (d) improving the entire airport's safety culture. A key component of an SMS is safety risk management that considers the probability of occurrence of an accident/incident and the severity or consequences of that accident/incident. The TRB *Guidebook* assists in developing an effective airport SMS for different airport sizes based on FAA regulations and provides a timely and useful source to airports in developing and implementing a SMS consistent with their guidance. The TRB SMS *Guidebook* describes the associated concepts, methodologies, processes, tools, and safety performance measurements that can be applied by airports based on their level of operations and complexity.

Since safety is the number one priority for the airport industry, it needs to be very well understood and correctly implemented by the airport industry stakeholders so that the airport would be fully compliant with ICAO requirements. For this objective, the Airport Council International (ACI) is providing training and guidance for its constituency that includes:

- Developing participants' knowledge of SMSs for airports based on ICAO requirements and international best practices
- Providing participants with sufficient specific tools, knowledge, and know-how allowing for planning, development, and implementation of the airport SMSs
- Providing participants with adequate training materials containing examples and experiences that can be used to reinforce their knowledge of airport SMSs

9.2 AIRPORT SECURITY

No airport has sufficient built-in resources to cope with emergency situations independently. But while emergency management is essentially an operations function, not planning or design, it is important that airports be engineered to handle emergencies if and when they arise. Emergencies could be natural disasters, man-made (terrorism or sabotage), or simply system breakdown.

Since its formation after September 11, the TSA has become the primary agency for plans and concepts devised and implemented for emergency situations. TSA literature on airport emergency management and security situations is covered in this chapter.

Another U.S. federal agency, the Federal Emergency Management Administration (FEMA), published a state and local document, "Guide for All-Hazard Emergency Planning," (discussed later), that provides basic information for FEMA's concept for developing risk-based, all-hazards emergency operations plans (EOPs).

Another concept of airport emergency planning that provides airports with a systematic approach for planning purposes is comprehensive emergency management (CEM)—a process that recognizes four separate but related actions in an emergency—mitigation, preparedness, response, and recovery. Each action, or step in an emergency, should be considered during the airport planning process.

On the international level, ICAO Annex 17 to the Convention on International Civil Aviation incorporates all amendments adopted by the council (4). it provides recommended practices in emergency situations to airports states should consider and adopt in their national standards for airport security. In the United States, TSA standards and regulations are strictly complied with by all airports. The IATA provides useful insights into airport emergency management, with focus on communication as discussed later.

Chronology of Airport Security Threats

Threats and unlawful interdictions to civil aviation of any kind, called "aviation security risks," impacted airports in cycles and waves starting in the late 1950s. Causes and underlying reasons for them were different, and so were their disruptive impacts and countermeasures adopted against them. The reactions from governments, civil aviation authorities, airlines and airports, and the traveling public at large took different forms and at times were so significant and far reaching that how airports were planned, built, and operated changed forever.

These aviation security cycles and waves were:

- Airline hijacking out of Cuba during the 1960s
- Middle East airline hijacking and bombing during the 1970s
- World terror groups activities against civil aviation in the1980s
- Personal hijacking in reaction to regional political conflicts
- Organized terror campaigns during the first decade of the 21st century—September 11, 2001, in the United States, July 7, 2005, in the United Kingdom, and Madrid Train bombings in 2004

Protecting Critical Transport Infrastructure

In the United States, the President's Commission on Critical Infrastructure Protection (5) concluded after months of evaluating the national infrastructure, assessing vulnerabilities, and deliberating assurance alternatives that infrastructure protection should be looked at differently in the future. The commission argued that "the collective dependence on the information and communication infrastructure drives us to seek new understanding about the 'Information Age.' Essentially, we recognize a very real and growing cyber dimension associated with infrastructure assurance."

The commission continued: "Our national defense, economic prosperity, and quality of life have long depended on the essential services that underpin our society. These critical infrastructures—energy, banking and finance, transportation, vital human services, and telecommunication—must be viewed in a new context in the 'Information Age.' The rapid proliferation and integration of telecommunications and computer systems have connected infrastructures to one another in a complex network of interdependence. But this inter-linkage has created a new dimension of vulnerability, which, when combined with an emerging constellation of threats, poses unprecedented national risks." Indeed, within an airport emergency context, these vulnerabilities are fully exposed whenever a terrorist act is committed or a catastrophic power or telecommunication breakdown takes place, with a sudden natural disaster, with an outbreak of an epidemic, or with any other unforeseen emergency.

9.3 AIRPORT EMERGENCY PLANNING

In the United States, since September 11 and the Katrina hurricane, there has been a plethora of studies to assess an airport's capability to handle emergencies. For airports, the FAA published the first airport emergency plan (AEP) in 1984, as part of the guidance to comply with 14 CFR Part 139- Airport Certification. This document, despite its age, formed a suitable framework for emergency planning at airports. The AEP Advisory Circular as updated in 1999, and the FAA recently published a consolidated document updating the AEP (6).

But no matter how ingeniously an AEP and other disaster or crisis management plans are drafted, the new paradigm identified by the President's Commission requires that the first line of defense against such emergencies be ingrained in our culture, beginning with a comprehensive program of education and awareness that includes both infrastructure stakeholders and the general public.

Such education must cover the basics of risk identification, analysis, management and control, and the qualitative and quantitative disruptive impacts on system operation, because disruption of any infrastructure (here the airport as one part of the much larger system, the NAS) is always inconvenient, costly, and even life threatening. Major disruptions could lead to major losses and affect national security, the economy, and the public good. The mutual dependence and interconnectedness made possible by the information and communication infrastructure have led to the possibility that the entire infrastructure may be vulnerable in ways never recognized or realized before. Intentional exploitation of these new vulnerabilities could have severe consequences for the national economy, security, and way of life. Moreover, technologies and techniques that have fueled major improvements in the performance and expansion of the infrastructure can also be used to disrupt it.

The commission's view was that "threats" are real enough, and "real vulnerabilities" do exist. It is ironic that the commission initiated the discussion that could have prevented the catastrophic events of September 11 in the United States, July 7 in the United Kingdom, and the Madrid train bombings in Spain. The commission argued that terrorist attacks have typically been against single targets but are getting increasingly more sophisticated in nature, can exploit emerging vulnerabilities associated with the complexity and interconnectedness of the infrastructure, and utilize the Internet to perfect the plan and cause maximum disruptive effects at minimum costs.

Preparing Effective AEPs (6)

Airports are unique and intrinsically different in size, function, and operational complexity, where each has distinct features of its own. Airports can be diverse in their management and operation and be owned by a city or county or by an authority representing multiple local governments; some are owned and operated by public or private companies. What they have in common that they all can be subject to a myriad of emergencies and disasters.

Emergencies can happen anywhere, any time of the day or night, under any weather condition; can vary in magnitude and severity; and can occur instantaneously or develop slowly over time. They can last for a short time or a long time and be natural or man-made, and their impact can vary. But, while emergencies can seldom be predicted, they may be anticipated and prepared for. However, regardless of how an airport can prepare for emergencies, it may not have the right resources to respond to a specific emergency occurrence. Very few airports may have sufficient resources to respond to every emergency situation independently. Each airport must depend to some degree on resources from its surrounding communities, state and federal governments, or other organizations. Airport owners and managers must involve all airport-related parties during emergencies and use the collective expertise and resources for the mutual benefit of all. But this intensely collaborative, interactive, and hopefully coordinated effort must be conducted within a preset framework—the AEP. Moreover, since airports are major public facilities of prime economic and national security importance to the society and general public, governments have a vested interest in safeguarding them against emergencies. The United States was one of the first to require that emergency plans be prepared and maintained by airports as part of the regulation to certify their operation under Part 139.325 of 14 CFR (7).

Worldwide, Australia provides another example of adopting emergency plans by government to safeguard airports. The Civil Aviation Authority of Australia adopted regulations for all airports subject to licensing to prepare and maintain an AEP under the Australian Civil Aviation Regulation (CAR) 891 (8).

International air transport and aviation organizations have provided varying levels of guidance on preparing emergency plans in crisis situations. The ICAO recommendation on this matter is basically contained in Section 9.1, "Aerodrome Emergency Planning," of Annex 14 (9). From time to time, the ICAO provides guidance to contracting states in response to specific requirements in response to emergencies, such as spread of SARS epidemic in Asia through air travel (10).

The IATA provided assistance on crisis management in emergency situations to its constituency, the airlines. This assistance would be equally beneficial to the airports airlines operate in, where both entities are essentially partners in ensuring that operation and business at the airport is not disrupted during emergencies. As stated in the IATA *Crisis Communication Manual* (11): "Crisis communication is an essential component of the crisis management process, which mainly deals with the continuity of operation and business during an airport emergency."

In the United States, the federal agency responsible for managing emergencies, FEMA, has published the State and Local Guide (SLG 101) (12) to provide emergency managers and other emergency service providers with information regarding FEMA's concept for developing risk-based, all-hazards emergency operation plans (EOPs). The EOP could constitute a reasonable framework airport operators can adopt for actions and assigning tasks during emergencies. Invariably, information presented in AEPs is based primarily on the guidance provided in SLG 101, in both content and format, to provide a standardized basis for the development of the AEP and assist in the overall coordination effort in the EOP.

For airports specifically, the FAA AEP advisory circular is used as the template for developing the operation and management framework for emergency planning that airports can adopt and implement. The AEP would provide the necessary guidance for airports to prepare a comprehensive AEP and to meet the requirements to comply with the mandatory airport certification process under U.S. 14 CFR Part 139 (7).

The FEMA document SLG 101 indicates that there are no typical emergencies and there are no typical or standard preparedness plans that are ideal for all airports or communities. However, some common phases to preparedness for disasters can provide a systematic approach for planning purposes. This systematic approach to emergencies is manifested in CEM, a process that recognizes four separate, but related elements: mitigation, preparedness, response, and recovery. An effective AEP however does not need to reflect all four phases of the CEM but must focus instead on the response and initial recovery issues.

In addition, other FAR regulations, standards, and guidances that the airport has to comply with under 14 CFR would be included as viable elements of the effective AEP. These include FAR Part 107, "Airport Security"; Part 108, "Airplane Operator Security"; Part 109, "Indirect Air Carrier Security"; National Fire Protection Association (NFPA) 424, "Airport/ Community Emergency Planning"; NFPA 1600, "Recommended Practice for Disaster Management"; and the federal response plan. International airports would adopt the ICAO Airport Services Manual, Part 7, "Airport Emergency Planning."

Components of AEP (6)

The major characteristics and components of a typical AEP include a definition of the scope and purpose, content and function, organization and development framework, training, and communication:

1. *Definition.* An airport emergency is an occurrence or instance, natural or man-made, which warrants action to protect and save lives, maintain public health, prevent or minimize property and infrastructure damage, and bring the airport back to normal operation and regular business.
2. *Purpose.* As prerequisite to airport certification, airports shall develop and maintain an AEP designed to minimize the possibility and extent of personal injury and property damage on the airport in an emergency. The AEP must be developed to facilitate the timely and appropriate response to emergencies occurring on or in the immediate vicinity of airports. The principal goal of the AEP is to prepare the organization to render adequate assistance and minimize further injury and damage to persons and property involved in the emergency situation.

3. *Structure and Content.* The AEP must include the procedures for prompt response to the emergencies, including:

   - Aircraft incidents and accidents, including bomb incidents, where designated parking areas must be ready for aircraft involved
   - Structural fires
   - Natural disasters
   - Medical and health disasters and radiological incidents
   - Acts of terrorism, sabotage, hijack incidents, and other unlawful interference with operations
   - Catastrophic failure of power
   - Water rescue situations

4. *Function and Organization.* The AEP can provide the functional framework that:

   - Assigns responsibility to organizations and individuals to carry out specific actions at projected times and places in responding to a specific emergency
   - Sets forth lines of authority and organizational relationships and shows how all actions should be coordinated
   - Describes how people and property will be protected in emergencies and disasters
   - Identifies personnel, equipment, facilities, supplies, and other resources available—within the airport or by agreement with other agencies or communities—for use during response and recovery operations
   - As a public document, cites its legal basis, states objectives, acknowledges assumptions, and sets communication links for coordination
   - Facilitates response and short-term recovery to set the stage for successful long-term recovery

   The functional elements of the AEP are structured into:

   - Direction, command, and control
   - Communication
   - Alert and warning
   - Emergency public information
   - Protective actions
   - Law enforcement
   - Fire and rescue
   - Health and medical
   - Resource management
   - Airport operations and maintenance

5. *Plan Preparation*. Development of the AEP includes:

   - A rough draft of all elements to serve the planning team
   - Committees to manage the AEP sections, through developing timelines, tasks, and schedules for follow-up meetings
   - Liaising with airport stakeholders, agencies, and committees

- Preparing standardized graphics, charts, maps, etc.,
- Producing the AEP document and circulating it to the stakeholder representatives on the planning team
- Prepare airport facilities' plans and drawings based on the current and updated airport master plan and related engineering drawings.
- Obtaining concurrence from agencies, airport stakeholders, and associated organizations with identified responsibilities for AEP implementation
- Presenting the AEP document to the appropriate executives for promulgation
- Distributing the AEP to all parties with duties and responsibilities under the plan. Records are kept on AEP distribution, which should be limited and on need-to-know basis.

6. *Verification of Conformity.* The complete and endorsed AEP should always be checked for conformity to the applicable laws, regulation(s), and standards and to ensure that it functions as planned. Verification and validation of the AEP are done through consultation with the stakeholders' emergency management officials regarding its review cycle. As part of this process, full-scale exercises are conducted to offer the best option to determine if an AEP actually works and is understood.

7. *AEP Familiarization.* On- and off-airport personnel familiarization with each other's equipment and facilities' plans must be part of the plan. Off-airport personnel need to become familiar with the unique operating environment of an airport, and this is particularly critical during nighttime and low visibility. Manpower and staff assigned to support the AEP must get fully familiar with their roles and responsibilities and sufficiently tested through drills and exercises.

8. *AEP Training Programs.* The above is achieved through proper training. Personnel's knowledge of the AEP, its facilities, equipment and vehicles, and the emergency response organizations' (e.g., fire, medical, and police) knowledge of their responsibilities relative to the AEP, its facilities, equipment, and vehicles should follow rigorous training programs. For initial training, airport personnel should be primarily devoted to standard operating procedures (SOPs), and general training should be provided to *all* airport employees.

Emergency response personnel should receive specialized training based on their individual job responsibilities. Furthermore, periodic training should be scheduled in order to prevent loss of knowledge and skills over time.

Training should familiarize the personnel with:

- Standard operating procedures
- The airport layout plan (ALP) and facilities' plans and engineering drawings of the current airport master plan.
- Communications, IT, and utilities' systems and equipment, including cabling, circuit drawings, location of equipment, and routing of lines
- Emergency equipment
- Reporting systems

9. *Training Methods and Equipment.* As part of the AEP, an emergency training handbook with formal methods for training personnel should be prepared. Formal methods include, but are not limited to, classroom instruction, on-site familiarization, emergency training drills (for airport personnel, emergency response personnel, and the public), audiovisual (AV) training programs, and simulations (computer as well as live simulations). The handbook should also include such training methods as orientation seminars, drills, tabletop exercises, functional exercise, and full-scale exercises as well as the steps taken to develop them. These steps include needs assessment, definition of the scope and statement of purpose, identification of the goals and objectives, building scenarios, problem statements, and assessment of the success of the exercise.

10. *Hazard Control during AEP Routine and Periodic Training*. Because of the intense activity characteristic of most full-scale exercises, if not managed carefully, the exercise itself can cause accidents. Potential hazards during mounting AEP exercises at normal airport operation may occur and should be avoided. For operation-based exercises, since participants may be unfamiliar with aircraft operations, some could unintentionally interfere with the operation and accidents may result. The AEP should therefore include preventive actions and awareness measures. Other preventive measures of the AEP are related to potential injuries during exercise, victim training instructions, liability issues, public awareness and notification of the exercise through media, and undertaking corrective actions.

Communication during Crises

A crucial component of emergency management is communication during crises. Significant planning is needed to ensure there is no breakdown in communication when a crisis unfolds, including adequate training within a crisis environment. The IATA prepared a thorough sourcebook to assist the airlines in managing and handling crises at airports (11). A crisis is defined by IATA as any event or set of circumstances that significantly affect the ability of the airline and/or airport to carry out its regular business.

In any airport emergency, or crisis, the "crisis mode" is declared and initiated with an official signal put out by an authorized airport emergency planning management staff. Consequently, the AEP kick in and the internal notification system becomes operational. Normal business operations get automatically disrupted as normal operational functions get disrupted by the crisis. As employees from different divisions abandon their normal tasks, they need to be promptly instructed to take the AEP roles for which they have been trained. Senior emergency management staff may assess the crisis situation and find that only a partial crisis operating mode is really required. Here communication is very critical, as only certain airport and airline personnel would be instructed to move to crisis mode. When partial crisis mode is declared, only specific parts of normal operations would be disrupted.

The crisis communication facilities that AEP management would deploy in a crisis include:

1. *Crisis Center*. The nerve center of the emergency management team as the crisis mode kicks in and is officially declared. When key information is reported to this center, the situation would be continuously assessed and strategic decisions are made and communicated to AEP teams to be implemented. The crisis center should provide suitable communication systems capabilities, as designated in the AEP. Otherwise, if the designated facility is unavailable for any reason, any suitable office or conference or meeting room equally equipped could be used instead.

2. *Headquarters Information Center*. Media activity related to the crisis would be managed from this center located at the organization headquarters. It would be the primary working area for crisis communication teams associated with public and media relation and internal communication—radio, telephone, video, and internal dispatches and briefs. This facility has to be operated 24/7, and media access to it must be restricted.
3. *Headquarters Media Briefing Center*. In the advent of an emergency or crisis, all direct media briefings are conducted within this facility, located close to the crisis center, preferably in the organization headquarters.
4. *Site Information Centers*. These are the communication facilities and work areas for certain parts of the airport, as the emergency management situation requires. It is where the site's personnel and crisis-related work groups report. Certainly, these facilities must not be accessible to the media or public.

In addition, other communication facilities may be set up ad hoc during a crisis. An off-site media briefing center may be helpful for any off-airport emergency. The airport and/or airlines could use their Internet websites to post available information cleared for the public regarding the crisis, including press releases and media reports. The Internet site would help distribute the official information and briefs and alleviate public anxiety about the crisis, hence reducing telephone traffic to the crisis information center.

An essential communication element of the AEP is a simple one—emergency telephone trees. These are basically lists of telephone numbers (personal, office, and mobile) of all essential personnel of the AEP. This would initiate cascading telecommunication to all the AEP working-level personnel at the onset of a crisis and when the crisis mode kicks in.

The IATA *Crisis Communication Manual* (11) provides detailed working-level material to assist emergency managers with a practical source to:

1. Handle crisis communication from staff preparation and training to handling the public and managing crowds
2. Provide the means to understand and respond to media and manage their interactions, including handling of reporters
3. Prepare for and giving interviews
4. Prepare for and conducting press conferences
5. Prepare and disseminate statements, news releases, and advisories

9.4 PLANNING OF AIRPORT SECURITY

Planning for protecting the airport from unlawful acts depends largely on the kind of danger and level of threat to airports. In the United States, it started with restricting access to the "sterile areas" of the airport and established security procedures for access control as part of the 14 CFR—Transportation.

In response to increased frequency and threat level of terrorism worldwide, the President's Commission on Aviation Security and Terrorism provided certain recommendations that resulted in the enactment of the Aviation Security Improvement Act

(ASIA) of 1990. This law directed the FAA Office of Aviation Security to work closely with the aviation industry to develop guidelines for airport design and construction to allow for maximum-security enhancements. The parts of this law (14 CFR) relevant to aviation security are:

Part 91: Aircraft operator security under general operating and flight rules

Part 107: Airport security

Part 108: Aircraft operator security

Part 109: Indirect air carrier security

Part 129: Foreign air carrier security

Part 191: Protection of sensitive security information

As a direct consequence of the unprecedented events of September 11, the Aviation and Transportation Security Act (ATSA) of 2001 was enacted, and the Transportation Security Administration (TSA) was established to take over all responsibilities of aviation security from the FAA. This act authorizes increased federal responsibility for all aspects of aviation security, including a federal take-over of passengers and baggage screening. Months later the Department of Homeland Security (DHS) was established by the Homeland Security Act to prevent terrorism acts to the United States, protect its critical infrastructure, and minimize damage and assist recovery from any such acts.

The parts relevant to aviation security under the new ATSA law (49 CFR) are:

Part 1520 (previously 14 CFR 191): Protection of sensitive security information

Part 1542 (previously 14 CFR 107): Airport security

Part 1544 (previously 14 CFR 108): Aircraft operator security

Part 1546 (previously 14 CFR 129): Foreign air carrier security

Part 1548 (previously 14 CFR 109): Indirect air carrier security

Part 1550 (previously 14 CFR 91): Aircraft operator security under general operating and flight rules

Security-based facility planning for airport terminals, as per TSA design requirements, is described in Section 10.5

Airport Access Control

Airport access control, covered in TSA 1542, is a major airport security issue. The TSA requires that each airport operator must allow the TSA, at any time or place, to make any inspections or tests, including copying records, to determine compliance of an airport operator, aircraft operator, foreign air carrier, indirect air carrier, or other airport tenant with this provision and any security program under it. Each airport operator must also provide evidence of compliance with TSA regulations and its airport security program. At the request of the TSA and upon completion of the required airport security program, the airport operator must issue to TSA personnel access and identification media to provide TSA personnel with unescorted access to, and movement within, secured areas, air operation areas (AOAs), and security identification display areas (SIDAs).

The airport must establish the Airport Security Program (ASP), subject to TSA approval, that covers provisions for the safety and security of persons and property on an aircraft operating in air transportation or intrastate air transportation against an act of criminal violence, aircraft piracy, and the introduction of an unauthorized weapon, explosive, or incendiary onto an aircraft.

The structure and content of the ASP is as follows:

- Description of all the secured areas, including maps, facility plans, and drawings detailing boundaries and pertinent features; each activity or entity on, or adjacent to the secured area that affects security; measures used to perform the access control functions required under this law; procedures to control movement within the secured area, including identification media; and description of the notification signs
- Description of the AOA, including maps, facility plans, and drawings detailing boundaries and pertinent features; each activity or entity on, or adjacent to, an AOA that affects security; measures used to perform the access control functions; measures to control movement within the AOA, including identification media as appropriate; and description of the notification signs required
- Description of the SIDA, including maps, facility plans, and drawings detailing boundaries and pertinent features; and each activity or entity on, or adjacent to, a SIDA
- Description of the sterile areas, including diagrams, maps, facility plans, and drawings with dimensions detailing boundaries and pertinent features; access control measures used when the passenger-screening checkpoint is nonoperational and the entity responsible for that access control; and measures used to control access as specified
- Procedures used to comply with regulations regarding fingerprint-based criminal history records checks
- Description of the personnel identification systems
- Escort procedures in accordance with the TSA regulations
- Challenge procedures in accordance with TSA regulations
- Training programs required to implement the program
- Description of law enforcement support used to comply with TSA regulations
- Airport system for maintaining its records
- Procedures and description of facilities and equipment used to support TSA inspection of individuals and property and aircraft operator (Part 1544) or foreign air carrier screening functions (Part 1546)
- Contingency plan as required by the TSA
- Procedures for the distribution, storage, and disposal of security programs, security directives, information circulars, implementing instructions, and, as appropriate, classified information
- Procedures for posting of public advisories
- Incident management procedures used to comply with TSA regulations
- Any alternate security procedures that the airport operator intends to use in the event of natural disasters and other emergency or unusual conditions (see section on AEP)
- Exclusive area agreements specified in TSA regulations
- Airport tenant security programs required and specified by the TSA

In addition, airport operators must also include s*upporting programs* and *partial programs* in their ASP describing the following:

- Name, means of contact, duties, and training requirements.
- Description of the law enforcement support used to comply with TSA regulations
- Law enforcement personnel training program for personnel required
- Records maintenance system
- Contingency plan required to comply with TSA regulations
- Procedures for the distribution, storage, and disposal of security programs, security directives, information circulars, implementing instructions, and, as appropriate, classified information, as well as procedures for public advisories
- Incident management procedures used to comply with TSA requirements

After approval of the ASP in its entirety, the airport operator must notify the TSA when changes have occurred to:

- Measures, training, area descriptions, or staffing, described in the security program
- Operations of an aircraft operator or foreign air carrier that would require modifications to the security program
- Layout, facility plans, and drawings and or physical structure of any area under the control of the airport operator, airport tenant, aircraft operator, or foreign air carrier used to support the screening process, access, presence, or movement control functions

If in the TSA's judgment the overall safety and security of the airport and aircraft operator or foreign air carrier operations are not diminished, the TSA may approve a security program that provides for the use of alternate measures. Such a program may be considered only for an operator of an airport at which service by aircraft operators or foreign air carriers is determined by the TSA to be seasonal or infrequent.

The TSA may approve an airport tenant security program, where the tenant must assume responsibility for specified security measures of the secured area, AOA, or SIDA, but the tenant may not assume responsibility for law enforcement support. However, the tenant must assume the responsibility within the tenant's leased areas or areas designated for the tenant's exclusive use. A tenant may not assume responsibility under a tenant security program for the airport passenger terminal. Shared responsibility among tenants is not permitted and must be exclusive to only one tenant, and the TSA must find that the tenant is able and willing to carry out the airport tenant security program adequately.

The airport tenant security program must include the following:

- Description of the airport public and nonpublic areas as per the current master plan, and diagrams, facility plans, and drawings of the boundaries and pertinent features of each area over which the airport tenant will exercise security responsibilities
- Description of the security measures the airport tenant has assumed
- Measures the airport operator adopts to monitor and audit the tenant's compliance with the security program
- Monetary and other penalties to which the tenant may be subject if it fails to carry out the airport tenant security program

- Circumstances when the airport operator will terminate the airport tenant security program for cause
- Provisions acknowledging that the tenant is subject to inspection by the TSA in accordance with the law
- Provisions acknowledging that individuals who carry out the tenant security program are contracted to or acting for the airport operator and are required to protect sensitive information in accordance with Part 1520 and may be subject to civil penalties for failing to protect sensitive security information

Other important elements of the airport access control and security program include security of secured areas, AOAs, and SIDAs; access control systems; and fingerprint-based criminal history records checks (CHRCs).

Control of Secured Areas

Each airport operator is required to have a security program for all secured areas of the airport and to establish a secured area that must prevent and detect unauthorized entry, presence, and movement of individuals and ground vehicles into and within the secured area by doing the following:

- Establish and carry out measures for controlling entry to secured areas of the airport.
- Provide for detection of, and response to, each unauthorized presence or movement in, or attempted entry to, the secured area by an individual whose access is not authorized in accordance with its security program.
- Establish and carry out a personnel identification system.
- Subject each individual to employment history verification before authorizing unescorted access to a secured area.
- Train each individual before granting unescorted access to secured areas.
- Post signs at secured area access points and on the perimeter to provide warning of the prohibition against unauthorized entry. Signs must be posted by each airport operator in accordance with the security program.

Security of AOA

Each airport operator is required to have a security program establishing an AOA, unless the entire area is designated as a secured area, to prevent and detect unauthorized entry, presence, and movement of individuals and ground vehicles into or within the AOA by:

- Establishing and carrying out measures for controlling entry to the AOA of the airport.
- Providing for detection of, and response to, each unauthorized presence or movement in, or attempted entry to, the AOA by an individual whose access is not authorized in accordance to the security program.
- Providing security information to each individual with unescorted access to the AOA.
- Posting signs on AOA access points and perimeters that provide warning of the prohibition against unauthorized entry to the AOA. Signs must be posted by each airport operator in accordance with the security program.

- Designating all or portions of its AOA as a SIDA, or using another personnel identification system, to meet the requirements of this section. If another personnel identification system is used, the media must be clearly distinguishable from those used in the secured area and SIDA.

Security of SIDA

Each airport is required to have a security program to establish at least one SIDA. Each secured area must be a SIDA, and for each SIDA measures must exist to prevent unauthorized presence and movement of individuals in the SIDA, including:

- Establishing and carrying out a personnel identification system
- Subjecting each individual to employment history verification before authorizing unescorted access to a SIDA
- Training each individual before granting unescorted access to the SIDA

Access Control Systems

The airport must provide access control systems for secured areas, where measures for controlling entry to secured areas required must:

- Ensure that only those individuals authorized to have unescorted access to the secured area are able to gain entry
- Ensure that an individual is immediately denied entry to a secured area when that person's access authority for that area is withdrawn
- Provide a means to differentiate between individuals authorized to have access to an entire secured area and individuals authorized access to only a particular portion of a secured area

Required measures for controlling entry to AOAs must incorporate accountability procedures to maintain their integrity.

Role of Airports in Regional Emergencies

Airports must maintain a robust emergency response framework to respond to all emergencies, as they could play a truly leading and effective role in unforeseen and unanticipated emergencies that they were not designed for. In such an event, an airport may find itself at the center of unfolding regional emergency that requires use of its facilities and systems in ways not normally experienced or even planned or designed for in order to provide assistance. Airport management must quickly realign its function and re-orient its operation to adapt and respond properly to the emergency. Two examples are worthy to presents:

1. *September* 11 *NAS System Grounding*

   Halifax, Nova Scotia, Canada, is a community of about 350,000 located on the far eastern coast of the country. On average, the airport handles approximately 150 flights a day. But on September 11, 2001, while the world watched in horror the devastation in the United States, Halifax International Airport employees had to endure a memorable time, but not as tragic as that in New York or Washington, D.C. At 9:40 a.m., all flight operations were halted at U.S. airports for the first time in history—never before was the entire U.S.

NAS completely empty and idle. The U.S. authorities immediately instructed the air traffic control system (ATC) to ground aircraft in the air: in U.S. airports for domestic flights and outside the NAS for international flights—all North Atlantic and Pacific flights headed to the closest airports in Canada.

At 10 a.m. that day, Halifax International Airport was notified to expect between 40 and 50 diverted aircraft. To receive nearly one-third of the average daily traffic all at once was an unprecedented load on the airport system and its personnel. Approximately 8000 passengers were processed through an arrivals facility that has the capacity to handle 900 per hour. Security was also a major concern, as no one knew at that time whether other terrorist operatives were among the passengers diverted to the airport.

In the end, Halifax International Airport received the largest number of aircraft in Canada. A total of 250 aircraft were diverted to 15 Canadian airports, with Halifax playing host to 41 from far-away countries.

2. *Katrina Disaster Relief*

On August 29, 2005, hurricane Katrina hit Louisiana, and at least 1,836 people lost their lives and total property damage was estimated at $81 billion. During the Katrina hurricane disaster, the entire city of New Orleans was evacuated, and those who refused to or could not evacuate became homeless. The city's entire infrastructure was destroyed, but the New Orleans International Airport was still operational after withstanding the forces of nature with acceptable damage. However, it was not operating only as a commercial airport, but as the major disaster relief facility using its own facilities, plus other support that local government could provide. The airport was turned into a major medical emergency and patient processing and care facility. Medivac flights were serving the airport more than commercial airliners. Besides being the central transportation hub in the disaster area, it was also a telecommunication hub, as there was no communication system left working in the city. FEMA used the airport as the main logistics hub for its much needed disaster relief operation. The experience of the airport to respond to an emergency situation far beyond any AEP could anticipate is a model of pushing the envelope of airport emergency plans.

9.5 SAFEGUARDING THE AIRSPACE

Consider the following:

- Air travel is growing at a considerable pace worldwide, more so in the developing world, where air travel markets are expanding and new and larger airports are being built.
- As these airports grow and attract more travelers and businesses, they become powerful economic engines in their regions and locales. Development expands around the airport, and the area becomes prime real estate which attracts more and intense development.
- With this fast pace of wide-scale development, safeguarding the airport's airspace may become increasingly difficult to monitor and regulate, particularly when political boundaries abut, overlap, or intersect.

- Advancements in air navigation and flight management technologies, particularly in GPS-based airport departure and arrival procedures, are increasingly used today to improve air traffic management and ease the congestion at and around airports. But the unintended consequence of this is diverting flights from a prespecified area or route where navigable airspace safeguarding standards are implemented to a wider area where safeguarding and marking obstacles may not be applied or enforced.

Therefore, a delicate balance exists between safeguarding the navigable airspace around airports, airport-induced urbanization and structures erected caused by economic growth around them, and advances in aircraft navigation and flight management technologies.

To ensure a sustainable and effective balance between airport-induced development and airspace safeguarding, a process has to be devised and regulated to control airspace obstruction and monitor hazards to navigable airspace around airports.

This process is four dimensional:

1. Planning: to establish airport airspace safeguarding planning criteria
2. Operational: to develop standards derived from aircraft performance based on terminal IFR/VFR operation maneuvers
3. Safety: to describe acceptable methods and guidelines to ensure minimum safe operation even at worst-case scenarios
4. Physical: to establish a robust system to map the heights of tall objects around airports through conduct on-site airport surveys to monitor compliance with the three criteria above

In the past, safeguarding planning criteria were set to control airspace obstruction and monitor hazards to navigable airspace around airports. The United States was the first to identify and tackle this problem through regulations, criteria, and planning standards (13). Such standards were later adopted by the ICAO for all contracting states to follow through standards set forth in ICAO Annex 14 (9). These criteria were always used to plan the airport airfield and its immediate airspace in the United States and worldwide.

Operationally, aircraft performance data, procedures, and local terrain and obstruction data were, and still are, used to design navigation procedures for aircraft terminal IFR operation maneuvers for approach and departures, based on worst-case operations scenario. This procedure is based on the terminal instrument procedures (TERPS) in the United States (14) to define aircraft maneuvers for normal airport approach and takeoff and when executing missed approaches. The ICAO provides the same in the PAN-OPS (15) procedures worldwide.

Safety planning for worst-case scenarios is also covered in U.S. regulations (16). It involves setting guidelines with acceptable methods to develop takeoff and initial climb-out airport obstacle analyses and in-flight procedures to comply with FAA aircraft engine-out requirements.

However, practice has shown that it is not easy or practical to establish an effective monitoring and enforcing mechanism to ensure that airport safeguarding is complied with on the ground. This is particularly true when airports under different neighboring jurisdictions are closely located. In such cases the jurisdictional boundaries may overlap and monitoring may be disrupted or even lost. Unless the oversight and enforcement mechanisms are effective across these boundaries, a situation of noncompliance would arise, resulting in hazards to the safety of airspace operations in and around airports.

Applicable Standards

ICAO standards on safeguarding, while effective as planning criteria for airports, cannot be easily implemented for monitoring or used to verify these standards against what actually gets build. Moreover, without a compliant and responsive municipal height restriction zoning ordinance applied and suitably enforced, permanent implementation of these standards remains difficult for some contracting states' civil aviation authority. In the United States, this authority, the FAA, has set such standards—mostly as guidelines to local government (17) that state and local government would have to adopt and legislate. In regulating and enforcing the construction of tall structures around airports in the United States, the FAA has issued guidance notifying authorities on proposed construction around airports (18). The major applicable standards for safeguarding airport airspace are planning, operational, and safety.

Planning Standards. The FAA has been implementing Part 77 regulation to assist in controlling the heights of objects within the U.S. NAS that are sufficiently tall to warrant formal marking on aeronautical charts and lighting for visual identification for overflying aircraft. It later became law and was included in 14 CFR as Federal Aviation Regulations FAR Part 77 (13). FAR Part 77 establishes standards for determining obstructions (features that penetrate the imaginary surfaces) in the United States. It has become the primary, and often sole, regulatory document that is referenced by private developers and municipal planning agencies alike, with respect to the potential impact on the navigable airspace of future infrastructure. However, it is important to underline two facts:

1. The obstruction criteria set forth in Part 77 are merely planning standards to determine if it is necessary to further study the impact of a construction proposal. They are not regulatory in nature, and exceeding the prescribed standards is by no means a disqualifying factor for a proponent, and hence an obstruction is not necessarily a hazard!
2. By congressional mandate, the FAA cannot prohibit any construction activities as a result of applying Part 77 criteria. Instead, the FAA has to evaluate the "proposed construction" and work as necessary with the proponent and sponsor to mitigate any impact in navigable airspace that may result.

Description and specification of the Part 77 imaginary surfaces are discussed previously in Section 8.5. The dimensions of the imaginary surfaces are well defined in terms of impacts on airport categories and operating aircraft mix.

The FAA regulations require that any planned construction or development in the vicinity of an airport must be submitted to the airport authority for evaluation of risk of penetrating the airspace around the airport. Trees and other terrain features (e.g., hills) may be required to be cut or removed. Other obstructions that cannot be removed include airport features, such as navigational aids (navaids, e.g., radar, ATC tower, meteorological tower, electric light poles, and terminal buildings). Obstructions outside the airport boundaries include tall buildings, radio, TV, and telecommunication towers, electric transmission poles, water tanks, wind turbines, and construction cranes, as well as numerous other types of objects. These obstructions are required by the FAA to be marked and lighted to warn aircraft pilots of their presence during daytime and nighttime operations (19). Aeronautic light beacons are used to mark an obstruction, an airport, a landmark, and certain points on airways in mountainous terrain.

The airport obstruction identification surfaces are specified to protect the navigational airspace around an airport and define potential obstacles on, in, or near the departure flight path and approach glide slope path. These standards for identifying obstructions to navigable airspace apply to terrain, natural-growth objects, other existing and planned man-made objects, and temporary construction-related objects, such as cranes. These protocols imply that avoidance of collision with obstructions and tall structures will minimize the third-party risk to the public under the flight path. It has been widely suggested that regulating agencies have largely neglected this aspect in airport and land use planning, where most compatible land use regulations are based only on community noise contours, environmental impacts, and other public acceptance criteria (20). This matter is described later in detail.

In implementing these standards, municipal planning agencies have formally adopted regulations that require future development to be assessed with respect to FAR Part 77 policies and regulations, prior to granting permission for development. Under the FAA regulation in implementing Part 77, the impact proposed development would have on navigable airspace around airports typically begins with the submission of FAA Form 7460-1, Notice of Proposed Construction or Alteration (shown in Figure 9.3). This notice is required for any proposed construction or alteration that will exceed 200 ft above ground level (AGL), or when in proximity to an airport, a height that exceeds a maximum height commensurate with a sloped surface, as specified in the obstacle limitation surfaces standards.

An *obstruction notice* is filed with the FAA to establish standards and notification requirements for objects affecting navigable airspace. Sponsor of any of the following construction or alterations must notify the FAA of:

- Any construction or alteration exceeding 200 ft AGL
- Any construction or alteration:
  - Within 20,000 ft of a public-use or military airport which exceeds a 100:1 surface from any point on the runway of each airport with at least one runway more than 3200 ft.
  - Within 10,000 ft of a public-use or military airport which exceeds a 50:1 surface from any point on the runway of each airport with its longest runway no more than 3200 ft.
  - Within 5000 ft of a public-use heliport which exceeds a 25:1 surface
- Any highway, railroad or other traverse way whose prescribed adjusted height would exceed that above noted standards
- When requested by the FAA
- Any construction or alteration located on a public-use airport or heliport regardless of height or location

Please Type or Print on This Form

Form Approved OMB No.2120-0001
Expiration Date: 9/30/2010

U.S. Department of Transportation
Federal Aviation Administration

Failure To Provide All Requested Information May Delay Processing of Your Notice

Notice of Proposed Construction or Alteration

FOR FAA USE ONLY
Aeronautical Study Number

1. Sponsor *(person, company, etc. proposing this action)*:
Attn. of:
Name:
Address:
City: State: Zip:
Telephone: Fax:

2. Sponsor's Representative *(if other than #1)*:
Attn. of:
Name:
Address:
City: State: Zip:
Telephone: Fax:

3. Notice of: ☐ New Construction ☐ Alteration ☐ Existing
4. Duration: ☐ Permanent ☐ Temporary (____ months, ____ days)
5. Work Schedule: Beginning ____ End ____
6. Type: ☐ Antenna Tower ☐ Crane ☐ Building ☐ Power Line ☐ Landfill ☐ Water Tank ☐ Other ____

7. Marking/Painting and/or Lighting Preferred:
☐ Red Lights and Paint
☐ White - Medium Intensity
☐ White - High Intensity
☐ Dual - Red and Medium Intensity White
☐ Dual - Red and high Intensity White
☐ Other

8. FCC Antenna Structure Registration Number *(if applicable)*:

9. Latitude: ____ ° ____ ' ____ . ____ "
10. Longitude: ____ ° ____ ' ____ . ____ "
11. Datum: ☐ NAD 83 ☐ NAD 27 ☐ Other
12. Nearest: City: ____ State ____
13. Nearest *Public-use* (not private-use) or Military Airport or Heliport:
14. Distance from #13. to Structure:
15. Direction from #13. to Structure:
16. Site Elevation *(AMSL)*: ____ ft.
17. Total Structure Height *(AGL)*: ____ ft.
18. Overall Height (#16 + #17) *(AMSL)*: ____ ft.
19. Previous FAA Aeronautical Study Number *(if applicable)*: ____ -OE
20. Description of Location: *(Attach a USGS 7.5 minute Quadrangle Map with the precise site marked and any certified survey)*

21. Complete Description of Proposal:

Frequency/Power (kW)

Notice is required by 14 Code of Federal Regulations, part 77 pursuant to 49 U.S.C., Section 44718. Persons who knowingly and willingly violate the notice requirements of part 77 are subject to a civil penalty of $1,000 per day until the notice is received, pursuant to 49 U.S.C., Section 46301(a)

I hereby certify that all of the above statements made by me are true, complete, and correct to the best of my knowledge. In addition, I agree to mark and/or light the structure in accordance with established marking & lighting standards as necessary.

Date	Typed or Printed Name and Title of Person Filing Notice	Signature

FAA Form 7460-1 (2-99) Supersedes Previous Edition Electronic Version (Adobe) NSN: 0052-00-012-0009

Figure 9.3 FAA Form 7460-1, Notice of Proposed Construction or Alteration. (*Source*: FAA (18).)

This notification allows the FAA to identify potential aeronautical hazards in advance, thus preventing or minimizing the adverse impacts to the safe and efficient use of navigable airspace. This notification serves as the basis for:

- Evaluating the effect of the construction or alteration on operating procedures
- Determining the potential hazardous effect of the proposed construction on air navigation

- Identifying mitigating measures to enhance safe air navigation
- Charting of new objects

Applications for on-airport and off-airport construction must both be filed whether the proposed modification is located on or off of airport property. Evaluations for on-airport proposals are administered by the local FAA Airports Division with coordinated assistance from Flight Procedures, Airway Facilities, and Air Traffic Divisions.

On their part, the airport operators are required to inform the FAA of the following and work to ensure compliance with:

- For airports that have received federal funds, airport owners and operators are obligated by grant assurance to identify and mitigate hazards to navigable airspace at their airport.
- Construction or alteration of objects on or around airports must not result in an adverse impact to operations at the airport.
- Construction of objects must not result in an increase to approach minimums to airport runways.
- The location of constructed objects must not impact runway protection zones, safety areas, object-free areas, and obstacle-free zones.
- The transmitting frequency of the proposed facility must not impact the proper operation of navigational aide facilities at your airport

In short, it is prudent for airport owners to protect the airspace around their airport to prevent loss of existing approaches or other negative impacts affecting utilization of their airport.

All modifications, *whether permanent or temporary*, are subject to the obstruction notice requirements outlined above. Airport owners and operators must ensure that all such improvements are properly evaluated by the FAA *prior to* commencement of work. Typical examples of permanent construction or temporary alterations include:

- Antennas
- Automated weather observation stations (AWOS)
- Buildings/structures
- Elevated signs
- Fences
- Light fixtures
- Navaid facilities (including FAA's)
- National weather service (NWS) facilities
- Power and cable lines
- Radio antennas
- Roadways
- Storage tanks
- Towers
- Batch plants' cranes

Temporary construction of alterations includes:

- Construction equipment
- Drilling rigs
- Haul routes
- Staging areas
- Stock piles
- Temporary lights

Form of Notification. As per 14 CFR Part 77.13-15 (13), individuals and organizations proposing construction or alterations must submit (Form 7460-1) a notice of proposed construction or alteration form, including pertinent information on the alteration and appropriate attachments showing the type and location of the alteration. Information needed for the FAA review includes the following:

- Scaled drawing showing location of alteration in relation to nearest runways—may be a marked-up airport layout plan or terminal area sheet
- Perpendicular distance of the proposed alteration to the nearest runway centerlines
- Distance along centerline (actual or extended) from runway end to the perpendicular intercept point
- Ground elevation at the site of the proposed alteration
- Height of the proposed alteration including antennas or other appurtenances
- Accurate geodetic coordinates conforming to the North American Datum of 1983 (NAD 83)
- Sketches, drawings, and so on, showing the type of construction or alteration being proposed

For horizontal infrastructure, such as roads, railroads, or seaway channels, the submission of Form 7460-1 is required based on the maximum height AGL of the "traverse way" plus a vehicle height factor as illustrated in Figure 9.4. Submission of

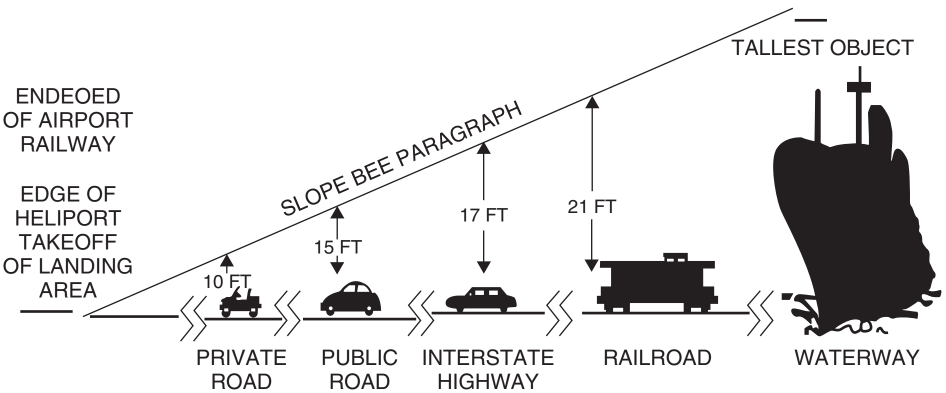


Figure 9.4 Transverse way requirements for submission of FAA form 7460-1. (*Source*: FAA.)

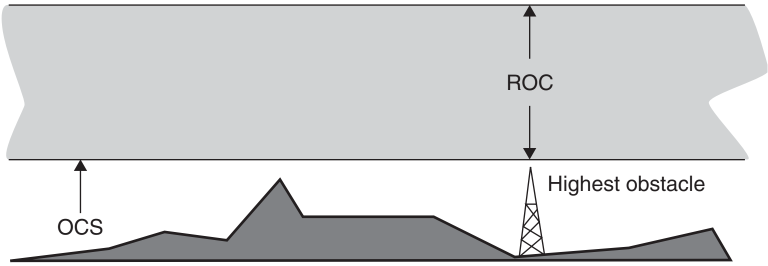


Figure 9.5 Schematic of obstruction-free zones for aircraft takeoff and climb flight path.

the form is required for any such infrastructure, whether it be a permanent facility such as buildings, towers, antennas, and roadways or temporary items such as construction cranes, derricks, or other such equipment. Part 77 regulations require that prior to actual construction or alteration Form 7460-2 must be submitted.

The FAA evaluates proposed development for its potential impact on navigable airspace by a process described in FAR Part 77, Subpart C-2. Objects that penetrate these surfaces or exceed other height standards are considered “obstructions” and can be further studied as potential “hazards to air navigation” if the project sponsor is unwilling to lower the proposal to the height not exceeding obstruction standards. The imaginary surfaces are illustrated in Figure 9.5 and identified in detail in Figure 9.6. As illustrated in Figure 9.7, these surfaces exist for distances up to 14,000 ft around airport runways and 50,000 ft extending from runway centerlines and thus encompass very large areas of potential infrastructure development.

Aeronautical studies may be required to evaluate objects that are found to be obstructions based on the evaluation of their heights in relation to FAR Part 77

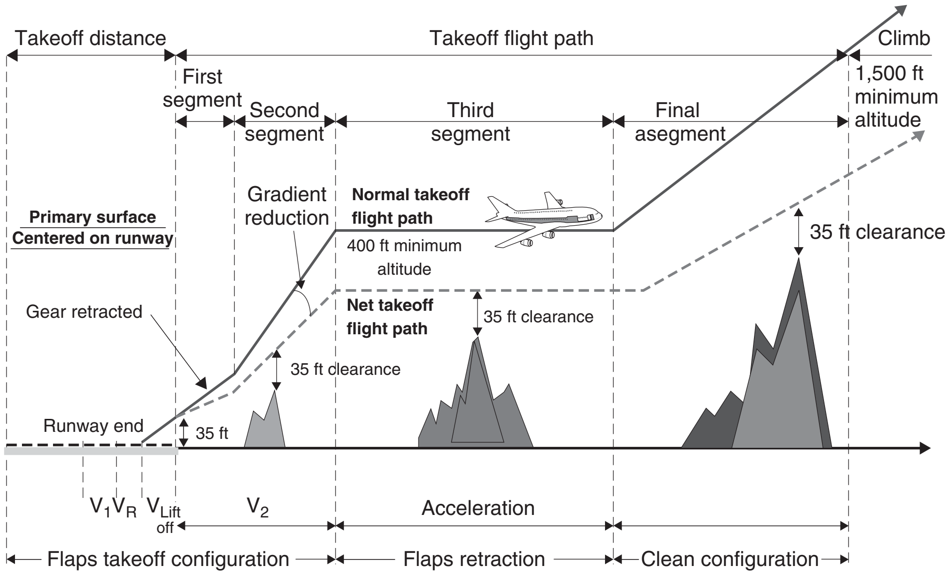


Figure 9.6 En route obstacle clearance standards. (*Source*: FAA.)

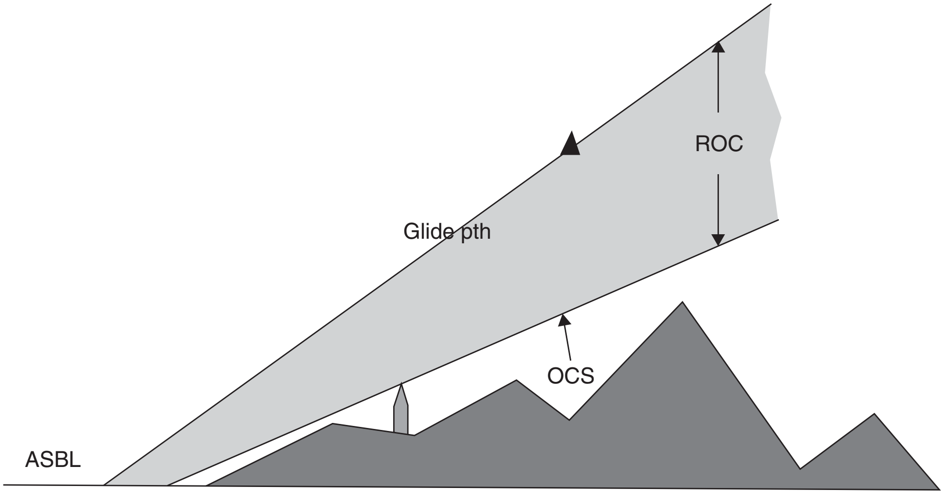


Figure 9.7 Approach obstacle clearance criteria. (*Source*: FAA.)

obstruction criteria. These objects are presumed to be hazards unless cleared through further aeronautical studies. Such studies include evaluating their heights and locations relative to any published instrument flight procedures followed by aircraft arriving and departing from nearby airports, in accordance with aviation approach and departure terminal instrument procedure standards, as described below.

Operational Standards. Operational standards aircraft actually follow in terminal airspace around airports are defined by the FAA Order 8260.3B: *Terminals Instrument Procedures*, or TERPS (14). The purpose of the TERPS is to define criteria for the creation of published instrument flight procedures for aircraft departing and approaching runways. A set of analog- and digital-based "instrument" technologies are used for navigation (as opposed to navigating by visual references). The goal of the TERPS process is to define such procedures so that aircraft applying these procedures are safely clear of natural terrain and man-made infrastructure.

TERPS contains more than 300 pages of specifications for defining safe aircraft departure and runway approach procedures based primarily on aircraft performance characteristics, various types of analog (land-based radio frequency emitting stations) and digital [as referenced by the U.S. global positioning system (GPS)] aids to air navigation, and currently existing natural and man-made objects surrounding an airport runway environment. As part of the definition of such procedures, minimum climb-out gradients for aircraft departures and minimum descent gradients as well as minimum safe operating altitudes for aircraft approaches are defined.

While FAA Order 8260.3b contains standards for creating such procedures, for any given runway at any given airport, one or more approach and departure procedures may be defined, each of which may be entirely unique, based on the environment at and surrounding the airport itself. As such, further evaluation of any given obstruction in the vicinity of any given airport with respect to TERPS becomes its own unique and often complex process.

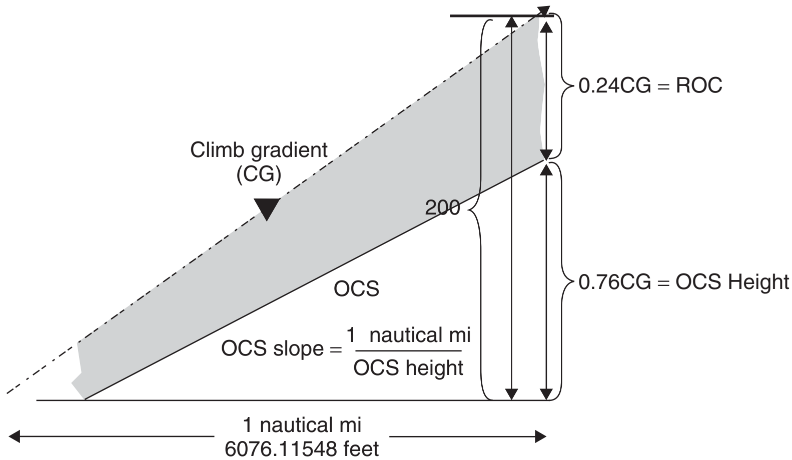


Figure 9.8 Calculation of OCS and ROC gradients. (*Source*: FAA.)

Specifically, TERPS defines a required obstacle clearance (ROC) value as a required altitude for aircraft to fly with a certain margin of safety over the height of the highest obstacle in the immediate vicinity of the procedure. Slightly above critical obstacles, a planar surface is established, known as the obstacle clearance surface (OCS), around which procedures will be designed, as depicted in Figure 9.8 [FAA Order 8260.3B Chapter 19, Chapter 2, Section 202 (14)].

Typical ROC values are 1000 ft for en route segments (2000 ft over mountainous terrain), 500–1000 ft for initial-approach segments, and 350, 300, or 250 ft in final-approach segments nearest a runway environment.

For segments of a TERPS procedure that dictate an aircraft's climb or descent at a given rate of altitude change, the flight path and OCS have varying slopes, determined by simple geometric formulas, resulting in varying values for ROC, as in Figure 9.8.

Flight Path. Typical glide path angles are on the order of 3.00°, or approximately 318 ft/nautical mi for approach segments. For climb segments, the ROC and OCS values are typically determined using a flight path standard minimum climb gradient (CG) of 200 ft/nautical mi, which has an OCS rising at 76%, equivalent to a slope of 40:1, as indicated in Figure 9.9. This climb gradient is easily achievable for most civil aircraft under normal operating conditions.

A typical TERPS procedure consists of a series of segments, including climb, en route, initial-approach, intermediate-approach, final-approach, and missed-approach segments, that are created based on the above standards and the existing terrain and obstacle environment for any given runway, as illustrated in Figure 9.9.

However, there are many variations of the "typical" TERPS procedure, as illustrated in Figure 9.10. Figure 9.10 provides examples of various geometries of approach segments, created based on initial aircraft entry points, performance characteristics of aircraft and navigation technologies, and existing terrain, man-made obstacles, and other land uses. Because of these variations, TERPS obstacle clearance surfaces are significantly more varied in shape and coverage than those defined in FAR Part 77, which are standard regardless of individual navigational procedures to any given airport.

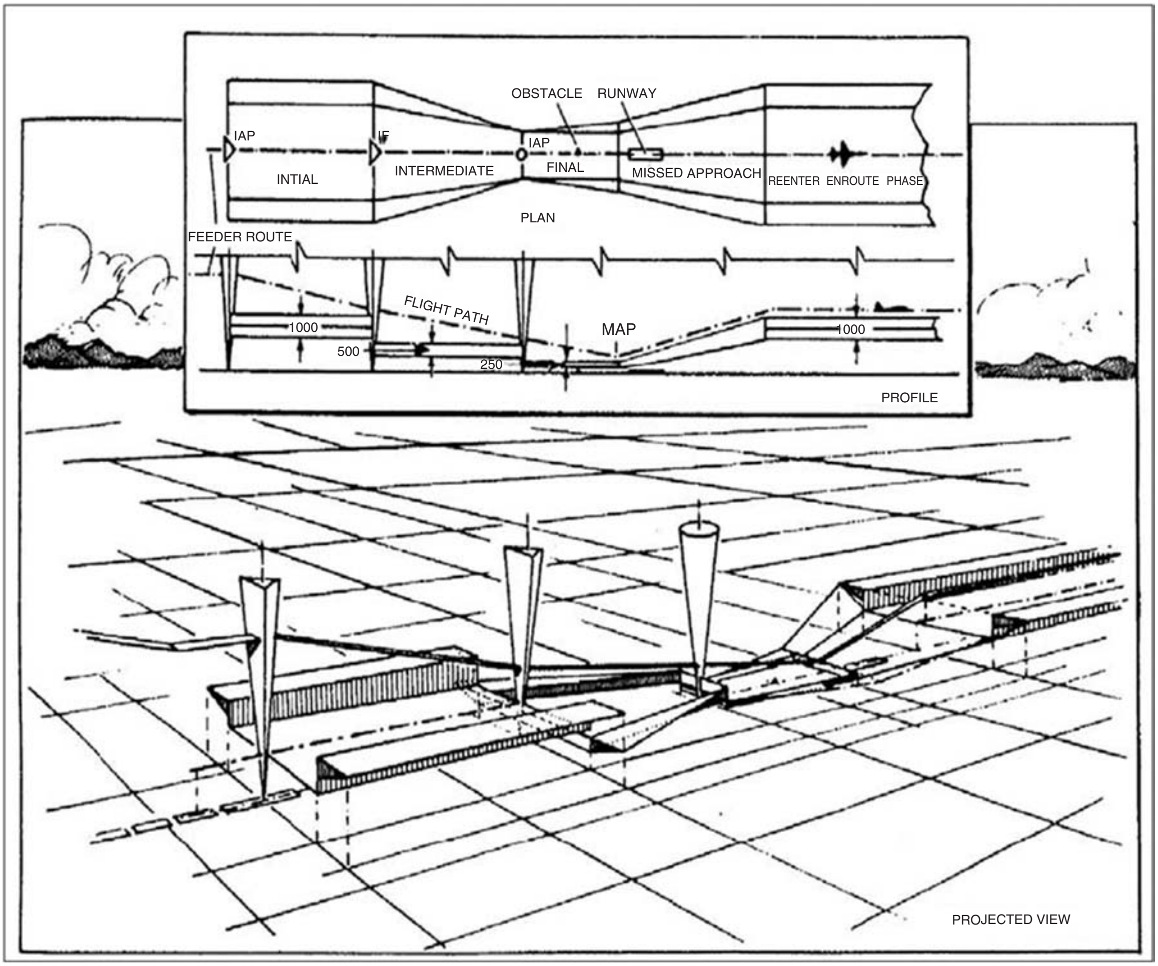


Figure 9.9 Typical TERPS procedure segments. (*Source*: FAA.)

TERPS procedures are published for public use in the form of standard terminal arrivals (STARs), defining en route arrival paths; instrument approach procedures (IAPs), defining final approaches and missed approaches in terminal areas; and standard instrument departures (SIDs), defining climbs from runway to en route airspace.

When the FAA has classified an object as an obstruction and the developer of the object is unwilling to lower the proposed height to the height not exceeding obstruction standards, further evaluation is performed, primarily against IAPs.

Safety Standards. This refers to the safety-based scenarios that 14 CFR embedded in the FAA regulations to provide a safety margin to the air services capability standards. These include worst-case scenarios for aircraft losing an engine upon takeoff (Part 25.121—One Engine Inoperative Climb Procedures) and for maximum-load aircraft takeoff hazard (14 CFR 121.189—Airplane Take-Off Limitations), as stated by the FAA (21) in Parts 121 and 135.

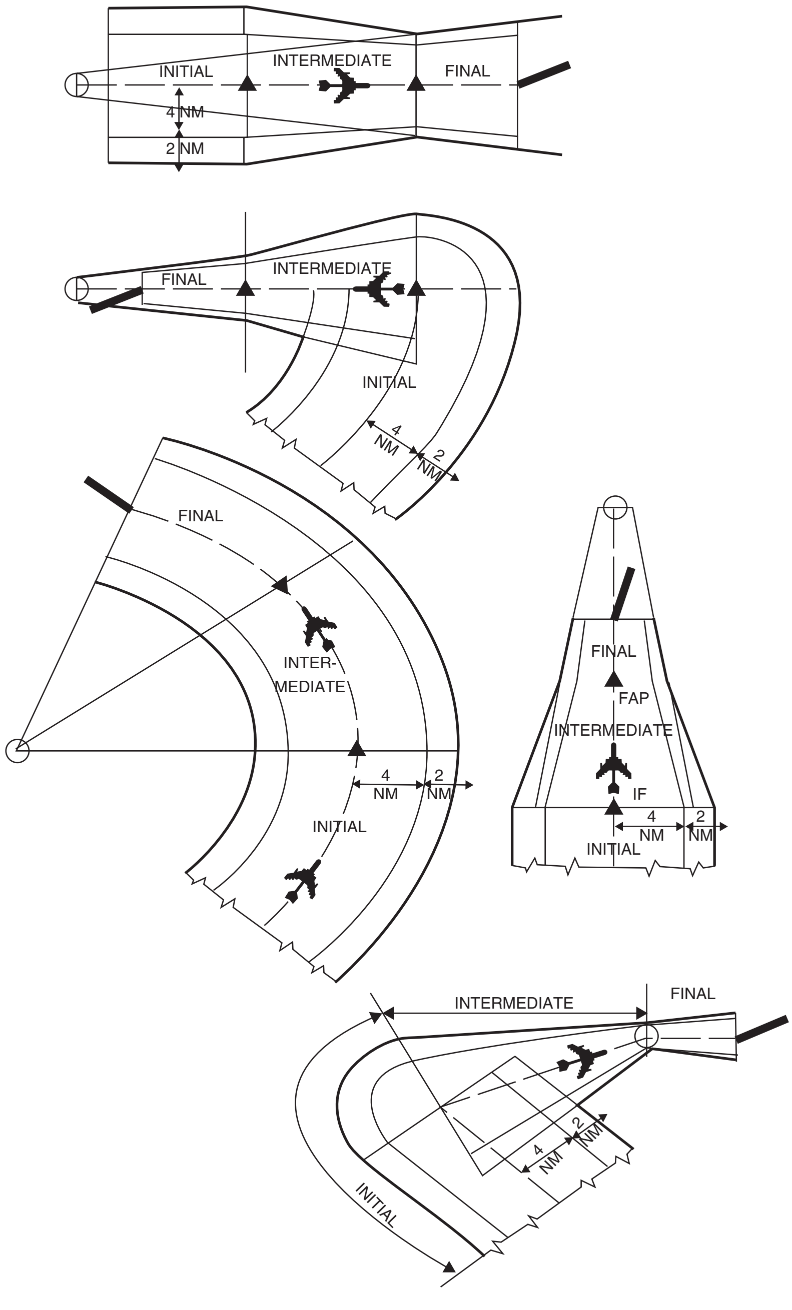


Figure 9.10 Variations of TERPS approach segments. (*Source*: FAA.)

The FAA has set guidelines for developing takeoff and initial climb-out airport obstacle analyses and in-flight procedures to comply with the intent of the regulatory requirements of 14 CFR Federal Aviation Regulations Sections 121.177, 121.189, 135.367, 135.379 and 135.398 and other associated engine-out requirements relating to turbine engine powered airplanes operated under Parts 91 (Turbojet Operators), 121 (Domestic, Flag and Supplemental Carrier Operators), and 135 (Large Transport, Commuters and On-Demand Operators).

These apply to operating requirements conducted under the above parts, particularly to airport required data (in relation to obstacles affecting takeoff and landing performance computations in accordance with the airplane performance operating limitations as well as any controlling obstacles), airplane weight limitations, airplane landing limitations, and airplane takeoff limitations.

While these FAA methods and guidelines have been derived from extensive FAA and industry experience and are considered acceptable by the FAA when appropriately used, they are neither mandatory nor the only acceptable methods. Operators may use other methods that ensure compliance with the regulatory sections if shown to provide the necessary level of safety and are acceptable to the FAA.

The three obstacle clearance standards—planning, operational, and safety, described above—are depicted in Figure 9.11 for the Dallas Fort Worth International Airport.

Addressing Airspace Safeguarding Issues

Given the discussion above and rationale of applying each of the three FAA standards, the implementation of these airport safeguarding standards by local planning agencies to evaluate potential hazard of vertical development on airports' navigable airspace should therefore be expanded. The increasing use of GPS-based navigational procedures in terminal airspace may not cope with local government's lax enforcement of regulating the airspace safeguarding process (and standards adopted) with intensive urbanization and commercial development around airports.

To date, little attention has been given to the issue of quantifying the mutual impacts of implementing future navigation technologies and vertical infrastructure development. But recent research (22) reveals that the proliferation of the GPS-based navigation procedures will in turn allow approaching aircraft to approach these runways under poor weather conditions to lower altitudes prior to making visual contact with the runway.

At commercial service airports, additional obstacle clearance requirements, pertaining to safe navigation of aircraft experiencing one-engine failure upon takeoff, may need to be considered further. These one-engine-inoperative (OEI) procedures are often more varied that even TERPS, and their impact on obstacle clearance criteria has not been covered along with TERPS and Part 77 standards.

It is hoped that when all three standards are integrated in implementation, they would bring about a critical balance between the economic-induced localized vertical development and the airport airspace safeguarding that will expand to properly protect the NAS and its airports. The ultimate goal to be achieved is to balance these two important elements of national economic and infrastructure development. Then airports and civil aviation will be efficiently and safely optimized with the economic benefit to the local community and wider society.

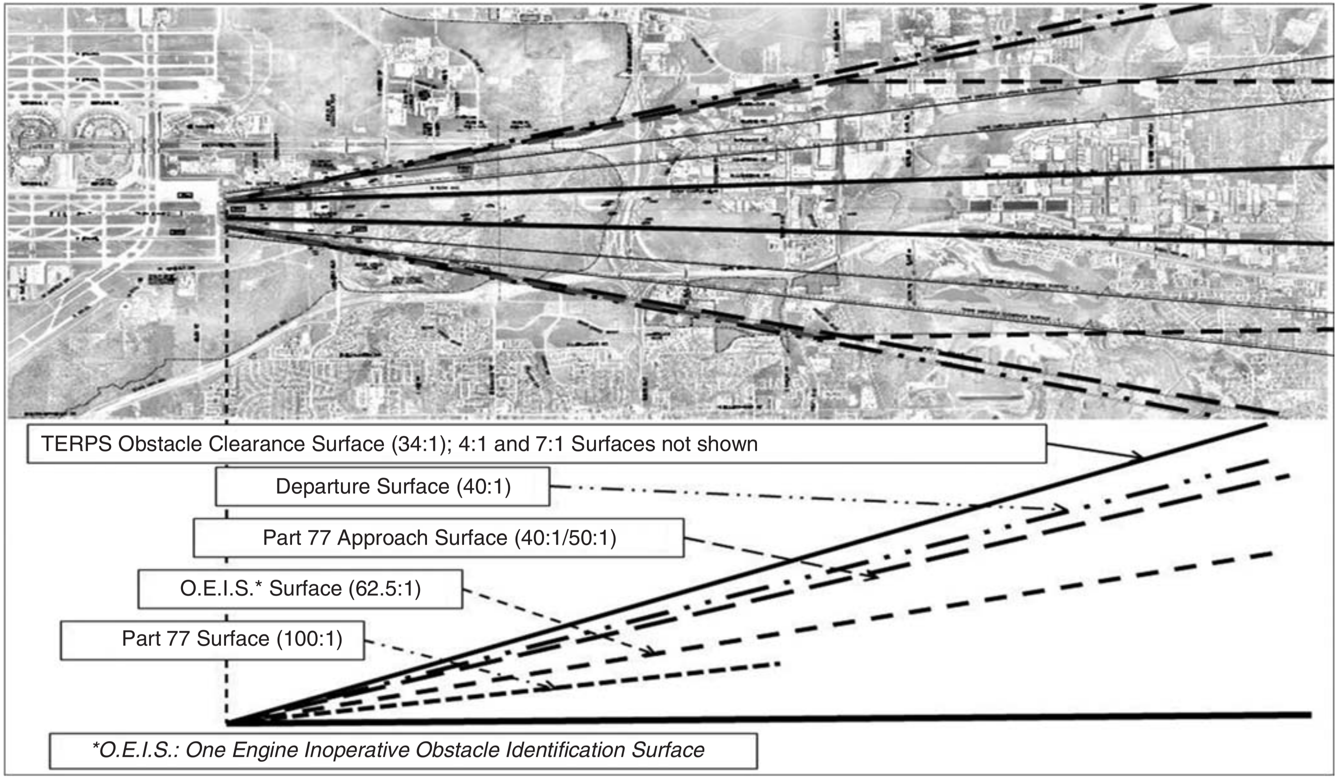


Figure 9.11 Obstacle clearance surfaces standards—Planning (FAA Part 77); Operational (FAA TERPs and ICAO PAN-OPS); and Safety (14 CFR OEIS) Superimposed on DFW Airport Runway 36R Plan Profile. (*Source*: DFW International Airport.)

FAA Obstruction Evaluation Process. At present, the FAA has instituted an obstruction evaluation (OE) study process to evaluate, mitigate, or eliminate the impact of tall structures and other obstructions on navigable airspace. This process is in compliance with applicable FAA standards for obstruction to navigable airspace, as per aeronautical studies conducted under the provisions of 14 CFR Part 77. These studies are requested by FAA regional offices and are administered by several FAA offices, including air traffic, flight procedures, airway facilities, and airports.

FAR Part 77, Obstruction Standards states that standards the OE will evaluate structures and obstructions against are:

- A height more than 500 ft AGL
- A height AGL or airport elevation, whichever is greater, exceeding
  - 200 ft within 3 mi
  - 300 ft within 4 mi
  - 400 ft within 5 mi
  - 500 ft within 6 mi
- A height that increases a minimum instrument flight altitude within a terminal area (TERPS criteria)
- A height that increases a minimum obstruction clearance (MOCA) (en route criteria)
- The surface of a takeoff and landing area of an airport or any imaginary surface established under Part 77 (77.25, 77.28, or 77.29 for civil airport imaginary surfaces (77.25)); horizontal, conical, primary, approach, and transitional surfaces are:
  - A height exceeding a horizontal surface; 150 ft above airport elevation within a 5000- or 10,000-ft radius of a public-use airport
  - A height exceeding a primary surface; length based on runway surface, width based on runway type/most precise approach existing or planned
  - A height exceeding an approach surface; extends outward and upward from each end of primary, applied to each runway end based on type of approach available or planned for that runway end
  - A height exceeding a transitional surface; slopes outward from side of primary and approach surfaces at 7:1, limited to 5000 ft either side of approach surface beyond limits of conical surface
  - Airport imaginary surfaces for military airports (77.28); inner horizontal, conical, outer horizontal, primary, clear zone, approach clearance, and transitional surfaces
  - Airport imaginary surfaces for heliports (77.29); primary, approach, and transitional surfaces

Due to the extensive development that typically takes place around busy airports and erection of tall communication towers in urban areas, the number of FAA-administered OE studies has been increasing steadily in recent years. In 2000, the FAA conducted more than 43,000 aeronautical studies to determine the impact of proposed structures on the airspace system nationally—100% increase in five years.

A typical OE process is composed of the following steps:

Step 1. *Inform FAA of Intention to Build*. As per FAR Part 77, Notice Criteria, and articles 13, 15, and 17, the FAA OE process is initiated with the submission of FAA Form 7460-1, Notice of Proposed Construction or Alteration (23). Details of the Part 77 notice criteria include:

- Proposed construction or alteration more than 200 ft AGL at its site
- Sites within 20,000 ft of a public-use or military airport having at least one runway more than 3200 ft in length and exceeding a 100:1 slope
- Sites within 10,000 ft of a public-use or military airport having no runway more than 3200 ft in length and exceeding a 50:1 slope
- Sites within 5000 ft of any public-use heliport and exceeding a 25:1 slope
- Any highway, railroad, or other "traverse way" for mobile objects of a height which, if adjusted upward to the height of the highest mobile object that would normally traverse it, would exceed the above-mentioned criteria
- When requested by the FAA, any construction or alteration that would be in an instrument approach area and available information indicates it might exceed a FAR Part 77 obstruction standard
- Any construction or alteration on any public-use or military airport

Step 2. *Processing FAA Form 7460-1*. Once this form is filed, an aeronautical study commences with assignment of a number and case, and it is entered into the OE automation program. Subsequently, processing commences with verification of airport coordinates and site elevation, and the review of all procedures involved.

Step 3. *Obstruction Criteria Applicable*. The FAA evaluates Form 7460-1 to determine the obstruction criteria applicable:

In case the proposed structure height exceeds obstruction standards and the FAA's preliminary review does not indicate a substantial adverse effect, a determination of presumed hazard is issued. The following options are available with the respective courses of action:

- The proponent may opt to lower the height of the structure so that it DNE obstruction standards; a no-hazard determination would be issued.
- The proponent may request further study at the original requested height; it is circulated to the public for comments.
- If more than 60 days have elapsed without attempted resolution, a new FAA Form 7460-1 would need to be submitted to reactivate the study.

In case the proposed structure height exceeds obstruction standards and the FAA's preliminary review indicates a substantial adverse effect, the FAA requests that the proponent lower or move the structure so as to eliminate the substantial adverse effect. The following options are available with the respective courses of action:

- If the proponent is able to lower the height and the revised height would not exceed obstruction standards, a no-hazard determination would be issued.

- If the proponent is able to lower the height and the revised height would still exceed obstruction standards, the proposal would be circulated for comments.
- If the proponent opts to move the structure, a new study would be necessary.
- If the proponent is unable to lower or move the structure, a determination of hazard to air navigation would be issued.

Step 4. *Circulation of Proposals*. Not all proposals or studies are circulated to the aeronautical committee for comment. In particular, if the obstruction in question is short enough or distant enough from any airport or navigational aide, no useful purpose would be served by opening the issue to the public and unnecessarily prolonging the process.

FAA Order 7400.2, Procedures for Handling Airspace Matters (23), provides guidance on circulating public notices for comments. Proposals requiring public notice are distributed to the proponent/consultant, county commissioner/mayor of the city in which the structure would be located, ATC facilities within 60 nautical mi, public-use airport managers within 13 mi and private-use airport managers within 5 mi.

Proposals requiring public notice include:

- Proposals that would affect a public-use airport
- Proposals requiring change in aeronautical operations or procedures
- When a structure exceeds obstruction standards
- When a structure would have possible impacts on VFR operations

Comments are accepted for a 30-day period, and all comments are analyzed for valid aeronautical objections.

Step 5. *Evaluating Aeronautical Effect and Issuance of Determination.* When the FAA determines whether an object exceeds the obstruction standards outlined in Part 77, the next step would be to determine if it is actually a hazard to the aeronautical community. It is important to recognize here that since the obstruction criteria set forth in Part 77 are just planning standards to determine if it is necessary to further study the impact of a construction proposal, they are not regulatory in nature, and exceeding the prescribed standards is by no means a disqualifying factor for a proponent, and hence an obstruction is not necessarily a hazard.

Therefore, in order for an object to be considered for "adverse effect," one or more of the following conditions must be met:

- An object must exceed the obstruction standards outlined in Part 77 and/or have a physical and/or electromagnetic effect on air navigational facilities.
- A change is required to an instrument procedure or minimum flight altitude.
- Airport control tower line of sight is restricted.
- Airport capacity and efficiency are reduced.
- Usable runway length is adversely affected.

For a hazard determination to be issued, a "substantial adverse effect" must exist. This requires a combination of two factors. First, an object must create an adverse effect, as described above. Second, a "significant volume" of aeronautical operations must be affected. FAA Order 7400.2 defines what constitutes significant volume as follows:

- When one or more aeronautical operations per day would be affected (regardless of the type of activity)
- An average of one aeronautical operation a week for an affected instrument approach procedure or minimum altitude if the procedure serves as the primary procedure under certain conditions, for example, a crosswind runway with an instrument approach procedure

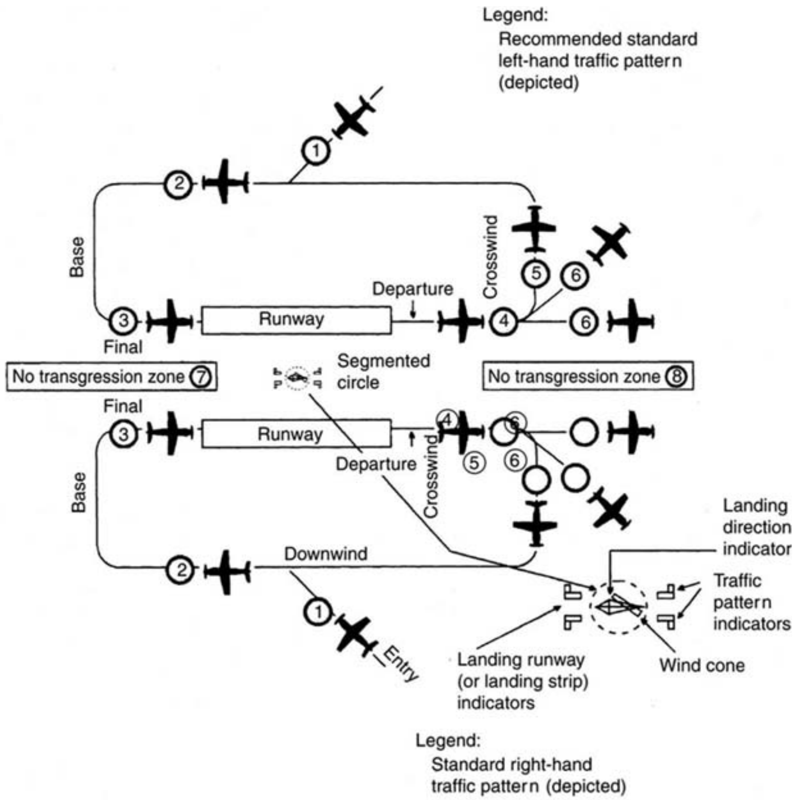
If the OE study determines that a substantial adverse effect is found to exist, a determination of hazard to air navigation is issued.

If the OE study determines that no substantial adverse effect is identified, a determination of no hazard to air navigation is issued, and supplemental notice would be requested at least 10 days prior to beginning construction and/or within 5 days after the structure reaches its greatest height. Also, a site survey may be requested if required by the flight procedures office.

Safeguarding Regulations versus Local Planning Evaluation Criteria. The basis for the derivation and design of the Part 77 surfaces is not very clear, and the literature does not delve into or offer any justification for specific elements of the "imaginary surfaces." But close examination of the elements seems to suggest that they may have been related to the airport approach and missed-approach procedures for the type of aircraft when Part 77 was first released in May 1965. At that time, the typical airport approach/departure procedure pattern, depicted in Figure 9.12, resembles some of the Part 77 imaginary surfaces' planes. More specifically, resemblance between the two includes the primary surface (for runway), horizontal surface (for downwind, base, and crosswind), approach surface (for final approach and departure), transitional surface (for missed approach), and conical surface (for maneuvering). However, it is critical to remember that navigating aircraft at the airfield is drastically different and more efficient now than it was in the early 1960s, when the Part 77 (and Annex 14) safeguarding airspace concept was conceived. Today, aircraft navigation and more related to procedures defined by operational standards set in the FAA (TERPS) and ICAO (PAN-OPS). Today's pilots are not particularly concerned with those old maneuvers that Part 77 concept and its imaginary surfaces are based upon. Therefore, in practical and realistic terms, more attention should be paid to applying the TERPS basic concept for safeguarding. However, the nature and complexity of TERPS may not support this premise.

Moreover, the FAA obstacle clearance evaluation process is often interpreted by developers, municipal planning departments, and often airport management, and evaluation of a proposed development with respect to operational standards only occurs when one or more FAR Part 77 surfaces are penetrated. As such, future vertical development is almost always evaluated on a local level with respect to FAR Part 77 surfaces. If the development does not penetrate any FAR Part 77 surface, then no further evaluation is assumed to be needed.

However, despite compliance with all FAR Part 77 surfaces, further evaluation with respect to the operational standards may lead to findings of incompatibility between



① Enter pattern in level flight, abeam the midpoint of the runway, at pattern altitude. (1000' AGL is recommended pattern altitude unless established otherwise.)

② Maintain pattern altitude until abeam approach end of the landing runway, on downwind leg.

③ Complete turn to final at least 1/4 mile from the runway.

④ Continue straight ahead until beyond departure end of runway.

⑤ If remaining in the traffic pattern, commence turn to crosswind leg beyond the departure end of the runway, within 300 ft of pattern altitude.

⑥ If departing the traffic pattern, continue straight out, or exit with a 45° turn (to the left when in a left-hand traffic pattern; to the right when in a right-hand traffic pattern) beyond the departure end of the runway, after reaching pattern altitude.

⑦ Do not overshoot final or continue on a track which will penetrate the final approach of the parallel runway.

⑧ Do not continue on a track which will penetrate the departure path of the parallel runway.

Figure 9.12 Runway approach and departure patterns. (*Source*: FAA.)

future development and current airspace procedures. This is in part due to the complexity of these standards and their associated obstacle clearance requirements. Consequently, local planning agencies have historically avoided use of operational analysis standards as part of their criteria for initially evaluating potential development. This is evident in the land use and infrastructure planning guides authored by state, regional, and local planning agencies. While most such guides do describe the FAA's initial obstruction evaluation process under FAR Part 77, virtually none make mention of any analysis with respect to the operational procedures in place.

Furthermore, the FAA's published "model" guidance for local agencies to develop zoning ordinances to limit the height of objects around airports is based entirely on the surfaces described in FAR Part 77 without any consideration for the operational or safety standards in the obstacle clearance criteria (17).

As a result, the evaluation process conducted by local planning agencies and developers often results in neglecting further review of complex and unique airspace procedures and requirements, especially when obstruction criteria described in FAR Part 77 are not exceeded. This process often results in approvals to making significant investments in planning, design, land use acquisition, and imminent construction for infrastructure development that unintentionally conflict with local approach and departure procedures to nearby runways, significantly impacting the optimal use of the airfield infrastructure. Only upon filing of FAA Form 7460-1 and the subsequent FAA review process does any potential operational conflict become evident, which can oftentimes occur well after the initial investments toward development are underway.

In many obstacle clearance evaluations, failure to evaluate applicable airspace procedure criteria after satisfying FAR Part 77 obstruction criteria does not result in any future conflict between proposed infrastructure development and navigable airspace, as the FAA TERPS and other hazard criteria are often higher than FAR Part 77 obstruction criteria. However, there have been several cases where significant conflict has arisen between new infrastructure development and local navigable airspace where proposed structures did not exceed obstruction criteria and local go-ahead was received prior to formal FAA review. These cases are described below.

Observed Discrepancies in Application of Standards. In the FAA OE process, it is not customary to conduct such extensive and comprehensive analyses that would cover all three standards stated in Section 9.2. Given the advisory, nonmandatory nature of the FAA OE process, the three standards are actually applied in only a few cases. In particular, applying the operational standards of TERPS tends to be data intensive and must be specific to the airport, aircraft types operating in it and the terrain and man-made structures in its vicinity, and more likely it will not be applied. These two reasons—nonmandatory nature and data requirement of applying the operational standards for the OE—may invariably imply that certain, sometimes serious, obstructions impacting the navigable airspace may be overlooked and pass with a no-hazard determination by the FAA.

However, in the few cases where the three standards were considered and applied, certain discrepancies were observed. These are related to two airports in California where thorough TERPS evaluation was conducted in an aeronautical study as part of an FAA OE study process (24). This analysis went beyond the formal FAA OE process and quantitatively and graphically revealed those discrepancies. Further aeronautical analysis showed that an obstruction was found to create an unsafe environment for aircraft following a given TERPS-defined procedure. The obstruction was classified as a hazard to air navigation. In this case, the FAA would normally contact the developer in an attempt to negotiate a height for not exceeding (HFNE) any of the hazard criteria found during further aeronautical study. If the sponsor agrees to the lowered height, a determination of no hazard (DNH) can be issued for the lowered height. If the sponsor does not agree, the FAA will issue a determination of hazard (DOH). This determination of hazard is issued by the FAA to discourage the proposed development subject to the jurisdiction of local authorities. Alternatively, the FAA may consider a modification to the procedure that is in conflict with the proposed construction, but this practice is rare because it generally results in diminished efficiency and capacity of the airport and sets a precedent that subsequent developers will attempt to follow.

Two cases of such discrepancies have been reported for two California airports: Oakland and San Diego.

Oakland International Airport One of the first revelations of this issue arose in 2002 during the later planning phases of enhanced infrastructure development at the Port of Oakland, California, a major shipping port, as well as the Oakland International Airport (25). The sea port is located approximately 5 mi northwest of Oakland International Airport, on the eastern edge of San Francisco Bay. The port's maritime facilities serve nearly 2000 cargo vessels annually, with 37 container gantry cranes. Oakland International Airport serves nearly 200,000 yearly commercial aircraft operations, most using the 10,000-ft primary runway.

In an effort to expand operations at the port's maritime facilities, additional gantry cranes were installed at the port and shipping channels and mooring facilities were dredged. An initial aeronautical evaluation to study the heights of these fixed and transient structures was required to evaluate them as potential obstacles to navigable airspace to and from Oakland International Airport. An FAR Part 77 analysis was conducted for the crane and vessel heights to evaluate their impact on the imaginary surfaces and other obstruction criteria. As a result of this initial analysis, it was found that the height and location of both the cranes and the transient and mooring positions of vessels did not penetrate FAR Part 77 surfaces and thus were not considered as obstructions to navigable airspace.

It was thought prudent from operational and safety perspectives to conduct a TERPS evaluation. TERPS (14) procedures are published for public use as standard terminal arrival (STAR) procedures that define en route arrival paths, instrument approach procedures (IAPs) that define the final and missed approaches to the airport in terminal areas, and standard instrument departure (SID) procedures that define aircraft climb from the runway to en route airspace. An example of a typical published IAP, a precision instrument landing system (ILS) approach procedure into Oakland International Airport's runway 11 (where the obstruction situation takes place), is illustrated in Figure 9.13.

However, upon formal FAA review of both FAR Part 77 and the TERPS obstruction criteria associated with standard instrument departure and approach procedures for the airport revealed critical areas whose criteria were below that of FAR Part 77 as well as criteria that extended far beyond FAR Part 77 surfaces, as illustrated in Figure 9.14. Specifically, TERPS obstruction criteria were more critical (by area) over approximately 70% of the FAR Part 77 surfaces and extended over an area more than three times the area under which Part 77 surfaces cover. Furthermore, the height of newly installed cranes at the Oakland Port exceeded existing TERPS obstacle clearance surfaces and thus posed a hazard to air navigation when certain aviation procedures were in effect.

Upon further analysis, it was revealed that this condition was mostly a result of a particular approach procedure into the airport which called for aircraft to descend to and maintain a relatively low altitude several miles from the airport. As a result of this finding, successful negotiations with the FAA were conducted which modified

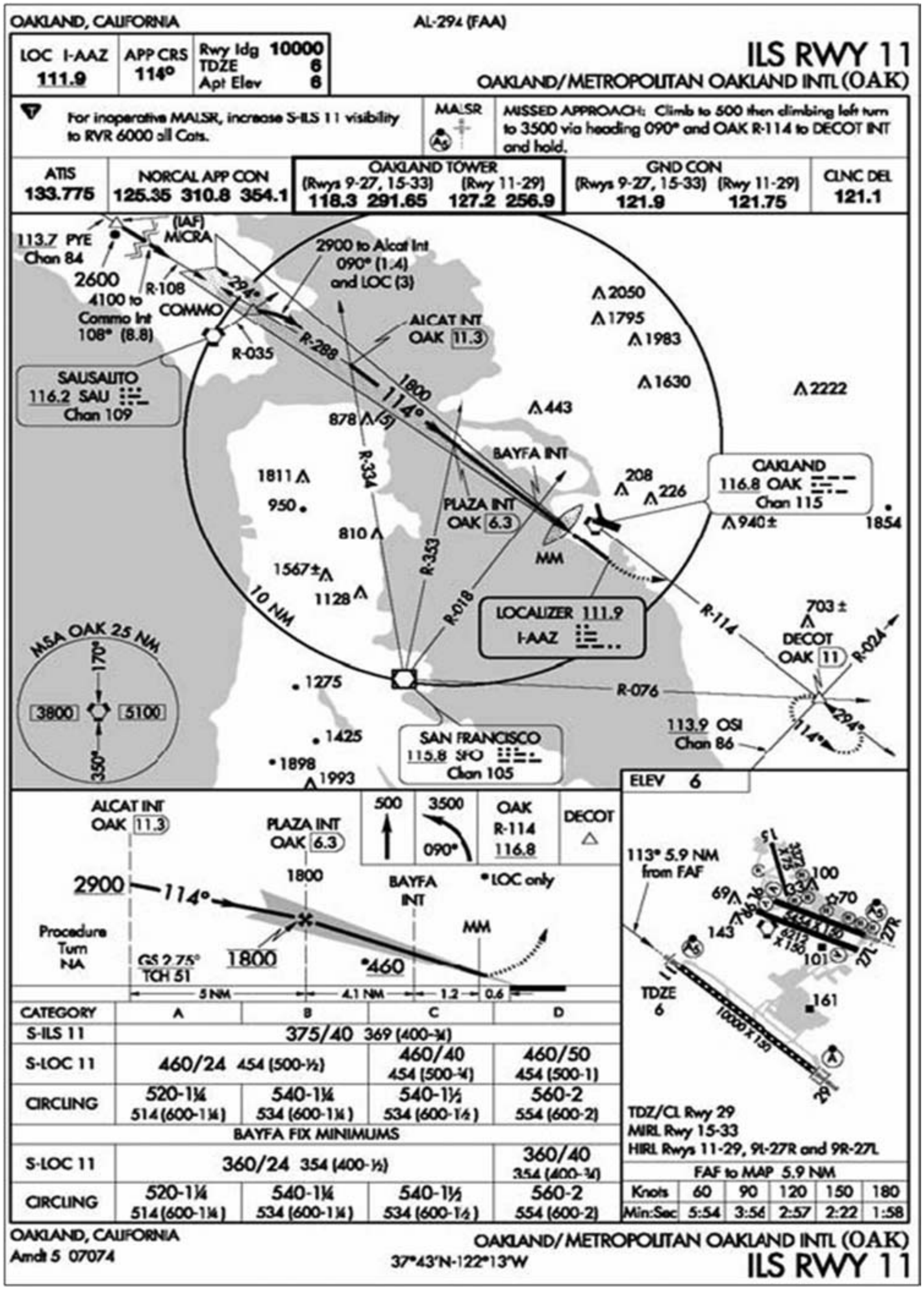


Figure 9.13 Typical TERPS approach chart (ILS runway 11, Oakland International Airport).

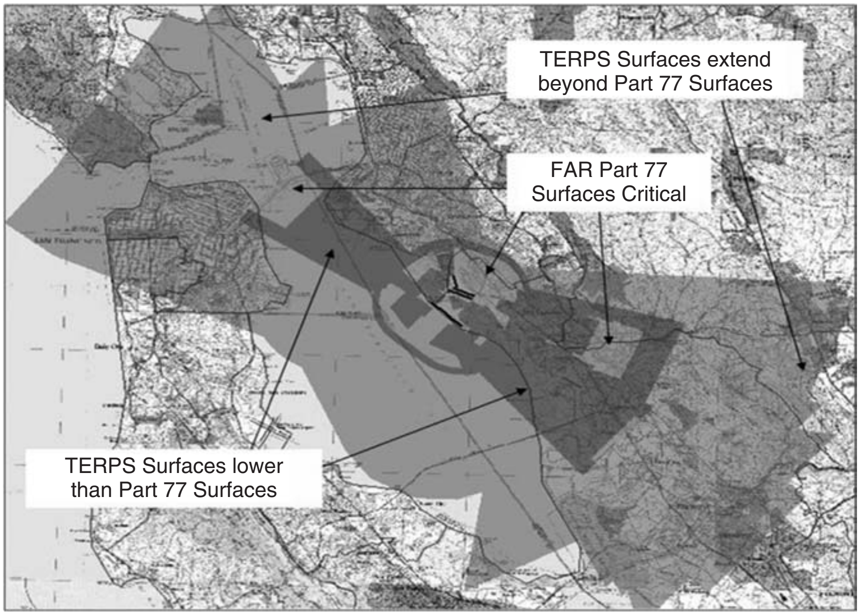


Figure 9.14 Comparison of TERPS versus FAR Part 77, Surfaces, Oakland International Airport. (*Source*: Ricondo & Associates, Inc. Used with permission.)

this procedure to allow for safe air navigation to the airport as well as be compatible with the infrastructure the port needed to install. This finding demonstrates that TERPS obstacle clearance criteria may often indeed be more critical than those of FAR Part 77.

Montgomery Field, San Diego, California Issues such as those revealed at Oakland are not limited to commercial service airports. Such issues have been found to exist at general aviation airports, between municipal planning agencies and private developers, and based on existing zoning ordinances and issues associated with the enforceability of the FAA's obstruction analysis findings.

Such is the case in the City of San Diego, where, since 2005, private developers have been at odds with city planning officials, the California Department of Transportation, and the FAA over the construction of an office tower located a mile to the north of Montgomery Field, an active general aviation airport located 5 mi north of the San Diego central business district CBD (26).

Stemming from a land use zoning policy that had not considered building height limits compatible with FAA obstacle clearance criteria until 2002, the City of San Diego, in 1997, gave initial approval for the construction of the 12-story office building, with maximum height of 180 ft (above ground level, AGL), despite FAA findings that the proposed construction would violate FAR Part 77 obstacle clearance criteria by 20 ft. The 12-story office building in question was identified as a 578-ft (elevation above seal level, ASL) obstruction located 1 mi north of the airfield. The building was deemed a hazard to navigation due to the building penetrating TERPS obstacle clearance criteria for one published instrument approach to the instrumented runway 28R circling approach, as illustrated in Figure 9.15 (27).

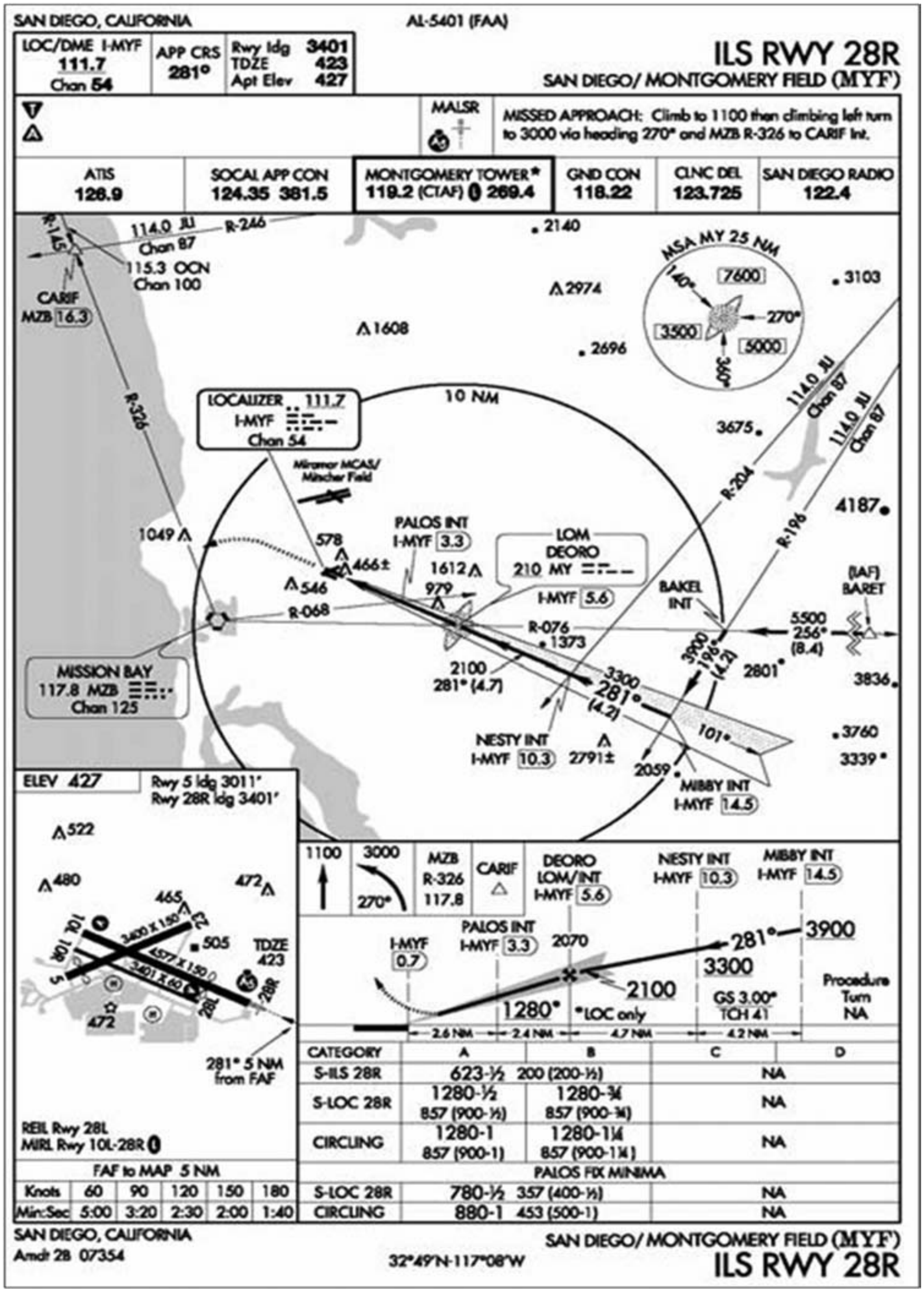


Figure 9.15 Runway 28R ILS procedure to San Diego Montgomery Field (27).

Despite nearly two years of debate, lawsuits, and what had been described in local media as local government "staff blunders," development of the building continued to its 180 ft planned maximum, forcing the FAA to temporarily adjust instrument approach procedures at Montgomery Airfield, until in late 2007 the developer finally agreed to deconstruct the building by 20 ft to comply with initial FAA determinations.

The above two examples demonstrate the differences between the planning and operational standards and they became known because they were published. Many other similar examples simply were not released beyond the OE process and the FAA interactions with the proponents and deliberations with airport sponsors. For many more airports, the important safeguarding and safety issues were not even identified and hence were not analyzed further.

In the next section, the position of two important airport stakeholders who are directly affected by the technical issues on this matter are presented and discussed.

Position of Stakeholders. The viewpoint of certain stakeholders who dealt seriously with the airport safeguarding issues are discussed—mainly airport operators and their planners and engineers (represented by the Airports Consultants Council, ACC) and pilots and aircraft owners (represented by the Airlines' Pilots and Aircraft Owners Association, AOPA).

Airports Consultants Council. After obtaining feedback from its membership of airport planners and designers, the Airports Consultants Council (ACC) in a letter to the FAA (28) summarized its views on cutting the confusion and plugging potential loopholes. The ACC position referred the FAA to the following issues:

- Since FAA Part 77 is a planning standard, it must be aligned with specific airport design standards. The FAA needs to provide clarifications and should align the planning and design standards of airports.
- How best to cross reference the TERPS and Part 77 imaginary surfaces? This issue is the crux of the discrepancies discussed in the previous section. In particular, the multiple and continuing changes in the TERPS criteria dictated by advancement in aircraft and navigation technologies over the years and since Part 77 was released it has created significant inconsistency between the two standards. This situation only adds confusion and inefficiency to the airport design standards and to the safeguarding process. While the FAA has recognized this situation and was working on narrowing the gap to bring about uniformity and consistency, the FAA safeguards and the OE process have not yet resolved this completely.
- FAA Part 77 configurations for primary and transitional surfaces are the same for all aircraft. While the 1000-ft primary surface and the 7:1 transitional surface are uniform for all aircraft, there is definitely a marked difference between large/heavy aircraft and much smaller general aviation aircraft, particularly in terms of wingspan and approach speed. This difference would be reflected and implicit in TERPS, but for Part 77 it is a case of one-size-fits-all, which brings confusion, and at best inefficiency. There is a need therefore for a graduated approach, at least for two classes of aircraft.

- By the same token, Part 77 provides a single standard for vertical clearance for traverse ways (23 ft). This clearance unnecessarily limits opportunities to locate public transportation infrastructure near airports. The ACC view is to consider different traverse way standards for the Part 77 obstruction standards.
- Part 77 should provide some "enforcement language" with respect to noncompliance, even at local jurisdictions, and regulate via tying it to local zoning codes and laws. As it stands today, Part 77 only provides "guidance" on obstruction to navigable airspace. Protecting the navigable airspace is a vital public responsibility of the FAA that should be conveyed as a regulation to local jurisdictions.
- To provide an enforcement role for Part 77, the ACC proposed to the FAA adding language that would turn FAA Form 7460, "Filing Obstruction Notice with the FAA," into a "true permit application" rather than simply a request for an FAA OE analysis. This language must also ensure the responsibility of local agencies/jurisdictions to issue building/construction permits as well as to verify that appropriate FAA determination has been submitted and complied with. If the FAA determinations are ignored and not complied with, the local agency/jurisdiction as well as the property owner would be open to federal action.
- With the proliferation of unmanned aerial vehicles/systems (UAV/S) for civilian use after its success in the military environment, the ACC suggests consideration be given to this technology in Part 77.

Airlines' Pilots and Aircraft Owners Association In evaluating the impact of tall objects on the navigable airspace, the position of the pilots on this issue is that it is recognized that balancing the needs of all aeronautical activities ensures that the FAA is not always in best position to evaluate every factor that needs to be assessed in any airspace obstruction study. This problem is not unique to the United States but is very typical of all governments regulating agencies all over the world.

The AOPA advised its membership of airline pilots and aircraft owners (29) that the OE for an airport, regardless of its public-versus-private status, should be responded to vis-à-vis:

- Will the structure/object impact the approach minimums at a public-use airport?
- If the FAA's circular indicates a change in approach minimums, how will this impact the aviation community? Is this the only approach predicated on a specific type of navigational aid? Does the impacted approach offer the lowest minimums at that facility?
- Will the structure in question be close to a visual landmark such as a highway, mine, reservoir, or any other point commonly used as a visual reference for VFR pilots?
- Will the structure in question underlie terminal airspace, creating traffic compression and with it an increased risk of a midair collision?
- Will the structure in question lie in an area in which a high volume of flight training activities is conducted?
- Will the proposed structure lie along commonly used VFR egress or ingress tracks to airports?

In general, comments generated on an OE would be assessed against factors impacting the safe and efficient use of airspace. If the comments do not constitute any adverse effect of the structure, then the FAA has no cause for concern, and a no-hazard determination will likely be the outcome.

This position is understandable. Obstruction evaluation typically involves all lines of business and stakeholders of airports. The FAA posture here is to take each obstruction study on its own merits and each object is analyzed prior to assuming it to be a hazard. This is consistent with the FAA primary mission of promoting aviation safety. If an object is found in an aeronautical study to have a significant adverse impact, a "hazard" determination is issued. However, in most instances negotiations between FAA and the proponents take place until the conditions are met for a "no-hazard" determination. This demonstrates the benefits of FAA participation on regional and local levels. For this purpose, the AOPA stresses to its members the importance of their participation and involvement in obstruction evaluation and the impacts on their aeronautical activities.

Physical Dimension of Safeguarding

The airport navigable airspace protection criteria described earlier provide the safeguarding necessary and constitute one side of this balance. On the other side are all the means and mechanisms implemented to ensure, in real terms, that those criteria are strictly complied with. Therefore, the physical dimension of airspace safeguarding is central to determining whether the delicate balance is actually attained.

Since the FAA issued the three-part airport safeguarding criteria (planning, operational, and safety) and the ICAO instituted Annex 14, as described previously, world civil aviation authorities in collaboration with town planning and municipal authorities and local government have gone in different ways in implementing safeguarding. But how successful implementation is relies entirely on iron-clad procedures to enforce building heights in locations critical to airspace and airport terminal approach and navigation—which is not a routine matter, on paper, and certainly not in any way trivial. The local monitoring and enforcement of building heights constitute the "soft belly" of maintaining the delicate balance. While it is the responsibility of both airports (for issues related to safety and compliance with navigation procedures) and local government (for issues related to compliance with national laws and zoning regulations) to safeguard airport navigable airspace, the loose monitoring or complacent enforcement of actual total structure heights (permanent or temporary) around airports may endanger the safety of the navigable airspace and render the safeguarding criteria almost meaningless.

In this section the various physical, practical, and technology aspects of obstacle monitoring and recording are discussed. World airport obstruction management practices and the processes involving the airports, civil aviation authorities, and local governments are first presented. Mapping and aeronautical surveys for airport safeguarding are described, technologies and processes for obstacle mapping and conduct of aeronautical surveys are presented, and an integrated approach to comprehensive safeguarding monitoring is proposed.

Airport Obstruction Mapping Surveys

Currently, the U.S. NAS handles more than 60,000 flights operating daily under the guidance of the FAA air traffic control system. The safety of the aircraft and passengers relies heavily on the safe and efficient use of airspace en route to and in the vicinity of airports. With the increasing role of airports as economic engines in their regions, airports invariably attract large-scale development around them. The continuing and projected increase in air traffic and the introduction of GPS-based aircraft departure and arrival procedures have intensified the need to expedite obstruction surveys.

To maintain the safety of aircraft and the integrity of navigable airspace around them, airports must always maintain current obstruction identification and mapping surveys. This section provides a background on the aeronautical surveys the FAA has been conducting for years as part of its mission, focusing on its obstruction surveys to ensure the integrity of safeguarding airport navigable airspace in the NAS. Recent development in this field is presented, particularly the FAA movement toward the integration of obstruction surveys with GIS and the role of third-party service providers. Traditional obstruction survey methods are presented and discussed together with new technologies that will greatly improve the conduct of obstruction surveys. A new remote sensing technology, LIDAR, is a promising technology that is specifically focused on. Airport obstruction databases of the FAA and ICAO are also mentioned.

FAA Aeronautical Surveys. The FAA has been using survey data and aeronautical obstruction charts provided by the U.S. National Geodetic Survey (NGS) to develop instrument approach and departure procedures, including GPS approach, certify airports for certain types of operations, including those conducted under FAR Part 139 and FAR Part 77, determine maximum takeoff weights for civil aircraft, and update official U.S. government aeronautical publications.

The aeronautical survey data are also used to provide geodetic controls for engineering projects related to airfield construction, navaid site selection, and ATC tower location. Airlines use these surveys to analyze flight paths for their aircraft. Airport managers are required to analyze when action is needed to avoid or remediate impingements on airspace (e.g., reduce the height of trees near runways), to update airport layout plan (ALP) drawings that may become the basis for restricting the heights of structures that could impinge on airspace, and to note locations of temporary potential obstructions (e.g., construction cranes). Airports also use these surveys for airport planning and land use studies in the airport vicinities. The FAA is expecting to outsource several hundred aeronautical surveys annually through third-party service providers under the FAA airport-surveying GIS program and use the NGS expertise for independent verification of data integrity and data quality assurance.

The NGS specifications of aeronautical surveys for several other applications have been used by the FAA under the direct supervision of the NGS. The FAA aeronautical surveys standards recommend that conduct of airport obstruction surveys follows three phases:

- Phase I. Establish a primary airport control station (PACS) tied to the National Spatial Reference System (NSRS)
- Phase II. Establish secondary airport control stations (SACSs) tied to:
  - IIa. PACS
  - IIb. Survey runway points
- Phase III. Airport survey obstructions

This framework parallels the three phases of NGS aeronautical surveys: geodetic control, imagery, and airport data. Third-party surveys are submitted to the FAA for quality assurance and verification of identified obstructions. The NGS networks of continuously operating reference stations (CORSs) with permanent continually monitored monuments of geodetic control stations enable accurate three-dimensional positioning through the United States. The NAD 83 for horizontal control and the North American Vertical Datum of 1988 (NAVD 88) for vertical control are specified as per FAA standards for airport obstruction surveys.

FAA Obstruction Surveys. Aeronautical surveys are used to provide essential information critical to the operation of the NAS (30). Most of this information is source data acquired by traditional field survey procedures augmented by photogrammetric methods. Information furnished under these standards includes surveys conducted under Federal Aviation Regulations that include:

- *Geodetic surveys*, covering control data for permanent survey "monuments" established in the airport vicinity. These monuments and their accurate connections to the NSRS assure accurate relativity between surveyed points on an airport and between these points and other surveyed points and facilities in the NAS, including the navigation satellites.
- *Runway and stopway surveys*, including runway end, stopway end, and displaced threshold positions and elevations, runway geodetic azimuths, touchdown zone elevations, and runway/stopway profiles.
- *Navigational aid surveys*, including data on navaid position and elevation, type, and distance from runway end and runway centerline.
- *Planimetric surveys*, providing details on airport taxiways and aprons and delineations of features of landmark value, such as rivers, lakes, tidal shorelines, and major highways.
- *Obstruction surveys*, including obstruction description, position and elevation, and amount penetrating the FAA obstruction identification surface (OIS).
- *Aerial photography and satellite imagery*, providing coverage of the airport vicinity.

The information above is necessary for different aspects of aeronautical surveys and is used in different ways for airport obstruction mapping. In general, data from the above surveys are used in a variety of ways for airports, but mainly for:

- Developing instrument approach and departure procedures
- Certifying airports for certain types of operations, including those conducted under FAR Part 139—Airport Certification
- Determining maximum takeoff weights for civil aircraft
- Providing geodetic control for engineering projects related to runway/taxiway construction, navaid siting, obstruction clearing, road building, and other airport improvement activities
- Assisting in airport planning and land use studies in the airport vicinity
- Supporting miscellaneous activities, such as aircraft accident investigations and special-purpose one-time projects

Technical terms critical to and used for these aeronautical surveys are defined in two main sources: FAA *Aeronautical Information Manual* (19) and the geodetic glossary published by the NGS (31).

These aeronautical surveys form the basis for the conduct of the FAA VFR and IFR procedures, where the FAA specifies standard routes, flight altitudes, and visibility minimums for approach and departure procedures. The standard methods required for control of safe aircraft flight conducting these procedures contain identifications of obstructions that pilots and ATC must use to communicate the flight control. These obstructions are observed, identified, surveyed, and entered into the FAA standard obstruction surveys. The FAA obstruction surveys are used to prepare 1:12,000 scale maps to generate aeronautical obstruction charts (AOCs). AOCs are used for graphic depiction of the runway layout plan, locations of navaids, the footprint of imaginary surfaces, identification of obstructions penetrating the imaginary surfaces which cannot be removed, other airport features, planimetric details in the airport vicinity, and information critical to safe and effective operation of the navigational space. The accuracy of the AOC survey has been paramount to the safety of pilots flying and passengers on airplanes operating in the airspace. For more than 50 years, the U.S. NGS of the National Oceanic and Atmospheric Administration (NOAA) has been conducting airport obstruction surveys and providing AOC maps to the FAA through its Aeronautical Survey Program (ASP). In 1996, the ASP was expanded to include the Area Navigation Approach (ANA) survey to support future air navigation systems, particularly those that are GPS based. This obstruction survey is specially designed to provide the data necessary to construct an instrument approach supported by new satellite-based navigation methods other than the typical ground-based navigational systems. The specifications for the AOC and ANA surveys are documented by the FAA (31) for implementation and as reference.

Satellite-Based GPS Procedures. AOC and ANA surveys conducted by the NGS have been the basis for developing traditional non–precision instrument and precision instrument procedures since using ground-based navaid equipment and expensive aircraft panel instruments. These procedures have been provided by the FAA for all-weather operations at all U.S. airports serving scheduled air carrier operations and at many busy general aviation airports. The FAA is also developing TERPS criteria using relatively new GPS-based satellite receivers for NAS implementation (32). The FAA has developed the following GPS-based navigation procedures:

- Un-augmented GPS receivers.
- WAAS: Augmentation to GPS provides a signal in space to support en route and precision/nonprecision navigational approach. The system adopts either lateral/vertical navigation guidance (LNAV/VNAV) or the more precise localizer performance with vertical guidance (LPV) concept. Aircraft equipped with this technology is steadily increasing in the United States.
- Local-area augmentation system (LAAS), which is an airport-based navigation augmentation system.

The introduction of GPS has enabled the FAA to provide instrument procedures at those airports where it could not justify resources before. The trend toward aircraft navigation under IFR not restricted by relatively expensive ground-based navigation aids has the following implications: While pilots are not restricted now to flight restrictions of the traditional ground-based navaids, GPS-based procedures open the entire airport airspace to be used despite the potential obstructions that previous procedures avoided.

Matching technological advancement in obstruction surveys may be slower in implementation than GPS navigation. These technological developments necessitated the conduct of obstruction surveys that are beyond the current capacity of NGS. Therefore, this function is outsourced and third-party providers are brought in to participate. In the FAA airport surveying and Geographic Information System (GIS) program, NGS will continue to perform quality review of obstruction survey data furnished by third-party survey service providers (33). This program introduced a new approach to obstruction surveys that would bring in another new technology—GIS— and a new player to conduct surveys—third-party service providers.

FAA Airport Obstruction Surveys and GIS Integration. Geodetic surveys and airport standards of navigation have been impacted by the advent of satellite navigation. With this new GPS technology comes the need to have a very accurate representation of the airport surfaces and obstructions based on the same coordinate used by the GPS. Unaugmented GPS will provide positions in the World Geodetic System (WGS) 84. However, the official horizontal and vertical datums of the United States are the NAD 83 and the NAVD 88. These datums are defined and maintained by the NGS as part of the NSRS. There are known relations between the two geodetic systems, WGS-84 and NAD 83 and NAVD 88, and they could supplement each other in obstruction surveys.

The FAA, in conjunction with the NGS, is engaged in a major effort to bring airports into compliance with the use of NAD 83 for latitude and longitude and NAVD 88 for orthometric heights. The NGS is working with the FAA and third-party private survey companies to provide position, height, and orientation information for airport runways, navigational aids, and obstruction requirements for GPS-based instrument approach development. The NGS has also developed standards and general specifications for conducting these surveys. The ANA survey data are critical for assisting FAA procedure specialists in the design of GPS-based instrument approach procedures for use in the NAS. These procedures include accurate determinations of the instrument approach, weather minimums, and obstacle clearance information for specific runways.

In view of the GPS-based LAAS and WAAS approach and departure procedure implementation and the current FAA program for airport surveying–GIS integration and to standardize the conduct of aeronautical surveys, the FAA has recently released new aeronautical survey standards and data management specifications. For that, the FAA has issued revised guidance and specifications for aeronautical surveys, contained in the following FAA advisory circulars:

- "General Guidance and Specifications for Aeronautical Surveys: Establishments of Geodetic Control and Submission to the National Geodetic Survey," FAA AC 150/5300-16A, September 15, 2007
- "General Guidance and Specifications for Aeronautical Surveys: Airport Imagery Acquisition and Submission to National Geodetic Survey," FAA AC 150/5300-17A, September 15, 2007

- "General Guidance and Specifications for Submission of Aeronautical Surveys to NGS: Field Data Collection and Geographic Information System (GIS) Standards," FAA AC 150/5300-18B, November 15, 2007

Types of surveys include runway data survey, navigational aid survey, and obstruction survey. The FAA is actively working to streamline the multiple existing survey applications into a single integrated system for the delivery of airport and aeronautical survey data to the FAA through the existing Web applications of airport GIS and the third-party survey system (TPSS). This integration is scheduled to introduce a single Internet portal for the submission of airport and related aeronautical data.

However, data requirements for FAA obstruction surveys could be substantial. To keep track of airspace obstructions, both existing and potential, around airports through surveys would undoubtedly require extensive and continuous airport obstruction surveys. FAA FAR Part 77 planning criteria define specific requirements for runway protection zones as well as requirements for determining obstructions in navigable space.

Runway protection zones include trapezoidal clear ground areas starting from the end of the runway primary surface to the point where the approach surface is 50 ft above the primary surface. This clear area is intended to minimize damage severity in the case of engine failure or runway overshoot/undershoot events. It was discussed earlier (shown in Figure 9.11) that there are three clearance standards for obstacle clearance:

- Operational standard based on aircraft departure/takeoff flight path
- Planning standard of minimum altitudes for a normal all-engine takeoff the aircraft to achieve at different segments of the takeoff flight path to clear obstructions established by Part 77 obstruction imaginary surfaces (OISs).
- Safety standard related to the net takeoff flight path with one inoperative engine (OEI)

Aircraft are required to clear the obstacle by a minimum distance of 35 ft. No obstructions should exist beyond the runway protection zone protruding from the horizontal surface, which is an imaginary horizontal plane 150 ft above the established airport elevation. Primary, horizontal, and approach surfaces are included in the imaginary obstruction identification surfaces.

The dimensions of the OIS depend on the specific airport category, each end of a runway, and the approach procedure (visual, nonprecision instrument, precision instrument, GPS-based instrument). To achieve safe operation in the airport, navigable airport obstruction surveys are required by the FAA at all airports using the related FAA standards with respect to various different aircraft approach and departure procedures. Obstruction surveys are also required if an additional runway or a major airport reconfiguration is expected due to projected passenger demand and increased aircraft operations.

Airport Obstruction Mapping Surveys

Traditional Methods of Aeronautical and Obstruction Surveys. For over the past 50 years, more than 6500 aeronautical surveys have been conducted by the NGS using a combination of traditional field surveying and aerial photogrammetry methods. Today, survey contractors and third-party service providers conduct these surveys using the

FAA standards (34). Ground-based field surveys using kinematic GPS or total station survey instruments are always required to establish geodetic controls and horizontal and vertical coordinates of selected points on the runway and other navaid equipment locations.

Conventional field topographic surveys are conducted on the ground by one or more survey crews using total station equipment. Actual productivity of a survey crew is affected by the airport location and time available when there is no aircraft operating on the runway. The conventional ground survey work is significantly affected by the following operating constraints:

(a) Good visibility (requiring daytime operation using a total station)
(b) Rain and other bad-weather conditions
(c) Productivity loss in wooded areas due to manual clearing of shrubs and branches and other difficult terrain problems
(d) Large physical obstacles (line-of-sight problems),
(e) Obstacles related to inaccessible areas
(f) Airside and ground-side traffic interference
(g) Physical interruptions by property owners where tall trees may present potential obstructions under the Part77 imaginary surface due to the intrusive nature of field survey operation
(h) Delays due to land disputes

Conventional or GPS-based field methods are also used to measure the position and heights of a limited number of potential "obstructions." The GPS coordinate data are collected on selected aerial control points for the purpose of aerotriagulation used for georeferencing and orthorectification in the photogrammetry process. Field GPS survey mission planning includes determining the optimum time of data collection when a minimum of four satellites are in view. Accurate geolocating of tall obstructions within the areas of FAR Part 77 imaginary surfaces airport features is accomplished historically through conventional ground surveying and aerial stereophotography and photogrammetry.

Routinely, commercial aerial photography (passive sensor) has been used to produce orthorectified photos and digital elevation models for most airport, highway, land use planning, and engineering studies. The georeferenced stereoscopic aerial photography (passive remote sensor imagery) has been well documented over the past several decades. Field surveys are still critical in identifying and positioning man-made and natural objects not readily visible in photography, such as transmission lines, tall and thin towers (cell, radio, and TV), antennas, and trees without canopies. Federal standards for airport aeronautical and obstruction surveys (stated above) provide detailed instructions for GPS surveying of aerial control panels and photo identification points, field flight mission altitudes, overlapping requirements, and other mission parameters in order to convert analog aerial stereo photographs by scanning onto raster images. The images are resampled to fit accurately onto a ground coordinate grid with high pixel resolution—usually 1 m. They may be used for geospatial analysis in combination with other types of cartographic data.

The new FAA standards state that ground survey control, aerial photogrammetry, and other remote sensing methods could be used to provide imagery and elevation data for obstruction mapping, airport layout plans, and other engineering applications, including creation of a GIS database. This provides immense opportunities for using new airborne and satellite technologies to accomplish all FAA survey data requirements by conducting one survey at any time of the day or season subject to permissible avionics rules.

Advantages and Limitations of Obstruction Survey Methods. With the complexity described above, there are many trade-offs, advantages, and key limitations associated with each method. Those related to survey technologies for collecting elevation data, location potential obstructions penetrating imaginary surfaces, measuring obstruction heights, and using data for airport layout plans and GIS applications include:

1. *Ground-Based GPS and Conventional Total Station Surveys.* These have the following advantages:

- Ground-based conventional surveys are essential for verifying the ground truth
- Practical for accessing remote and obscure areas and construction grade control
- Most cost-effective for measuring positions and heights of a limited number of known obstructions in the study area

However:

- They may not be efficient for obstruction surveys of large areas with unknown number of potential obstructions or large wooded sites.
- It is too expensive to create detailed survey maps due to time-consuming labor-intensive operation.
- Sometimes access to the property is problematic.
- Several operating field constraints exist, particularly with time of day and adverse weather conditions.

2. *Photogrammetry* (*Aerial Stereophotography/Data Processing*). The primary advantage of this method is that it is the proven remote sensing technology for obstruction mapping and topographic survey applications.
Its main disadvantages include:

- Field operating constraints associated with aerial photography (no nighttime mission and poor visibility/cloudy in daytime)
- Special survey techniques (leaf-on) required for obstruction surveys which are not suitable for the required accuracy of bare-earth terrain but needed for more accurate ground elevations
- Requires time-consuming and labor-intensive photogrammetry .
- Requirement to "seed" the feature extraction algorithms with elevation data of the obstruction feature for three-dimensional stereogrammetric analysis, a significant limitation

New Technology for Airport Obstruction Mapping

Remote Sensing Approach—LIDAR. The implementation and flight mission parameters are discussed with regards to airborne light detection and ranging (LIDAR) obstruction surveys. This technology generates digital data for mapping obstructions, including treetops, building tops, telecommunication towers, poles, construction cranes, and other tall structures and terrain. Nonintrusive daytime and nighttime operations make LIDAR surveys potentially more efficient and cost-effective than the traditional aerial photogrammetry and ground-based survey methods. Within cost and accuracy constraints, translating research results to acceptable operation procedures is expected to be the decisive factor in implementing the new LIDAR technology for airport obstruction mapping and other surveying needs.

Background on LIDAR. Using lasers to gather data from ground-based, airborne, and now space-borne remote sensing devices has given way to an effective new perspective on conducting accurate global measurements. These laser-based devices were used by NASA to study the atmosphere with high precision, as they can penetrate thin or broken clouds in the lower atmosphere or the earth's surface to measure the vertical structure of the atmosphere. A space-based LIDAR can provide global measurements of the vertical dimension of the earth's surface. A significant value of lasers as remote sensing tools is the unprecedented accuracy with which they can take measurements from a distance vertically.

How Does LIDAR Work? Similar to radar, which is commonly used to track everything from airplanes in flight to thunderstorms through bouncing radio waves off moving objects, LIDAR uses short pulses of laser light to detect objects. Traveling as a tight, unbroken beam, the laser light disperses very little as it moves away from its origin, such as from space down to the earth's surface. Some of the laser's light reflects off of the object, and the laser is reflected back to a device where it is collected, measured, and stored in a database. By precisely timing the collected light and measuring how much reflected light is received by the device, the location, distribution, shape, size, and nature of the object is accurately measured. LIDAR systems carry their own source of laser light and hence can make measurements both in the daytime and at night, and the result is a revolutionary new tool to measure the z dimension of objects in the earth's atmosphere and on its surface.

Airborne LIDAR Survey Technology. Utilizing airborne LIDAR systems could provide a particularly accurate and cost- and time-effective practical technology to conduct wide-area surveys of heights of man-made and natural objects in entire regions, particularly around airports. The airborne LIDAR system is composed of a laser subsystem consisting of the source, scanning assembly and timing electronics, a positioning and orientation subsystem consisting of the differential GPS and inertial measuring units, a data storage unit, and processing software. Data acquired by the system, from both the laser subsystem and the positioning subsystem, are written to large, high-throughput, removable hard drives and tagged with the GPS clock. The core of the system is the inertial measurement unit (IMU) and the positioning (POS) computer system with an embedded GPS card and data logger. The IMU measures the translation and rotational dynamics of the sensor.

LIDAR Data. The laser data stream also contains the GPS time word for subsequent time matching and processing. The embedded GPS receiver can be operated either stand alone or with differential pseudorange corrections applied in real time or post-processing. Real-time operation requires data transmission from a base station. The dual-frequency unit is initialized with a similar ground station that is used to compute precise positions of the sensor on board the aircraft. Certain software processes are used to assist quality control of the positioning solution. Final position and orientation parameters of the surveyed objects (X, Y, Z, w, f, k) and time (t) are provided for subsequent merging with the laser ranging information.

Performance Specifics. The system develops a sinusoidal scan pattern on the ground with a variable field of view from 1° to 75°. The system operates at altitudes from 2000 to 20,000 ft giving a swath width of 350–30,000 ft. The achievable point density may vary between 1.5 to 12 m with a horizontal range of 15 cm–1 m and a vertical accuracy of 15–60 cm.

Data Processing and Quality Control Specifics. Once the GPS positions are determined, the scanner position and sensor orientation are used to compute the position of the laser spot on the ground. Appropriate transformations are later employed to derive the final data product in the user-specified horizontal and vertical datum groups. Obstruction and vegetation objects are dealt with during the postprocessing phase, if required, and the data are closely examined for anomalies. The resulting LIDAR image, a digital evaluation model (DEM), is generated although the data will not be at regular grid spacings on the ground. The final DEM is then formatted to any user-defined GIS or may be delivered as ASCII point data (x, y, z). Commercially available LIDAR software to generate ArcGIS database eliminates the challenges faced by today's LIDAR users in a cost-effective, easy-to-use manner.

In summary, the LIDAR-GIS method and associated software are accurate, quick, and cost effective and can successfully define intermediate surfaces such as treetops (canopy) and power lines and differentiate them from other objects. Moreover, while stereo compilers can selectively collect a limited number of points per hour from photography, LIDAR allows the real-time accumulation of tens of thousands of points per second, and the data would be immediately available for DEM generation or topographic mapping.

Implementation of Airborne LIDAR Surveys. The LIDAR airborne technology was tested by the NOAA and used by NASA to research and document topographic changes and global phenomena. These data are collected with aircraft-mounted lasers capable of recording elevation measurements at a rate of 2000–5000 pulses per second and have a vertical precision of 15 cm (6 in.). After a baseline data set has been created, follow-up flights can be used to detect localized and specific changes. TRB, under the ACRP 3-01 program, developed a LIDAR deployment procedure for airport obstruction surveys that defines survey specifications and requirements for comprehensive LIDAR data acquisition and processing (35).

Collection of Data with Airborne LIDAR. LIDAR sensors are mounted onboard a DeHavilland Twin Otter aircraft, shown in Figure 9.16(a). Once in flight, the aircraft travels over the locality studied at approximately 60 m/sec. The aircraft conducts a flight pattern as shown with overlapping swath parallel to the survey axis. During the flight, the LIDAR sensor pulses a narrow, high-frequency laser beam toward the earth through a port opening in the bottom of the aircraft's fuselage. The

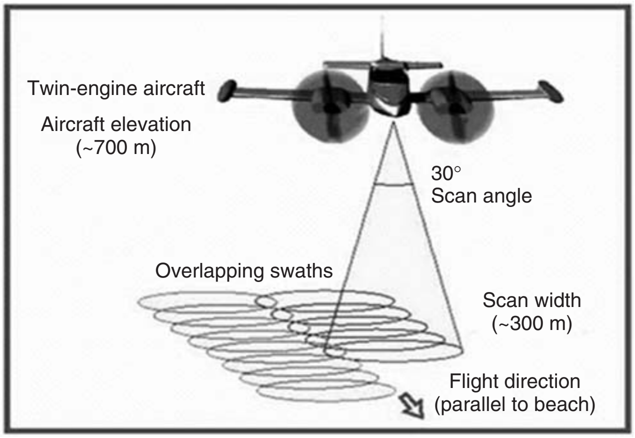
(a)

Figure 9.16(a) LIDAR-mounted aircraft. (*Source*: NOAA.)

LIDAR sensor records the time difference between the emission of the laser beam and the return of the reflected laser signal to the aircraft.

The LIDAR transceiver is rigidly fastened to the aircraft and does not move, and a scan mirror assembly is mounted beneath the transceiver. A 45°folding mirror reflects the laser pulses onto a moving mirror which directs the laser pulses to the earth. The reflected laser light from the ground follows the reverse optical path and is directed into a small capturing device (telescope). The moving mirror produces a conical sampling pattern beneath the aircraft over a 30°wide swath, thus permitting the collection of topographic information over a strip approximately 300 m (about 1000 ft) in width from the nominal 600 m (2000 ft) data collection altitude.

As shown in Figure 9.16(b), the LIDAR instruments only collect elevation data. To make these data spatially relevant, the positions of the data points must be known. A high-precision GPS antenna is mounted on the upper aircraft fuselage. As the LIDAR sensor collects data points, the location of the data are simultaneously recorded by the GPS sensor. Data are then downloaded and processed on the ground using specially designed computer software. The end product is an accurate, geographically registered



(b)

Figure 9.16(b) LIDAR scanning pattern. (*Source*: NOAA.)

longitude, latitude, and elevation (x, y, z) position for every data point. These x, y, z data points allow the generation of an exact digital demo (DEM) of the ground surface.

Certain guidelines for operating airborne LIDAR data collection have to be recognized and observed. Typically, flights duration is about 4 hr. Weather conditions must be monitored—LIDAR data cannot be captured during rain or fog as the water vapor in the air could cause the laser beams to scatter and give false readings. Moreover, it is not advisable that aircraft operate during high winds and turbulent weather, as the returned laser pulse will not be correctly captured and recorded by the receiving device.

Issues with Obstruction Measurements Using Airborne LIDAR. Low-altitude flight and an appropriately planned LIDAR mission can provide digital data for a computerized processing of obstruction measurements and a plot of dense elevation points for a runway and all other scanned airport areas. This generates bare-earth digital elevation models and contours by triangular irregular network (TIN) linear interpolation procedures. These can be imported into the GIS system as thematic color maps of elevation and contours, used to create planimetric features, overlaid on the imagery for obstruction locations and airport layout plan, and used for other engineering applications (36). Airborne LIDAR surveys could achieve the primary goal of the new FAA initiative on airport surveying–GIS integration through the georeferenced digital photo raster image draped over a DSM model and obstruction points overlying the three-dimensional vector model of imaginary surfaces. However, research has shown that there are issues related to the accurate extraction of narrow tall vertical obstruction features (tree tops or man-made towers) by automated LIDAR data processing of the traditional discrete return LIDAR systems (Figure 9.17).

Moreover, the same research has indicated that a small footprint on the top of a vertical tower structure may also be missed depending on the LIDAR point cloud

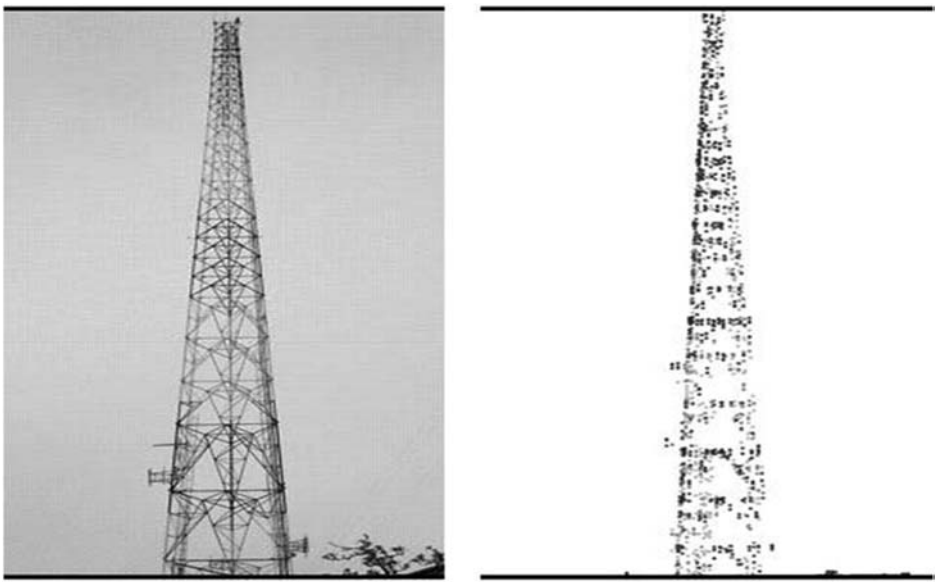


Figure 9.17 Image of Narrow Tall Communication Tower (left) and final reconstructed LIDAR point cloud representation of the extracted feature (right) (37).

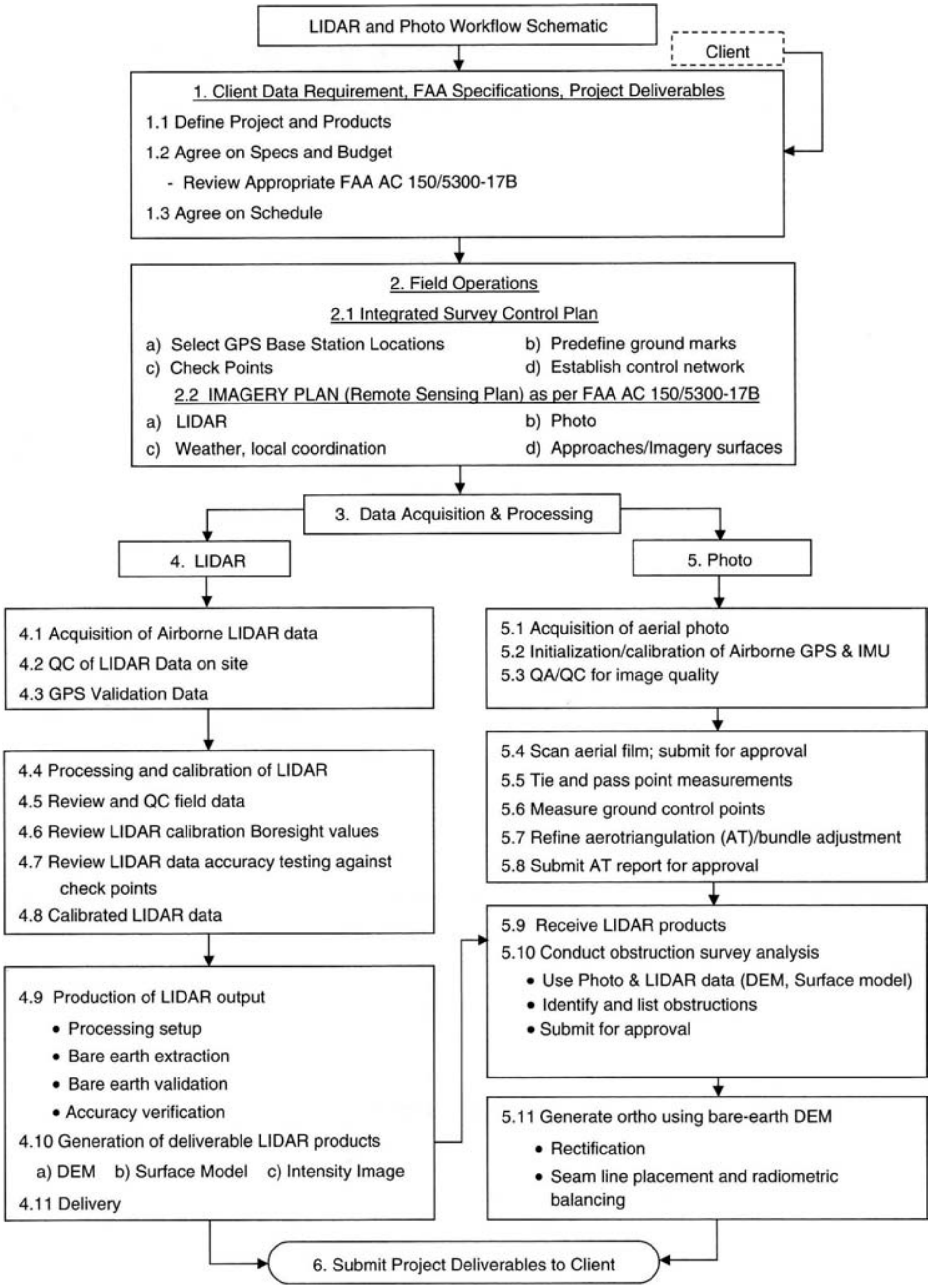


Figure 9.18 Implementation workflow for LIDAR deployment for airport obstruction surveys (35).

spacing of the first returns. Another significant limitation occurs in scanning areas with tall objects that may result in “blank areas” or missing data behind tall objects (36).

The ACRP 3-01 implementation procedure covers data properties, acquisition, processing, accuracy, format and standards, and data flow; specifies equipment and material used including LIDAR system and aircraft employed; horizontal and vertical point spacing specified; radiometric and spot spacing qualifications tests required; and LIDAR system calibration required (factory, bore-sight, and field test/validation); in addition to mission planning for flying height, clearances, imagery, and flight conditions. The procedure would also include data positioning and orientation, marking of ground-GPS and aircraft receivers, and airborne positioning and orientation. Figure 9.18 depicts the entire work flow of this implementation procedure (35).

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10

Passenger Terminal

10.1 FUNCTION OF AIRPORT PASSENGER TERMINAL

The airport passenger terminal constitutes one of the principal elements of infrastructure cost at the airport. Many terminals have been built as architectural monuments to the progress of regional or national aviation. Consequently, air travelers have become accustomed to lavish visual displays of design that have little to do with the functions the terminal is intended to perform. As this chapter points out, the functional design of the terminal can be made subservient to architectural design considerations only at the expense of the proper functioning of the component parts of the design. The passenger terminal performs three main functions:

1. *Change of Mode.* Few air trips are made direct from origin to destination. By their nature, "air" trips are mixed-mode trips, with surface access trips linked at either end to the line haul air trips. In changing from one mode to the other, the passenger physically moves through the airport terminal according to a prescribed pattern of movement. These movement patterns are accommodated by *passenger circulation areas.*
2. *Processing.* The terminal is a convenient point to carry out certain processes associated with the air trip. These may include ticketing and checking in the passengers, separating them from and reuniting them with their baggage, and carrying out security checks and governmental controls. This function of the terminal requires *passenger processing space.*
3. *Change of Movement Type.* Although aircraft move passengers in discrete groups in what is termed "batch movements," the same passengers access the airport on an almost continuous basis, arriving and departing in small groups mainly by bus, auto, taxi, and limousine. The terminal therefore functions on the departure side as a reservoir that collects passengers continuously and processes them in batches. On the arrivals side, the pattern is reversed. To perform this function, the terminal must provide *passenger holding space.*

Thus, the primary function of the terminal is to provide circulation, processing, and holding space. To operate smoothly and to ensure the premium level of service that traditionally has been associated with air travel, numerous facilities are necessary in a number of primary and support areas, which are more fully detailed in Section 10.3.

10.2 TERMINAL USER

The successfully designed air terminal facility must perform satisfactorily to meet the needs of those who can be expected to use it. It has three principal user classes: the passengers and those who accompany them, the airline, and the airport operator.

Most current terminal designs emphasize passenger needs. The volume of passengers is large in comparison with the number of airline and airport staff, and, as the prime reason for having the facility, the passengers are seen as a major source of airport income during the time that they spend in the terminal. Thus, the maximum accommodation of passenger needs is the chief objective of terminal design.

Airlines are another prime source of airport revenue, and they constitute one of the principal agents of airport operations as well. Satisfactory terminal design must provide a high level of service to the airline. In some airports, airlines are also a source of initial investment capital. In such cases, they can be expected to have a substantial role in terminal design decision making.

Design for the needs of the airport operator requires a balance: Facilities for the staff and operational areas must be adequate, but the overhead of unnecessarily luxurious installations should be avoided. Passenger terminals at larger airports are the work place of a large number of individuals, and terminal design should ensure that this environment is acceptable for its workers, even under peak-flow conditions. Within the category of airport operator should be included all concessionaires who may be regarded as carrying out part of the operator's function on a commercially delegated basis.

10.3 FACILITIES REQUIRED AT PASSENGER TERMINAL

The airport terminal acts as the transfer point between the landside and airside portions of the mixed-mode "air trip" made by the air passenger. The level at which the terminal functions is crucial in the passenger's evaluation of the level of service (LOS) provided by air travel, and it is in the interest of both the airport operator and the airline to have the terminal designed to permit a high LOS for passengers and visitors, the airlines, and the airport operator (1). The facilities can be categorized as follows: access (including the landside interface), passenger processing areas, passenger holding areas, internal circulation and airside interface, and airline and support areas.

Access and Landside Interface

Within the passenger terminal area, access facilities should ease the transfer of passenger flows from the available access modes to, from, and through the terminal itself, and vice versa. These facilities include curbside loading and unloading, curbside baggage check-in where this is permitted, shuttle services to parking lots and other terminals, and loading and unloading areas for cars, buses, taxis, limousines, and rapid surface modes (2).

Processing

Areas are designated for the formalities associated with processing passengers. The usual facilities include airline ticketing and passenger check-in, baggage check-in and seat selection, gate check-in where desirable, incoming and outgoing customs, immigration control, health control, security check areas, and baggage claim.

Since 2007, very significant advances have been made with respect to passenger ticketing and check-in. By 2010 more than 95% of all passengers were in possession of the equivalent of e-tickets purchased on-line. A very large and increasing proportion of passengers already have boarding cards and seat assignments and at many larger airports automatic bag labeling and bag drop facilities are available for passengers with hold luggage.

Holding Areas

A very large portion of the passenger's time at the airport is spent outside the individual processing areas (see Section 10.8). Of nonprocessing time, the largest portion is spent in holding areas where passengers wait, in some cases with airport visitors, between periods occupied by passing through the various processing facilities. It is in these holding areas that significant portions of airport revenue are generated. Consideration of revenue generation (Section 10.9) and concern for the LOS supplied by these necessary facilities warrant careful design of holding areas. The following are among the facilities that may be required:

(a) *Passenger Lounges.* General, departure, and gate lounges. At international facilities, transit passenger lounges may be necessary.

(b) *Passenger Service Areas.* Wash rooms, public telephone and Internet access, nurseries, post office, information, first aid, shoeshine, valet service, storage, barber shop, beauty parlor.

(c) *Concessions.* Bar, restaurants, newsstands, novelties, tax and duty-free shops, hotel reservations, banks and currency exchange, insurance, car rental, amusement areas, automatic dispensing machines.

(d) *Observation Decks and Visitors' Lobbies.* Including very important and commercially important (VIP and CIP) facilities.

Internal Circulation and Airside Interface

Passengers move physically through the terminal system using the internal circulation system, which should be simple to find and follow and also easy to negotiate. The airside interface is designed for secure and easy boarding of the aircraft.

Internal circulation is handled by corridors, walkways, people movers, moving belts, ramps, and tramways.

Airside interface requirements include loading facilities such as jetways, stairs, air bridges, and mobile lounges.

Airline and Support Activities

Although airline terminals are designed primarily for airline passengers, most of whom will be quite unfamiliar with their surroundings, the design must also cater to the needs of airline, airport, and support personnel working in the terminal area. Frequently, the following facilities must be provided (3–5):

1. Airline offices, passenger and baggage processing stations, telecommunications, flight planning documentation, crew rest facilities, airline station administration, staff and crew toilets, rest and refreshment areas
2. Storage for wheelchairs, pushcarts, and so forth
3. Airport management offices, offices for security staff, and offices for other terminal service functions

4. Governmental office and support areas for staff working in customs, immigration, police, health, and air traffic control; bonded storage and personal detention facilities
5. Public address systems, signs, indicators, flight information
6. Offices and support areas for maintenance staff, maintenance equipment, storage

10.4 PASSENGER AND BAGGAGE FLOW

An adequately designed airport terminal is the work of a designer who understands the various flows of passengers and baggage at a terminal. Figure 10.1 is a typical flow diagram for passengers and baggage at an airport catering to mixed international and domestic flights. Where domestic flights only are anticipated, the routing is significantly less complex, since customs, immigration, and health controls can be omitted and transfer passengers can move between flights without baggage, untroubled by governmental controls.

The usual enplaning pattern is to pass through the general concourse into the airline's check-in area. From there, less encumbered by baggage, the passengers move into the general departure lounge and finally into the gate lounge. On international flights, entry into the departure area may be preceded by customs control. (In many countries, airports must provide customs inspection space for outbound passengers, although such areas may be used quite infrequently.) Passengers then pass to the departure gate, which may consist of a small gate lounge for final holding purposes. If personal security control is not centralized, passengers may undergo a gate security check before entering the aircraft. International passengers may also have to pass some form of departing passport control. The layout shown also permits gate check-in at the gate lounge; this, of course, is not found at many airports. Gate check-in necessitates decentralized security checks, since these must be performed at the gates themselves. Since the Lockerbie bombing and the September 2001 hijackings, most jurisdictions require all boarding passengers and crew and all baggage to have passed security controls; this includes transit traffic.

Deplaning domestic passengers proceed directly to the baggage claim and pass immediately into the general arrivals concourse; international arrivals must first pass through health and immigration controls and proceed through customs inspection before entering the general concourse. In many non-U.S. airports, those who have goods to declare and those who have nothing to declare pass along red and green channels, respectively. This form of processing significantly speeds flow through the customs area, with no apparent increase in serious smuggling offences.

Outside the United States, international deplaning passengers en route to yet a third country (transit passengers) normally pass into a holding transit lounge without officially entering the country of transit. This is not permitted in the United States. Transit passengers are not subject to health, immigration, and customs formalities, and their baggage is transferred directly to their outgoing flight without passing through baggage claim and customs. Deplaning international passengers transferring to domestic flights must pass through all governmental controls and then recheck their baggage for the domestic leg of the flight. This is handled with differing levels of efficiency at different airports. In some airports, passengers must traverse significant distances

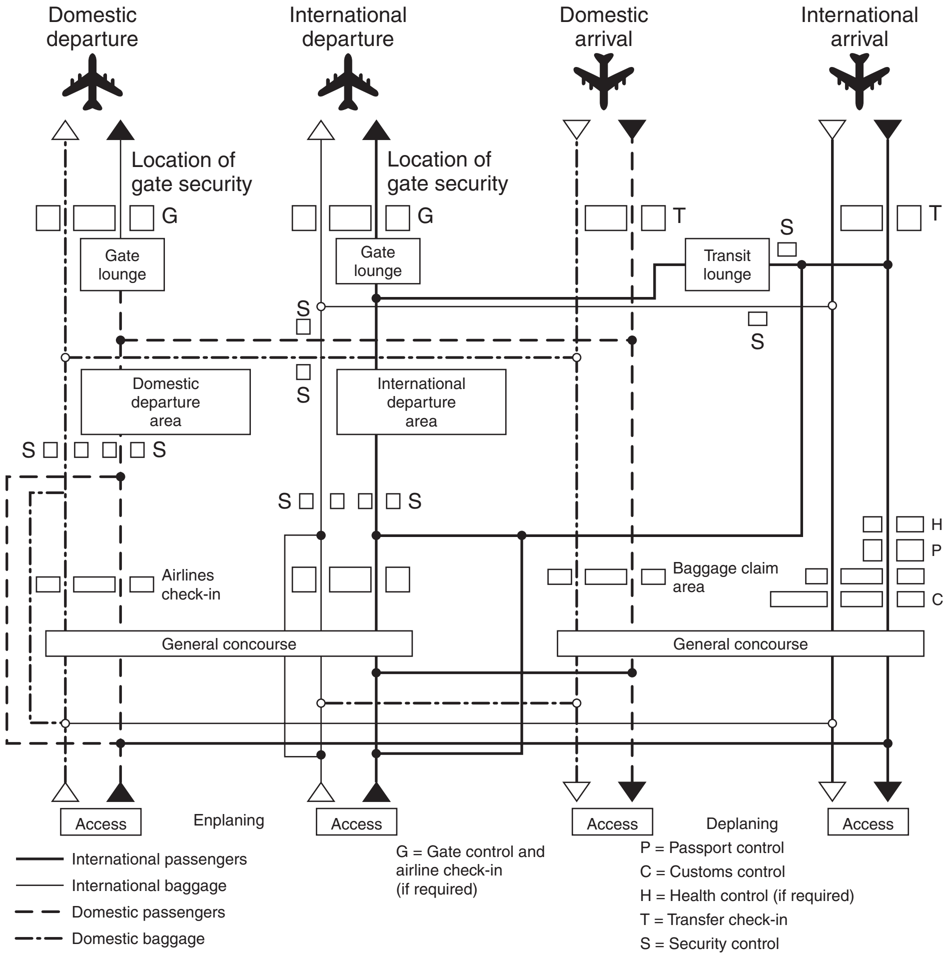

Figure 10.1 Passenger/baggage flow system. (*Source:* Adapted from ref. 4.)

between connections. Since departing customs controls are usually far less stringent, the domestic/international passenger usually does not face the same problem. Figure 10.1 shows a flow system where security is centralized. Gate security control may be used at international terminals with high levels of transfers, such as Schiphol Amsterdam.

10.5 SECURITY CONSIDERATIONS IN PASSENGER TERMINAL DESIGN AND LAYOUT

Since the early 1960s, threats to civil aviation from acts of terrorism in civil aircraft and airports have become commonplace. Originally these problems were almost exclusively associated with aerial hijackings, but the threat to civil aviation now encompasses terrorist bombing of aircraft and airports and terrorist attacks on passengers while in the airport terminal itself. Countermeasures against terrorism and other illegal acts against civil aviation are now virtually universal. Theoretically, all passengers on both international and domestic flights have been through security checks for weapons detection, and the aircraft and its load have been subject to security procedures that ensure that it has been kept safe from interference (2, 4, 5). Different countries have adopted different degrees of security which can even differ depending on the type of airport (e.g., local domestic or international). In the United States, FAA regulations and since 2001 the requirements of Homeland Security define aviation security procedures. In most countries, this is carried out to the requirements of a central government law enforcement agency, although the state, provincial, and local police authorities may also be involved. In the European Union (EU), both national and EU regulations must be observed. Most of the aspects of airport security are operational, but the form of security operation required has significantly affected design such that security considerations have become a fundamental element of the design and layout of airport passenger terminals. It is good practice to realize that satisfactory terminal design can be achieved only if the procedures required for aviation security are understood and integrated into any terminal design exercise.

The following considerations may have to be taken into account; if they are necessary, they will have varying effects on the design of the terminal. Some are minor, but some will have major implications on the provision and location of the passenger terminal space:

1. Physical separation of arriving and departing passengers on the airside. This may involve passenger movement on different levels of the terminal and will certainly involve additional circulation space for corridors, walkways, and so on.
2. Security combs for passenger and hand baggage search may be either centralized or decentralized at the gates. Centralized security will require one large area with space for search equipment. Decentralized gate search will require more overall terminal space and equipment, given that it is decentralized at the individual gate lounges.
3. Prohibition of visitors into the secure airside areas of the terminal. In most jurisdictions, even for domestic traffic, only passengers are permitted through the security combs. Security procedures which prohibit visitors from general circulation throughout the domestic terminal cause large numbers of visitors at the entry and exit points of the airside, necessitating the provision of extra terminal space in those areas.
4. Isolation of piers by physical barriers, for example, fast-acting drop grilles, at times of terrorist activity.
5. X-raying or bomb detecting of all hold baggage requires additional space, either at check-in or in the outbound baggage hall, depending on when this activity is carried out. For terminals designed before 1990, the introduction of inspection of all hold baggage imposed severe strain upon existing outbound baggage halls.
6. Provision of extra space in the check-in area for very high security flights to allow passenger interviewing and search.
7. Division of the terminal into a "clean airside—dirty landside" arrangement. This is a by-product of the decision to centralize or decentralize security combs. The provision of a clean airside may significantly reduce the market potential of commercial concessions on the airside. Even at terminals that operate gate

search, visitors are no longer allowed outside of the gate lounges, which was common practice in the United States prior to the 9/11 incidents.

8. Removing car parking from the terminal building. Integral car parks either above or below the terminal are attractive targets for car bombers. In times of high terrorist activity, these facilities may be rendered unusable.
9. Prohibition of left-luggage areas for unsearched baggage will require the provision of a manned left-luggage depository with X-ray facilities.
10. Observation decks overlooking aprons and other operating areas must be secure.
11. Avoidance of open mezzanine balconies in unsecure areas of the terminal will discourage terrorist attacks on passengers.
12. Construction of buildings to minimize injury from blast damage. Consideration should be given to avoiding the use of extensive areas of glass. In the past, this has caused considerable injuries to passengers in terminals attacked by bombs or hand grenades.
13. People movers to satellites may have to ensure that enplaning and deplaning passengers cannot mix.
14. For very sensitive flights, check-in areas where passengers gather in identifiable groups will have to be inside a secure area.
15. Gate arrival terminal systems which are based on a simple “bus-stop” type of operation may be infeasible.

Many existing terminals were designed prior to the need to provide aviation security, especially at the levels required since 2001. Consequently ad hoc alteration procedures have had to be adopted where existing terminals cannot be physically modified to achieve the desired form of security operation. There are many airports, however, where the security conditions which are, of necessity, accepted in existing terminals but would not be tolerated in new construction. The designer must therefore be careful not to assume that current procedures can be extrapolated into future designs.

10.6 TERMINAL DESIGN CONCEPTS

The design of a terminal depends on the nature of the air traffic to be handled at an airport (4, 5). The design concept chosen is a function of a number of factors, including the size and nature of traffic demand, the number of participating airlines, the traffic split between international, domestic, scheduled, and charter flights, the available physical site, the principal access modes, and the type of financing.

The most fundamental choice is that of centralized or decentralized processing. With centralized concepts, all the elements in the passenger processing sequence are conducted as far as is feasible in one localized area. Processes normally included are ticketing, check-in, customs and immigration, baggage checking and claim, and possibly security. All concessions and ancillary facilities are also grouped in the central terminal area. Decentralization involves a spreading of these functions over a number of centers in the terminal complex; the decentralized concept embraces the range of possibilities, from using independent terminals for various airlines (the unit terminal concept) to providing simple facilities at the aircraft for the lightly loaded traveler to perform a complete check-in (the gate check-in concept). In practice, many design solutions fall between the extremes of completely centralized and decentralized operations. Examples of the airport types discussed below appear in Figure 10.2.

Open-Apron or Linear Concept

The most centralized of all arrangements is the simple open-apron or linear arrangement, which can be operated with a single terminal, with passenger access to the aircraft directly across the apron, or by direct connection to the main terminal building. Operation can be with or without specific gate assignment to particular airlines on a permanent basis. Since this type of arrangement gives a small length of airside interface in relation to the size of the terminal, it is frequently used for low-volume airports where the number of gates required would not necessitate an inconveniently long terminal. An extension of the open-apron concept is the decentralized *gate arrival* concept, as exemplified by the Kansas City airport, where the terminal is arranged in such a manner that the traveler can park at a point opposite his or her departure gate, thereby minimizing walking distances. Terminal 1 of Munich Airport is designed along these lines, using alternating arrival and departure modules rather than individual gates. Gate arrival terminals are not suitable for airports which must accommodate hubbing traffic or large flows of international transfer traffic. The longitudinal passenger flows along the axis of the terminal conflict with the concept of short transverse flows in the typically narrow gate arrival terminal.

Central Terminal with Pier Fingers

Centralized terminal operation can be achieved with a large gate requirement by effectively increasing the airside periphery of the terminal with the construction of pier fingers. In this way, centralized processing can be achieved, even with a very large number of gates. The piers can also be designed to have limited holding and commercial facilities and possibly even gate check-in. Frequently, gates are assigned to individual airlines on a long-term basis to assist in orderly operation of the necessary apron equipment. This type of design, of which Amsterdam airport is a prime example, can be very economic to build; however, for the largest terminals, passengers may be required to walk long distances between the check-in area and the aircraft gate, and for interlining passengers the situation is often exacerbated with maximum gate separations of 1.5 km.

Pier finger terminals have been found to be very efficient for annual passenger volumes up to approximately 45 million for domestic operations and 35 million for international operations. At higher volumes, the physical size of the terminal is likely to give considerable problems with respect to passenger walking distances and transfer times through the terminal.

Central Terminal with Pier Satellites

The pier satellite terminal represents a move toward decentralization of the pier finger concept. Examples of this design are provided by the terminals at Newark, Milan Malpensa, and Dublin. In the simplest designs, the satellites simply provide decentralized holding areas for passengers adjacent to their gates. Decentralization can be increased by offering gate check-in, limited concessions and servicing facilities for refreshment, and so on. Unsurprisingly, this modification of the pier finger design has

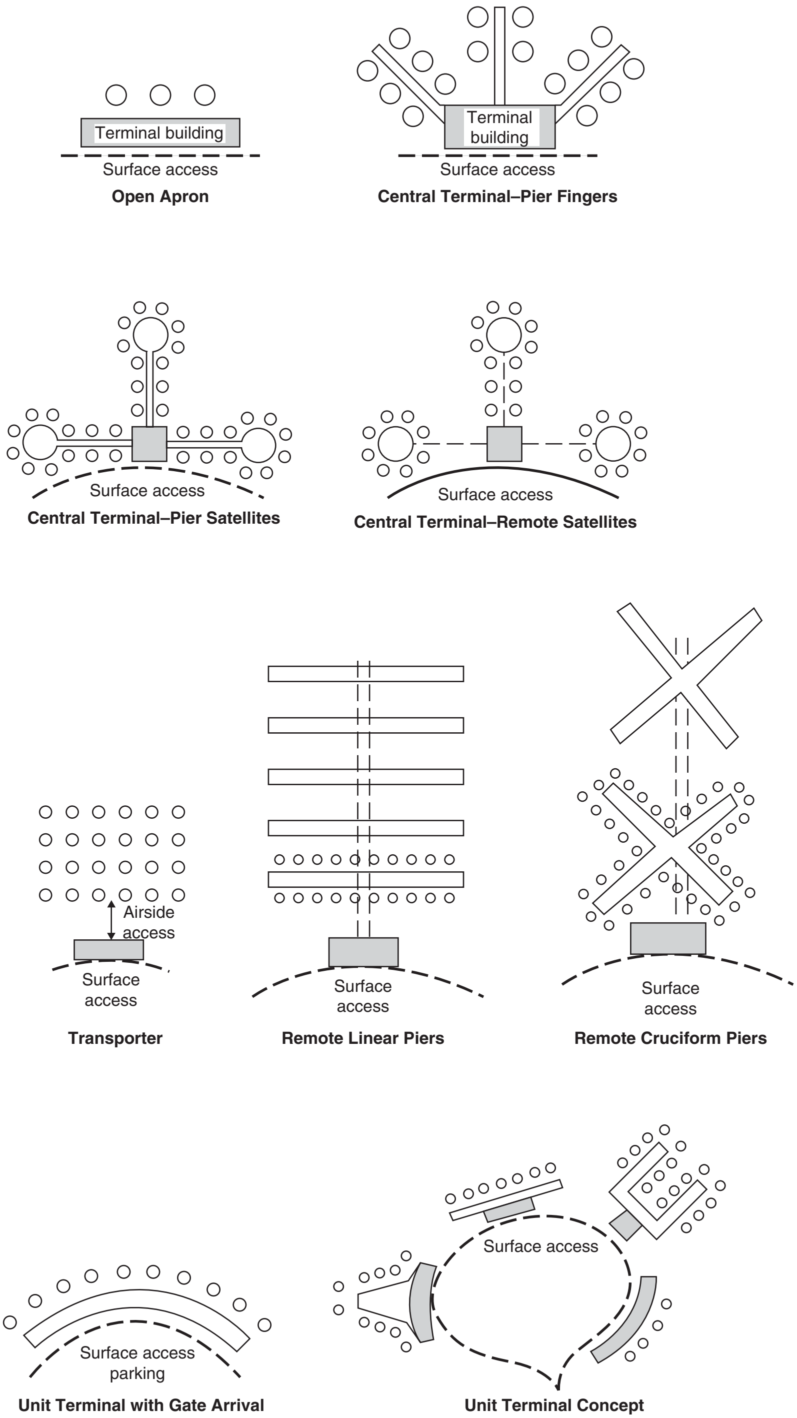

Figure 10.2 Terminal configurations.

similar problems related to walking distances. As the facilities of the satellites become more elaborate, the economies of the design disappear and the system tends to operate more as a series of unit terminals.

Central Terminal with Remote Satellites

Remote satellites of a central terminal are usually connected by some mechanized form of transport, either above (e.g., Automated People Mover (APM) APM vehicles at Tampa, Orlando, London Gatwick) or below the apron (e.g., moving belts at Paris Charles de Gaulle 1). In the latter case, there is no surface interference by the connection to the main terminal, and aircraft gates can be sited all around the satellites. Depending on the degree of centralization desired, the satellites can be designed with more elaborate facilities as more decentralized operation is envisaged. In the Tampa airport example as originally designed, all ticket purchase, baggage check and reclaim facilities, and other main passenger services are provided in the central terminal area; only holding lounges and supplementary check-in facilities for passengers not carrying baggage are located in the satellites.

Remote Apron or Transfer or Transporter

The servicing of remote stands by buses is common, both in the United States and Europe, for example, Kennedy and Milan Linate. The transporter concept is distinguished by the use of mobile lounges or buses, totally centralized processing, and gates that usually are not assigned permanently to any particular airline. Perhaps the most significant examples of the remote-apron type of design were Mirabel Montreal and Dulles Washington, D.C., neither of which still operates as a transporter airport. Mirabel closed in the1990s due to its poor location and expensive, inefficient operation. The open-apron concept of Dulles was also largely abandoned about the same time with its replacement by a conventional midfield satellite terminal that solved the embarkation/disembarkation problems of the mobile lounge–aircraft interface. The principal advantages of the design concept accrue from the separation of the aircraft servicing apron from the terminal, giving greater flexibility on the airside to changes in the size and maneuvering characteristics in aircraft; in addition, less time is required for taxiing on the ground. The principal disadvantages are the poor LOS given by the mobile lounges and buses, which delays passengers in the loading and unloading processes. Equally important are the difficulties associated with maneuvering the mobile lounges and the increased traffic on the aprons caused by bus or mobile lounge operation. Transporter terminals are extremely unpopular with airlines because of long ground turnaround times and poor passenger service.

Central Terminal with Remote Piers

The central terminal linked under the apron to remote piers has been found to be an effective layout for high-volume airports, especially where there is a great amount of domestic transfer and interlining. The large apron area can suitably fit between the twin parallel runways of a high-capacity facility. The subapron corridor connecting the terminals and piers is suited to automated movement of both passengers and baggage. Atlanta Hartsfield Airport, Kuala Lumpur, and Hong Kong are examples of this form of design. The remote piers can be either linear (Atlanta, Oslo, or Heathrow Terminal 5), or cruciform (Kuala Lumpur and Hong Kong).

Unit Terminal

The unit terminal concept is defined by the IATA as two or more separate, self-contained buildings, each housing a single airline or group of airlines, each having direct access to ground transportation. Kennedy International Airport in New York is a good example of the unit terminal layout, as is London Heathrow. Usually justified at high-volume airports, where walking distances become excessive with pier finger operation, this concept can cause severe problems for interlining passengers. Some designs have attempted to provide a high level of interline connection service by surface connection systems [e.g., Dallas-Fort Worth International Airport (landside APM), Paris Charles de Gaulle (airside and landside buses)]. Unit terminal systems can be designed to operate gate check-in facilities, which was the original conceptual design of the Kansas City airport. However, gate check-in facilities were more appropriate to the simpler needs of the 1960s, prior to modern requirements where security considerations have become paramount.

10.7 VERTICAL DISTRIBUTION OF ACTIVITIES

In small airport terminals, the passenger and baggage flows described can be accommodated on a single level. Where passenger flows are relatively small and there are few transfer passengers, the complexity and expense of multilevel terminal facilities is unwarranted. However, with larger traffic flows, the floor area required on one level rapidly becomes too large to serve the passenger flows efficiently. If the expansion requires the addition of a second level, this will require strengthening of foundations, columns, and roofs which, if not preplanned, will be prohibitively difficult, intrusive to operations, and expensive. Figure 10.3 shows the various ways of distributing activities vertically in the terminal.

The most common solution adopted for the separation of flows is the two-level operation. Typical flow arrangements separate enplaning passengers on the upper level from deplaning passengers, who enter the terminal, then descend to the lower level for governmental controls where necessary, and for baggage reclaim. Usually, arriving and departing passengers are separated on the landside access with two levels of bus and car curbside pickup and set down; design solutions in the past have also used single-level access at the landside interface. Two-level operation has the advantage of maximum site utilization and can provide good flow characteristics with a minimum of conflicting flows suitable for high-traffic volumes.

A variation of two-level design is *one-and-a-half-level* operation. This form of design offers the advantages of two-level apron operation, but passengers usually change level after entering the building. This design allows better service than the unilevel layout, but there can be serious conflicts of flow at the landside access interface.

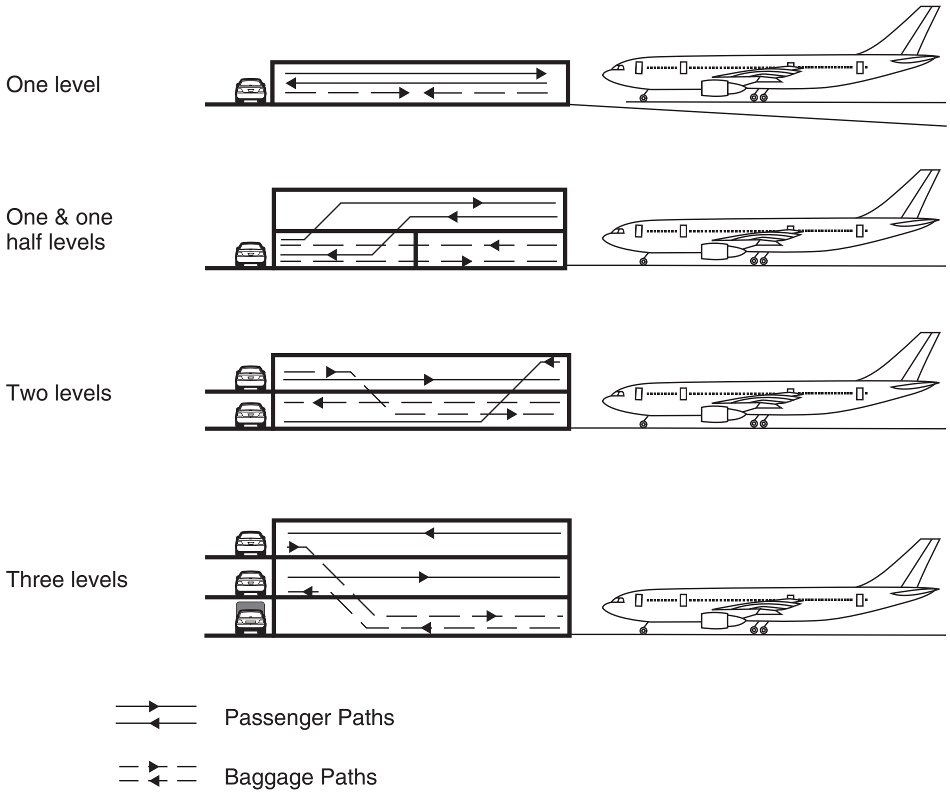

Figure 10.3 Typical vertical separation arrangements of passenger and baggage flows.

The one-and-a-half-level arrangement works well at lower volume airports, because departing passengers require more facilities than arriving passengers. Many domestic designs place arrival facilities and baggage handling on the lower level and departure facilities on the upper level. Where piers are used at multilevel terminals, single-level operation of the piers is the general rule, with the public operational level being above the airport and airline functions at apron level. Some airports such as Amsterdam Schiphol have reconstructed their piers to have operations at apron level and two segregated levels of passenger flows in a three-level pier.

In a number of countries, security regulations require complete separation in deplaning passengers and enplaning passengers who have been security cleared. In such cases, two levels of passenger operations may be provided in the piers or segregation provided by floor-to-ceiling glass screens. Both require considerable duplication of circulation space, resulting in larger and more expensive terminals.

Three-level designs are also possible. The most usual form of separation is departures, arrivals, and baggage flow. This arrangement seems to give the best separation of possibly conflicting flows, but the expense of the third floor of operations may not be warranted, even for relatively high flows. Where three floor levels occur in main terminals or piers, attention must be given to the effect on the air bridges, which can become excessively long due to maximum slope considerations.

10.8 PASSENGER BEHAVIOR IN TERMINAL (2–5)

Time spent in the terminal has long been considered to be an important portion of the overall air journey, even though the terminal's function is of modal transfer rather than part of the mode of carriage. Airports through their terminal design have traditionally sought to convey the same image of being part of the premier mode that was presented by airlines in their efforts to market air travel. Consequently, airport terminals have traditionally been constructed in a more lavish manner than bus stations. The premium mode design philosophy came under strain with the widespread introduction of cheap charter operations in the 1960s and later the widespread market entry of low-cost operators. Some low-cost terminals have been constructed to cater for the special needs of low-cost carriers (LCCs). With the spread of LCCs, charter- only operations have declined in most markets. Low-cost terminals are covered separately in Section 10.12. However, at many airports, facilities must now be designed to cater for a mix of passengers: leisure, business, long haul, short haul, full cost, low cost, domestic, and international.

Terminal design is customarily constrained by the needs of passengers, workers, and visitors, as discussed in Section 10.1. Of these three classes of user, the passengers are considered to be the most important. The comfortable accommodation of the passenger can be a reasonable and economic objective, since expenditures in the terminal area are a substantial proportion of the overall revenue of any passenger airport operation (Section 10.9).

It is clear that terminal design should reflect awareness of passenger needs and behavior. However, passenger behavior varies according to the purpose of the trip, the flight logistics, and the type of flight (6, 7). *Air travel purpose* is normally divided into leisure and business categories. Business travelers tend to use the airlines more frequently and consequently are more familiar with the workings of the terminal and the reliability of the access mode. Such travelers usually spend less time in the terminals and less money in areas of nondeductible business expenses (e.g., duty-free and novelty shops); however, areas such as restaurants and bars are patronized by these travelers. Business trips encourage few airport visitors as senders or greeters. Increasingly, business travelers also use LCCs. Consequently, since deregulation, the changed nature of the air passenger requires a more complete understanding of the market for which the terminals are to be designed.

Generally the longer the distance traveled, the greater the time allowed by passengers prior to time of scheduled departure. Figure 10.4(a) plots cumulative arrivals for passengers on transatlantic and European flights from a British airport. It can be seen that, for the intercontinental flights, the average arrival time was 17 min earlier than for an international European flight. Almost all passengers had arrived a full hour before scheduled time of departure.

Equally important is the type of flight—whether it is a scheduled flight, charter, or low cost (LCC). Because of the special difficulties encountered with charter flights (e.g., long processing times at passenger and baggage check-in and the nonavailability of alternate flights if the booked flight is missed), charter passengers tend to spend even more time in the passenger terminal than passengers on scheduled international flights. LCC passengers have their own needs. Figure 10.4(b) shows the cumulative distribution for chartered and scheduled passengers at a typical European airport.

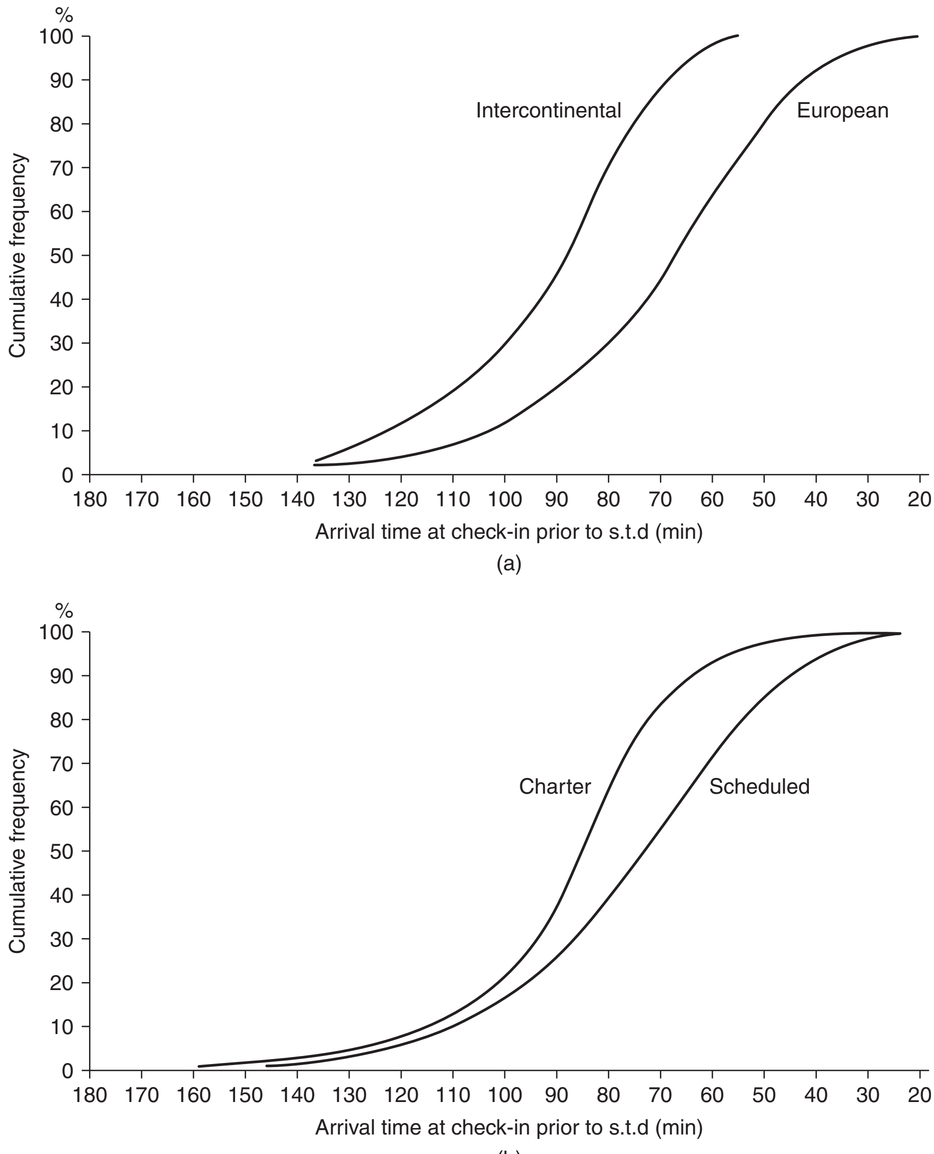

Figure 10.4 Example of relationship of arrival time for enplaning passengers and type of flight: (a) short and long haul, international; (b) charter and scheduled (7).

For security reasons, many airports and airlines have extended required closure times prior to the scheduled time of departure (STD). In 2010, check-in desks for many European flights no longer close 10 min before STD; minimum periods of 45 min prior to STD are common. At some airports, the closure time may well vary among airlines. The adoption of such operational rules can have profound implications on how long passengers spend in the terminal and where they are during that stay.

Design of any terminal cannot proceed without knowledge of the mix of passenger traffic envisaged. Clearly, the design of a terminal that serves mainly business domestic travel is the simplest, requiring the least range of facilities. The most complicated terminals must cater to a mix of business, leisure, and low-cost traffic traveling on a mixture of chartered, scheduled, and low-cost flights over domestic, short-haul international, and even intercontinental distances. Terminal design must take into account variations in traffic mix across these variables.

Until recently, airport operators collected data by observational surveys to establish the relationship between passenger arrival time and the STD, as shown in Figure 10.4. Now airports are able to obtain this information from overall baggage handling information systems (MISs) and from airline-specific departure control systems (DCSs) (4, 5).

Perhaps the most extreme form of influence on passenger dwell times in terminals is observed at Caribbean and Mediterranean airports that serve vacation areas. Passengers are ferried from the hotels by chartered buses to the airport at times that relate to the need for the hotel to have vacant rooms. Hundreds of passengers are then off-loaded at the airport departure areas often well before check-in desks are open to accommodate them. Huge crowds of luggage-burdened passengers crowd into the check-in areas causing extreme congestion and severe passenger dissatisfaction through no fault of the operator. Where these conditions are known to occur, the design must accommodate very large numbers of passengers at the departures hall and the pre-check-in areas. MIS and DCS information is unlikely to be of use at such airports; passenger dwell times in the terminal still have to be obtained directly from observations and surveys.

10.9 IMPORTANCE OF PASSENGER TERMINAL EXPENDITURES

Although departing passengers spend a considerable amount of time in holding and waiting areas in the terminal, a very small portion of the terminal time is, in fact, spent in the processing sequence. Consequently, terminal facilities are designed in a manner to attract passengers to patronize concessionary areas, such as restaurants, shops, and bars. The financial implications of nonaviation-related terminal concessions should not be underestimated, for, in practice, these facilities can contribute substantially to an airport's total revenue structure. As already seen in Chapter 1 (Tables 1.3 and 1.4), terminal revenues in their various forms supplant landing fees as the principal source of operational revenues. Clearly, the designer must consider passenger services not merely from a viewpoint of supplying reasonable facilities; the terminal must be also capable of providing a high level of fiscal support to the airport operation.

This has become particularly true outside the United States with the growing trend of privatized airports. Very dramatic changes in the internal layout and design of the passenger areas of terminals began to take place in the 1980s. Airports such as Copenhagen, London, Dubai, Amsterdam, Atlanta, Heathrow, and Singapore have developed extensive shopping mall facilities for the passenger. The requirement that airport management operate to a commercial ethic has meant that at many airports there is pressure toward maximum commercialization of facilities. Designers have been required to provide space which has a high rent potential in all areas of the terminal. The reader is referred to references 8 and 9.

10.10 SPACE REQUIREMENTS FOR INDIVIDUAL FACILITIES

To assure orderly and smooth functioning of the terminal, the individual facility areas that form the constituent parts should be designed to accommodate the level and type of passenger loading they are expected to experience. This process ideally requires the following steps:

Determination of peak-hour design demand
Statement of passenger traffic by type
Identification of individual facility volumes
Calculations of space requirements

Determination of Peak-Hour Design Demand

Although knowledge of annual passenger movements is important for the estimation of potential revenues, the demand that is manifested in the peak hours determines facility size. The most widely relied-on design parameter is the TPHP (typical peak-hour passenger) used by the FAA. This is not the absolute peak demand that can occur, but an estimate of a figure that will be exceeded only for very short periods. The FAA uses the peak hour of an average day of the peak month. In concept, it is similar to the 30th highest hour used in the design of highways. Some European designers still use the standard busy rate (SBR), which is usually the 30th highest hour of the year (2), although some airports use the 20th and others the 40th highest hours.

To compute the TPHP from annual passenger volumes, the FAA recommends the relationships shown in Table 10.1.

Statement of Passenger Traffic by Type

Studies of passenger movements in airport terminals have indicated that different types of passengers place different demands on the facilities in terms of space. It is therefore desirable to be able to categorize peak-hour passengers according to flight type, trip purpose, trip type, and access mode. Ideally, estimates of passenger volumes could be categorized into domestic or international scheduled or charter, transfer or transit, business or leisure, and intercontinental or short haul and by access mode.

Table 10.1 FAA Recommended Relationships for TPHP Computations from Annual Figures (7)

Total annual passengers	TPHP as a percentage of annual flows
30 million and over	0.035
20,000,000 to 29,999,999	0.040
10,000,000 to 19,999,999	0.045
1,000,000 to 9,999,999	0.050
500,000 to 999,999	0.080
100,000 to 499,999	0.130
Under 100,000	0.200

Note: Values apply separately to domestic and international passengers at any given location.

Identification of Individual Facility Volumes and Area Computations

The movement of the various categories of passengers through the terminal identifies the level of usage placed on the various facilities in the peak hour. Based on the number of passengers processed in each facility, areas can be computed so that reasonable levels of service can be furnished.

Standards of Space Requirements

In the past, the actual space provision in the design and operation of air terminals has varied capriciously. However, the FAA and other bodies have set down guidelines that, when related to the design peak figures, have given adequate and comfortable space provision to the terminal user. (3–5)

As previously discussed in Chapter 7, a set of space and time design standards has been published by the IATA based on the LOS concept, where level A is considered excellent, level D is desirably the lowest level achieved in peak operations, and level F is the point of system breakdown or congestion, see Table 10.2(4).

Space requirements relate to check-in queue space, waiting and circulation space, passport control, hold rooms, and baggage claim areas.

Processing and waiting times relate to total check-in times for economy and business class, inbound and outbound passport control waiting and processing time, baggage claim waiting time, and security waiting and processing time.

In attempting to estimate the overall gross area requirements for terminals, it has been found that, for basic domestic operations, 14 m^2 or 150 ft^2 per peak-hour passenger is a reasonable guideline. For international operations, this should be increased to 24 m^2 or 250 ft^2. These guidelines do not assume total separation of deplaning and security cleared enplaning passengers. For such designs, space requirements should be increased by at least 20%. Special consideration must also now be given to the space requirements that for security vary from jurisdiction to jurisdiction in terms of passenger and baggage search procedures and the separation of passengers into security-sterile areas.

For medium to large airport terminals accommodating both domestic and international traffic, another rule of thumb for the provision of terminal space that is often used is to supply 10,000 m^2 of floor space per 1 million passengers per annum (mppa). Where that figure drops to 7000 m^2/mppa, the available space becomes very limited. At provisions in the region of 15,000 m^2/mppa there is considerable space available to passengers in the form of atria and open concourses where levels of service appear to be very high.

Calculation of Space Requirements

It is beyond the scope of this chapter to attempt to cover the detailed design of space in the passenger terminal. This has been covered elsewhere, and the reader is referred to reference 1 for a deterministic approach to terminal design. It is now common practice to design even moderate-sized airport terminals using simulation programs which are widely available.

Table 10.2 IATA Level of Service (LOS) Standards, 2004

Check-in area for single queue (m^2/occupant) LOS	A	B	C	D	E
Few carts, little luggage, row width 1.2 m	1.7	1.4	1.2	1.1	0.9
Few carts 1 or 2 pieces of luggage, row width 1.2 m	1.8	1.5	1.3	1.2	1.1
High % passengers using carts. Row width 1.4 m	2.3	1.9	1.7	1.6	1.5
Heavy flights with 2 or more items per passenger high cart usage, row width 1.4 m	2.6	2.3	2.0	1.9	1.8

Circulation Space and Speeds

Location	Carts	Space m^2 per passenger	Speed m/sec
Airside	None	1.5	1.3
After check-in	Few	1.8	1.1
Departure area	Many	2.3	0.9

Single-Queue Passport control LOS	A	B	C	D	E
m^2 per passenger in passport control	1.4	1.2	1.0	0.8	0.6

Passenger Holding Areas LOS	A	B	C	D	E
Max. occupancy rate, % capacity	40	50	65	80	95

Bag Claim Area IATA Standard Assumes that 40% of passengers use carts

LOS	A	B	C	D	E
m^2 per passenger	2.6	2.0	1.7	1.3	1.0

The FAA and IATA have published material for the design of airport passenger terminals by deterministic methods using graphs and computer-based equations (3, 10). These have been replaced with more up-to-date spreadsheets published by the TRB (5, 11). Example 10.1 shows how the spreadsheets can be used to obtain rapid estimates of space design requirements.

Example 10.1 Design of Domestic Terminal Using ACRP* Spreadsheets In this example, the year in which the calculations are being carried out is assumed to be 2009. Annual throughput in design year (2025) is 4 million passengers, that is, 2 million enplanements. Using the relationships shown in Table 10.1, this is assumed to equate with 2000 design hour passengers. There is a further assumption of 60%

*The Airport Cooperative Research Program (ACRP) is part of Transportation Research Board (TRB) activities with research sponsored by the FAA.

arrivals or departures maximum imbalance of flow, giving a maximum one-way flow of 1200 passengers/hr; 80% of passengers terminate.

Estimated Breakdown by Functional Areas (Gross)

Airline	Other	Public	Services
ATO Administration Operations Baggage	Concessions Food and beverage Airport administration Miscellaneous	Circulation Waiting areas Restrooms Exits	Mechanical Shafts Tunnels Stairs Shops Electrical Communication
35% × 28,000 = 9800 m^2 (!0,550 ft^2)	20% × 28,000 = 5600 m^2(60278 ft^2)	30% × 28,000 = 8400 m^2(90420 ft^2)	15% × 28,000 = 4200 m^2(45210 ft^2)
Rentable and airport administration: 55% × 28,000 = 15,400 m^2 (165,770 ft^2)		Nonrentable: 45% × 28,000 = 12,600 m^2 (135,630 ft^2)	
		Total passenger terminal area: 2000 peak-hour passengers × 14 m^2 per peak-hour passenger: 28,000 m^2 (301,400 ft^2)	

Gate Model

The first spreadsheet to be used is the gate demand model. The model is entered with the following data for the previous three years (2006–2008):

Annual enplaned passengers, annual departures, and number of gates

From these data, the spreadsheet fills for the previous years the entries enplaned passengers per gate, enplaned passengers per departure, annual departures per gate, and daily departures per gate.

Forecasts are next entered of the annual enplaned passengers and annual departures for the planning period (2010–2025). With these entries, the model computes for the design year:

Enplaned passengers per gate
Enplaned passengers per departure
Annual departures per gate
Daily departures per gate

The spreadsheet now displays the gate requirement determined by two methods of calculation, the enplaned-passengers-per-gate approach and the departures-per-gate approach. The latter calculation can be fine tuned by the input of entries for the daily

Gate Demand

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Calculated Values	
Linked or Predetermined Values	

REQUIRED DATA: Enplanements, Departures, and Total Gates

Enplaned Passengers per Gate Approach

Year	Annual Enplaned Passengers	Annual Departures	# of Gates	Enplaned Passengers per Gate	Enplaned Passengers per Dept.
2006	1,900,034	24,004	14	135,700	79
2007	2,000,000	25,407	14	142,900	79
2008	2,100,013	26,098	14	150,000	80
2010	2,314,815	27,598	**15**	156,400	84
2015	2,777,778	31,906	**17**	162,300	87
2020	3,333,333	34,089	**18**	182,300	98
2025	4,000,000	37,016	**20**	201,500	108

Departures per Gate Approach

Year	Annual Enplaned Passengers	Annual Departures	# of Gates	Annual Departures per Gate	Daily Departures per Gate
2006	1,900,034	24,004	**14**	1,710	4.9
2007	2,000,000	25,407	**14**	1,810	5.2
2008	2,100,013	26,098	**14**	1,860	5.3
2010	2,314,815	27,598	**15**	1,820	5.2
2015	2,777,778	31,906	**18**	1,820	5.2
2020	3,333,333	34,089	**18**	1,860	5.3
2025	4,000,000	37,016	**20**	1,860	5.3

Average of Both Methods

Year	Passengers per Gate	Departures per Gate	GATES
2010	15	15	**15**
2015	17	18	**17**
2020	18	18	**18**
2025	20	20	**20**

Gate Equivalences Table

Design Group	Class and Aircraft	# of Gates	NBEG Maximum Wingspan	NBEG Index	EQA Typical Seats	EQA Index	% Share by Group
I.	Small Regional (Metro, B99, J31)	-	49	0.4	25	0.2	0.0%
II.	Medium Regional (SF340, CRJ)	1	79	0.7	50	0.4	5.0%
III.	Large Regional (DHC8, E175)	4	118	1.0	75	0.5	20.0%
III.	Narrowbody (A320, B737, MD80)	8	118	1.0	145	1.0	40.0%
IV.	757 (B757, B757 w/Wingletes)	5	135	1.1	185	1.3	25.0%
IV.	Widebody (MD-11, B767)	1	171	1.4	280	1.9	5.0%
V.	Jumbo (B747, B777, B787, A330, A340)	1	214	1.8	400	2.8	5.0%
VI.	A380 (A380, B747-8)	-	262	2.2	525	3.6	0.0%
	Total	**20**	**NBEG**	**21.4**	**EQA**	**21.6**	

Figure 10.5 Gate demand model screen (11).

departures per gate. The number of gates may be taken as the average of the two approaches as shown in the box at the right of the sheet.*

Check in/Ticketing Model

The model calculates:

- Staffed counter positions
- Kiosks
- Curbside

Inputs. Design hour departing passengers, percentage of connecting traffic, percentage of passengers in peak 30-min period, percentage of passengers using facility, peak 30-min originating passengers, processing time per passenger (min), desired maximum wait time (min), average width of position (ft), depth of check-in queue (ft),

*The gate demand model uses the concepts of equivalent aircraft (EQA) and narrow-body equivalent gate (NBEG), which rate the sizes of individual aircraft according to wingspan and seat capacity. It should be noted that the EQA rating of aircraft differs from the EQA of the former FAA terminal sizing method (3).

length of check-in counters (ft), passenger level of service, processing time per passenger (min), depth of curbside check-in (ft)

Outputs. required number of staffed service positions, average queue wait time, maximum queue wait time, maximum number of passengers in queue, required queue area, space provision per passenger, peak 30-min-originating passengers, desired maximum wait time (min), required number of available curb counter positions, length of curb check-in counters (ft), total curbside check-in area (ft^2)

Summary outputs in square feet for 2 million originating passengers per year are:

ATO airline office space 1700 ft^2
ATO counter area 850 ft^2
Active check-in zone area 850 ft^2
Counter queue 2125 ft^2
Kiosk area 900 ft^2
Curbside area 630 ft^2
Cross circulation 2420 ft
Total check-in/ticketing area 9475 ft^2

Baggage Screening Model

The inputs to the model include percentage of passengers checking baggage, average number of bags per passenger, percentage of oversize bags, scanning rates, and percentage of bags requiring level 2 and level 3 screening.

The outputs include the required number of level 1 explosive detection system (EDS) units (9), level 2 on-screen resolution units (3), level 3 explosive trace detection (ETD) units (3), and the area required for baggage screening (7620 ft^2). Figure 10.7 shows the computer screen for the baggage screening model.

Baggage Makeup Area Model

Two methods are used to calculate the area for baggage makeup and circulation; both are based on the EQA determined in the linked gate demand model. The average area approach gives a required area of 25,600 ft^2 for an EQA of 14.2. Using the expected number of departures per gate in the 2–4-hr staging period and an average area per cart, a space requirement of 30,500 ft^2 is computed. The result of the computation is shown in Figure 10.8.

Outbound Security Area Model

The passenger flow through this model is linked to the flows in the check-in/ticketing model, but this figure can also be overridden. Inputs are required of processing rate per security lane, maximum desired waiting time, and queue space per passenger. The output gives the number of security lanes required for the desired LOS, the number of passengers in the queue, and the overall areas, 4688 ft^2, required for the security layout. The resultant screen is displayed in Figure 10.9.

Check-In / Ticketing

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Total Staffed Positions	29
Total Equivalent Positions	37
Queue Area per Pax (sq. ft./pax)	16.2
Design Hour O&D Passenger per Check-In Positions	32.4
Equivalent Check-In Positions per EQA	2.6

Check-In Area Toggle Buttons: Counter | Kiosks | Curbside

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ATO: Ticket Counter 17 — Bag Drops 8

Counter Queue — Kiosk Area 16

CIRCULATION: Curbside 4

Staffed Counter Positions

DEMAND	INPUTS	OUTPUTS	
Design Hour Departing Passengers (example year)	1,200	(Use Design Hour Worksheet Value)	
% Connecting Traffic	0%		
% of Passengers in Peak 30 min. Period	50%		
% of Passengers Using this Facility	50%		
Peak 30 min. Originating Passengers		300	
Processing time per passenger (min.)	2	Starting Value ↓	
Desired Maximum Wait Time (min.)	10		
Required # of Staffed Service Positions		15	
QUEUE MODEL (PROCESSING)			
Modeled # of Staffed Service Positions	17	Decision Value Point ←	Adequate
AVG. Queue Wait Time using Model Inputs (min.)		5.0	
MAX. Queue Wait Time using Model Inputs (min.)		9.2	Adequate
MAX. # of Passengers waiting in Queue		79	
EXISTING CONDITIONS			
Actual # of ATO Counter Positions	17		
Average Width of Position (ft.)	5		
Depth of Check-in Queue (ft.)	25		
Length of Check-in Counters (ft.)		85	
Existing Queue Area (sq. ft)		1,275	
PASSENGER LEVEL OF SERVICE (SPACE)			
Passenger Space Required for LOS Input (sq. ft/pax)	14	(Review IATA data table)	
Required Queue Area for LOS Input (sq. ft)		1,338	
Passenger Space with Model Inputs (sq. ft/pax)		16.2	Adequate

Kiosks

DEMAND	INPUTS	OUTPUTS	
Design Hour Departing Passengers	1,200		
% Connecting Traffic	0%		
% of Passengers in Peak 30 Min. Period	50%		
% of Passengers Using this Facility	40%		
Peak 30 Minute Originating Passengers		240	
Processing time per passenger (min.)	1.5		
Desired Maximum Wait Time (min.)	2		
Required # of Available Counter Positions		12	
QUEUE MODEL (PROCESSING)			
Modeled # of Available Service Positions	16		Adequate
AVG. Queue Wait Time using Model Inputs (min.)		0.3	
MAX. Queue Wait Time using Model Inputs (min.)		1.7	Adequate
MAX. # of Passengers waiting in Queue		18	
Kiosks served per each staffed Bag Drop	2		
Required # of Bag Drop Positions		8	
REQUIRED QUEUE AREA (L.O.S. "C") (sq. ft)			
Actual # of Total Counter Positions	12		
Average Width of Position (ft.)	3		
Depth of Check-in Queue (ft.)	15		
Linear Kiosk Length (Equivalent Counter Length) (ft.)		36	
Existing Queue Area (sq. ft)		648	
PASSENGER LEVEL OF SERVICE (SPACE)			
Desired Passenger Space for L.O.S. (sq. ft/pax)	14	(Review IATA data table)	
Required Queue Area for L.O.S. (sq. ft)		479	
Passenger Space with Model Inputs (sq. ft/pax)		35.6	Adequate

Curbside

DEMAND	INPUTS	OUTPUTS
Design Hour Departing Passengers	1,200	
% Connecting Traffic	0%	
% of Passengers in Peak 30 Min. Period	50%	
% of Passengers Using this Facility	10%	
Peak 30 Minute Originating Passengers		60
Processing time per passenger (min.)	2	
Desired Maximum Wait Time (min.)	5	
Required # of Available Counter Positions		4
EXISTING CONDITIONS		
Actual # of Staffed Curbside Positions	4	
Average Width of Position (ft.)	5.25	
Depth of Curbside Check-in (ft.)	30	
Length of Check-in Counters (ft.)		21
Total Curbside Check-in Area (sq. ft)		420

Space Summary

ATO Airline Office Space	depth (ft)	20	1,700	sq. ft
ATO Counter Area	depth (ft)	10	850	sq. ft
Active Check In Zone	depth (ft)	10		
Active Check In Zone Area			850	sq. ft
Counter Queue			2,125	sq. ft
Kiosk Area			900	sq. ft
Curbside Area			630	sq. ft
Cross Circulation	depth (ft)	20	2,420	sq. ft
Total Check-In/Ticketing Area			**9,475**	**sq. ft**

Input Data Values	
Calculated Values	
Linked or Predetermined Values	

Figure 10.6 Check-in/ticketing screen (11).

Baggage Screening

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Input Data Values	
Calculated Values	
Linked or Predetermined Values	

DESIGN HOUR BAG LOAD			INPUTS	OUTPUTS	
Design Hour Passengers Checking In	Use Check-In Value	1200	1,200		linked to Check-In / Ticketing
% of Passengers Checking Bags			60%		
Average # of Bags per Passenger			1.5		
Total # of Bags to process in Peak Hour				1,080	
10 minute Baggage flow rate				180	
TSA Surge Factor (based on a 10 minute baggage flow rate)			Applied	1.15	
Equivalent Baggage Surge Rate (bags/hour)				1,241	
% of Total bags that are over-odd/sized bags & too large for EDS			3%		
# of over-odd/sized bags requiring ETD inspections				37	
Total # of Bags to process through Level 1 EDS Units				1,204	
EDS/ETD EQUIPMENT REQUIREMENTS					
Level 1 EDS Screening - Process Rate(bags/hour)			150		
# of Level 1 EDS Units required				9	
% of Scanned Bags requiring Level 2 Screening (**Alarm Rate**)			25%		
# of bags requiring Level 2 OSR				301	
Level 2 OSR rate (bags/hour per operator)			120		
# of Level 2 OSR Stations required(1 operator/station)				3	
% of Resolved OSR Bag Reviews (**Clear Rate**)			80%		
Total # of Bags needing Level 3 Screening in Peak Hour				98	
Level 3 ETD Screening - Process Rate(bags/hour/screener)			24		TSA suggests 24 bags/hr/screener
# of Level 3 ETD Units required (2 screeners/unit)				3	
BAGGAGE SCREENING SPACE REQUIREMENTS					
Level 1 Area per EDS Screening Unit (sq. ft.)			800		~ 800 sq. ft per Unit
# of Required EDS Units			9		
Level 2 Area per OSR Station (sq. ft.)			40		~ 40 sq. ft per Unit
# of OSR Stations required			3		
Area per ETD Screening Unit (sq. ft.)			100		~ 100 sq. ft per Unit
# of required ETD Units			3		
Total Area requirements for Baggage Screening (sq. ft.)				7,620	

Figure 10.7 Baggage screening screen (11).

Baggage Make Up

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Calculated Values	
Linked or Predetermined Values	

BAGGAGE MAKE UP SPACE REQUIREMENTS					
EQA (In Use)	User Specified Input	14.2	14.2		linked to Gate Demand
Expected # of departures per Gate (within 2-4 hour staging period)			1.3		
Staged carts/containers per EQA			3		range: 2 - 3 per EQA
Area required per cart/container (sq. ft)			600		
Make Up Area (sq. ft)				27,700	
Additional Allowance for Baggage Train Circulation			10%	2,800	
Total Make Up Area (sq. ft)				30,500	Comparison
ALTERNATE RATIO METHOD					
EQA (In Use)			14.2		
Actual Average Area per EQA (sq. ft)			1800		1500 - 2200 sq. ft
Total Make Up Area (sq. ft)				25,600	Comparison

Figure 10.8 Baggage make-up area screen (11).

Passenger Hold Rooms

Each hold room can be sized to suit the needs of the aircraft and passenger type it will serve. In this example, gate hold rooms are required for 13 gates serving aircraft ranging from group II to group V. The user is required to make a number of inputs, including the number of seats on the design aircraft, number of passengers to be accommodated, percentage of passengers to be seated, individual space allocation for standing and seated passengers according to the LOS required, provision of other amenities within the hold room, and the requirements for a service podium and a boarding and egress corridor. The output of the spreadsheet is the areas provided for passenger, podium, and

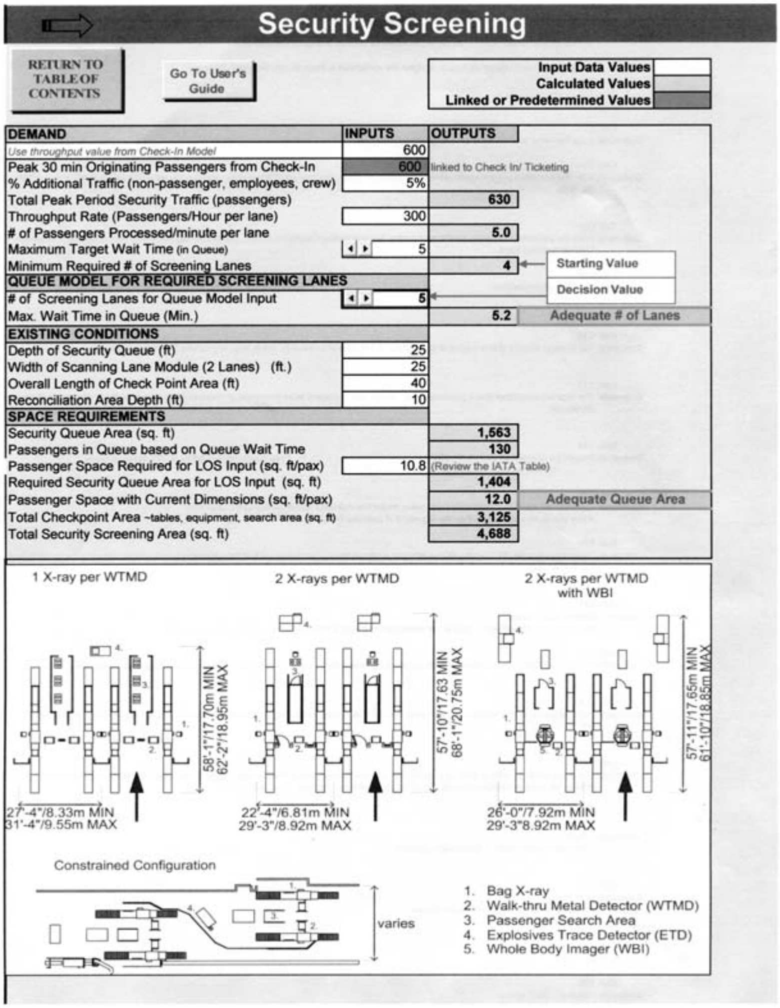
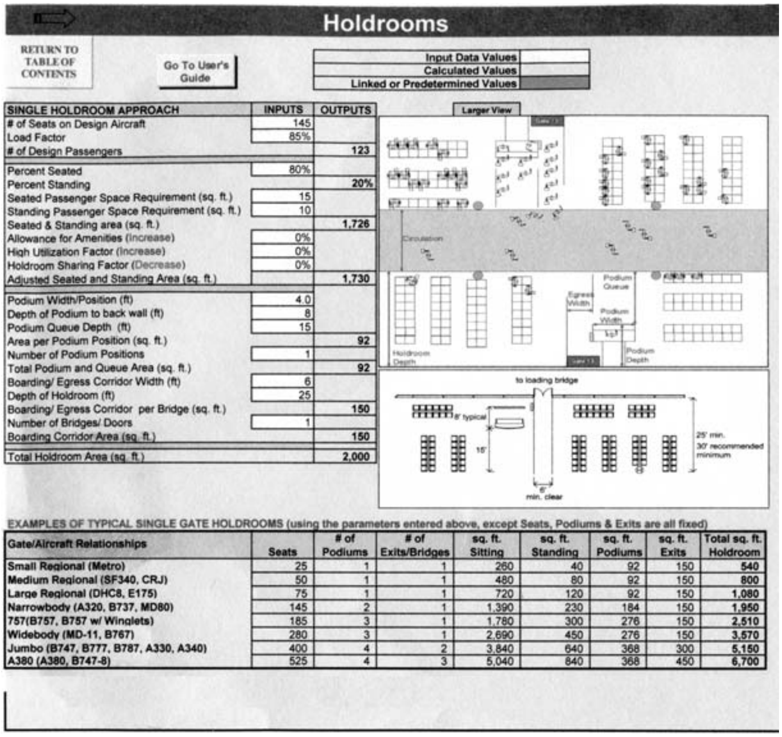


Figure 10.9 Passenger security screening area screen (11).

corridor. Figure 10.10 shows the output screen for a gate hold room for an aircraft in design group III. The procedure is repeated for each size of hold room to be provided and the total hold room space in this example is the aggregate of space required for: 1 Class II, 3 Class III Large Regional, 5 Class III Narrow Body, 2 Class IV 757, 1 Class IV Wide Body, and 1 Class V Jumbo. Using the typical sizes of hold room shown at the bottom of Figure 10.10, the aggregate total hold room area is 27,710 ft^2.

Baggage Claim

The inputs to the spreadsheet include the hourly number of terminating passengers, the percentage arriving in the peak 20 min, the percentage with checked baggage, the average number of bags per passenger, the average size of the traveling party, the required claim frontage per person, and the estimated claim unload rate. The output



Holdrooms

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SINGLE HOLDROOM APPROACH	INPUTS	OUTPUTS
# of Seats on Design Aircraft	145	
Load Factor	85%	
# of Design Passengers		123
Percent Seated	80%	
Percent Standing		20%
Seated Passenger Space Requirement (sq. ft.)	15	
Standing Passenger Space Requirement (sq. ft.)	10	
Seated & Standing area (sq. ft.)		1,726
Allowance for Amenities (Increase)	0%	
High Utilization Factor (Increase)	0%	
Holdroom Sharing Factor (Decrease)	0%	
Adjusted Seated and Standing Area (sq. ft.)		1,730
Podium Width/Position (ft)	4.0	
Depth of Podium to back wall (ft)	8	
Podium Queue Depth (ft)	15	
Area per Podium Position (sq. ft.)		92
Number of Podium Positions	1	
Total Podium and Queue Area (sq. ft.)		92
Boarding/ Egress Corridor Width (ft)	6	
Depth of Holdroom (ft)	25	
Boarding/ Egress Corridor per Bridge (sq. ft.)		150
Number of Bridges/ Doors	1	
Boarding Corridor Area (sq. ft.)		150
Total Holdroom Area (sq. ft.)		2,000

EXAMPLES OF TYPICAL SINGLE GATE HOLDROOMS (using the parameters entered above, except Seats, Podiums & Exits are all fixed)

Gate/Aircraft Relationships	Seats	# of Podiums	# of Exits/Bridges	sq. ft. Sitting	sq. ft. Standing	sq. ft. Podiums	sq. ft. Exits	Total sq. ft. Holdroom
Small Regional (Metro)	25	1	1	260	40	92	150	540
Medium Regional (SF340, CRJ)	50	1	1	480	80	92	150	800
Large Regional (DHC8, E175)	75	1	1	720	120	92	150	1,080
Narrowbody (A320, B737, MD80)	145	2	1	1,390	230	184	150	1,950
757(B757, B757 w/ Winglets)	185	3	1	1,780	300	276	150	2,510
Widebody (MD-11, B767)	280	3	1	2,690	450	276	150	3,570
Jumbo (B747, B777, B787, A330, A340)	400	4	2	3,840	640	368	300	5,150
A380 (A380, B747-8)	525	4	3	5,040	840	368	450	6,700

Figure 10.10 Hold room screen (11).

of the spreadsheet is the total claim frontage required and the length of single claim frontage. Figure 10.11 shows the baggage claim screen.

Other Models

The ACRP report also provides spreadsheets for the computation of space for circulation, particularly in piers and for the requirements of U.S. Federal Inspection Services on entry at airports serving international passengers. The latter spreadsheet can be adapted for the calculation of government space requirements at non-U.S. airports by changing the time and space inputs.

Table 10.3 is a summary table for the design of a domestic terminal using the ACRP methodology and spreadsheets

10.11 BAGGAGE HANDLING

Unlike most other modes, in air transport it is customary to separate passengers from their baggage during the line haul portion of the trip. This adds substantially to the complexity of handling the air trip and seriously complicates the design of passenger terminals, since it is essential that the separation and reuniting of passenger and baggage be carried out with maximum efficiency and at an extremely high level of reliability. Figure 10.12 diagrams the possible baggage flows from pickup and check-in through

Baggage Claim				
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			Calculated Values	
			Linked or Predetermined Values	
DEMAND			**INPUTS**	**OUTPUTS**
Peak Hour Deplaning Passengers	User Specified Input	1,200	1,200	link to Design Hour
Percent Deplaning in Peak 20 Min.			50%	
Percent Terminating Passengers			90%	
Peak 20 Min. Terminating Passengers				540
Percentage of Passengers Checking Bags			90%	
Passengers Checking Bags				486
Average Traveling Party Size			1.3	
Number of Parties				374
Percent Additional Passengers at Claim			30%	
Total People at Claim				407
Claim Frontage per Person (ft)			1.5	
Total Claim Frontage Required (ft)				611
TYPICAL SINGLE AIRCRAFT CLAIM UNIT SIZE				
Typical Aircraft Seating Capacity			145	
Design Hour Load Factor			90%	
Typical Aircraft Passenger Load				131
Percent Terminating Passengers			90%	
Peak 20 Min. Terminating Passengers				117
Percentage of Passengers Checking Bags			90%	
Passengers Checking Bags				106
Average Traveling Party Size			1.3	
Number of Parties				81
Percent Additional Passengers at Claim			30%	
Total People at Claim				89
Claim Frontage per Person (ft)			1.5	
Claim Frontage Required per Flight				133
BAGGAGE CLAIM USE TIME (domestic only)				
Average # of bags per passenger checking bags			1.5	
Total # bags to unload at Baggage Claim				159
Flight Buffer to allow for late pick up of bags (min)			10	
Unload Rate of bags at Claim (bags/min)			20	
Claim Use Time estimate (min)				17.9

Figure 10.11 Baggage claim screen (11).

the reclaim area. The most complex portion of baggage handling is the departures portion of the journey. Prior to arrival in the departures baggage hall, baggage may be checked at the car park, at curbside, at the town or satellite terminal, or at the terminal itself. Baggage also arrives from long- and short-term storage and by way of transfer baggage facilities. Depending on the size and nature of the terminal function and the local attitude to security, all or some of these facilities will be present (1).

Sorting for the individual flights in the baggage sort area depends greatly on the size of the airport and the number of flights with baggage requirements at any one time. At small airports, where only one flight is being checked in at any one time, baggage moves directly from check-in to the baggage hall, usually on a belt (12). It is then manually off-loaded to carts, which are pulled by tractor to the apron stand. Where a number of flights are dealt with simultaneously, baggage can be sorted manually from one or more carousels in the baggage hall.

At very large airports where there are many different airlines, many check-in desks feeding to numerous belts, and many destinations to be served by the sorting devices in the outbound baggage hall, the baggage handling procedure is becoming increasingly automated. The degree of automation varies according to the system adopted. As baggage comes by belt into the sorting area, its destination is encoded into the automatic system. This is usually achieved either by automatic scanning by a laser reader of a special tag attached at check-in or by manual encoding by an employee reading the ordinary destination tag. At the most modern terminals, such as Hong Kong, radio

Table 10.3 Summary of Space Requirements

	Airline ft^2	Airline m^2	Other ft^2	Other m^2	Public ft^2	Public m^2	Services ft^2	Services m^2
Ticketing	9,475	880						
Baggage screening area	7,620	708						
Baggage make-up area	25,600	2,379						
Security screening	4,688	436						
Hold rooms					27,710	2,575		
Baggage claim excluding devices	8,718	810						
Baggage devices	5,600	520						
Public waiting areas, rest areas, exits, exhibitions, etc.					55,000	5,110		
Concessions, food and beverage, airport administration and miscellaneous			60,000	5,575				
Airline and ground handling offices	40,000	3,716						
Heating, ventilation, air conditioning, mechanical							44,000	4,088
Totals	101,701	9,449	60,000	5,575	82,710	7,685	44,000	4,088

Total terminal area excluding structure is 288,411 ft^2 (26,797 m^2).
With additional 5% for structure total terminal area is 302,832 ft^2 (28,136 m^2).

frequency identification technology has been introduced to improve the accuracy of tag identification.

Depending on the system used, the bag is then automatically directed to a point in the sorting area where it is loaded directly into apron baggage carts or it makes its way either singly in a tray or batched in transfer carts to the aircraft gate. Baggage is either packed on baggage carts, which are driven to the aircraft baggage hold for individual baggage storage, or is placed directly into baggage containers which can be mechanically loaded and unloaded from the aircraft. Figure 10.13 shows the layout of an automated outbound baggage system.

Security searches are now required of all baggage before loading on an aircraft on all international and most domestic fights. At most airports these searches are conducted by scanner systems which either pass the baggage item or divert it for closer scrutiny if suspect. Most modern systems have four levels of scan ending finally in reconciliation with the passenger and manual opening and search of the most suspect items.

It is important to ensure, in the design of the inbound baggage claim hall, not only that the overall size of the facility is adequate to cope with the design peak baggage flow but also that the individual claim devices are matched to the size of aircraft anticipated.

The treatment of arrivals baggage is simpler, although requiring elaborate equipment in the passenger baggage claim unit. The aircraft is unloaded, either manually or,

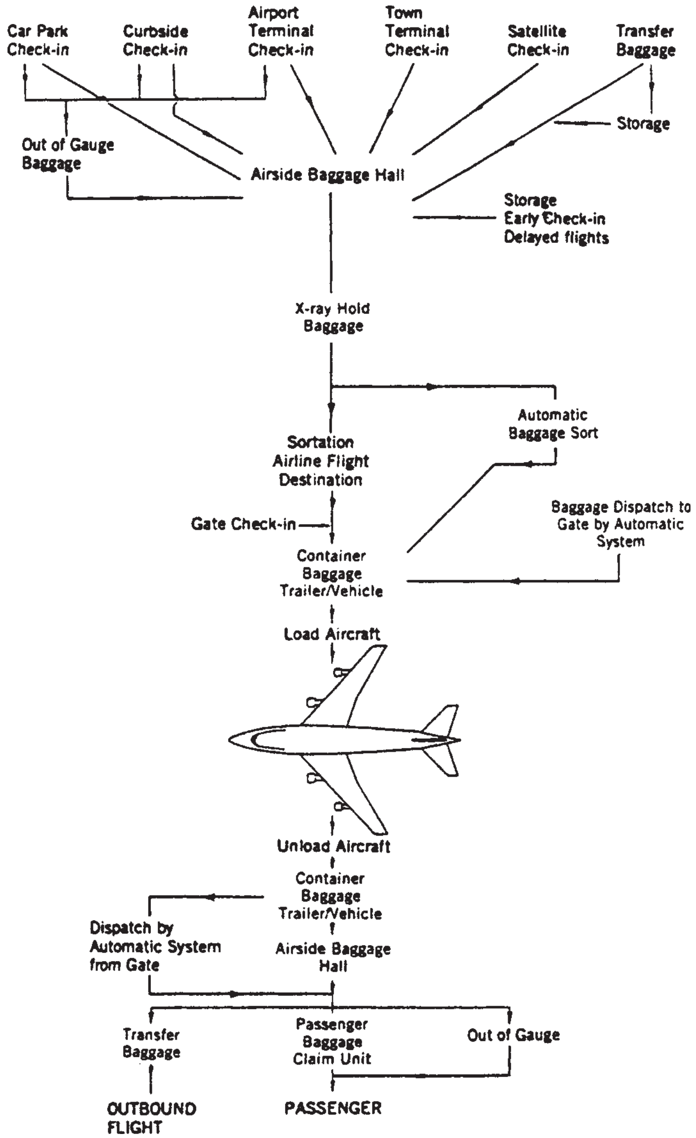


Figure 10.12 Baggage loading and unloading sequence.

if container pods are used, semimechanically. The baggage is brought to the airside baggage hall either in carts or by automatic devices, where it is unloaded into the passenger claim system. Again, the form of system used is dependent on the volume of traffic the baggage claim hall handles and the size of aircraft unloaded. Figure 10.14 depicts five different forms of delivery. The simplest system is the linear counter: Here baggage carts are unloaded manually, directly onto a counter, where the passengers are waiting. A simple mechanized system is the linear track, where the carts are unloaded onto a moving belt which carries the baggage on to a roller track. The more elaborate

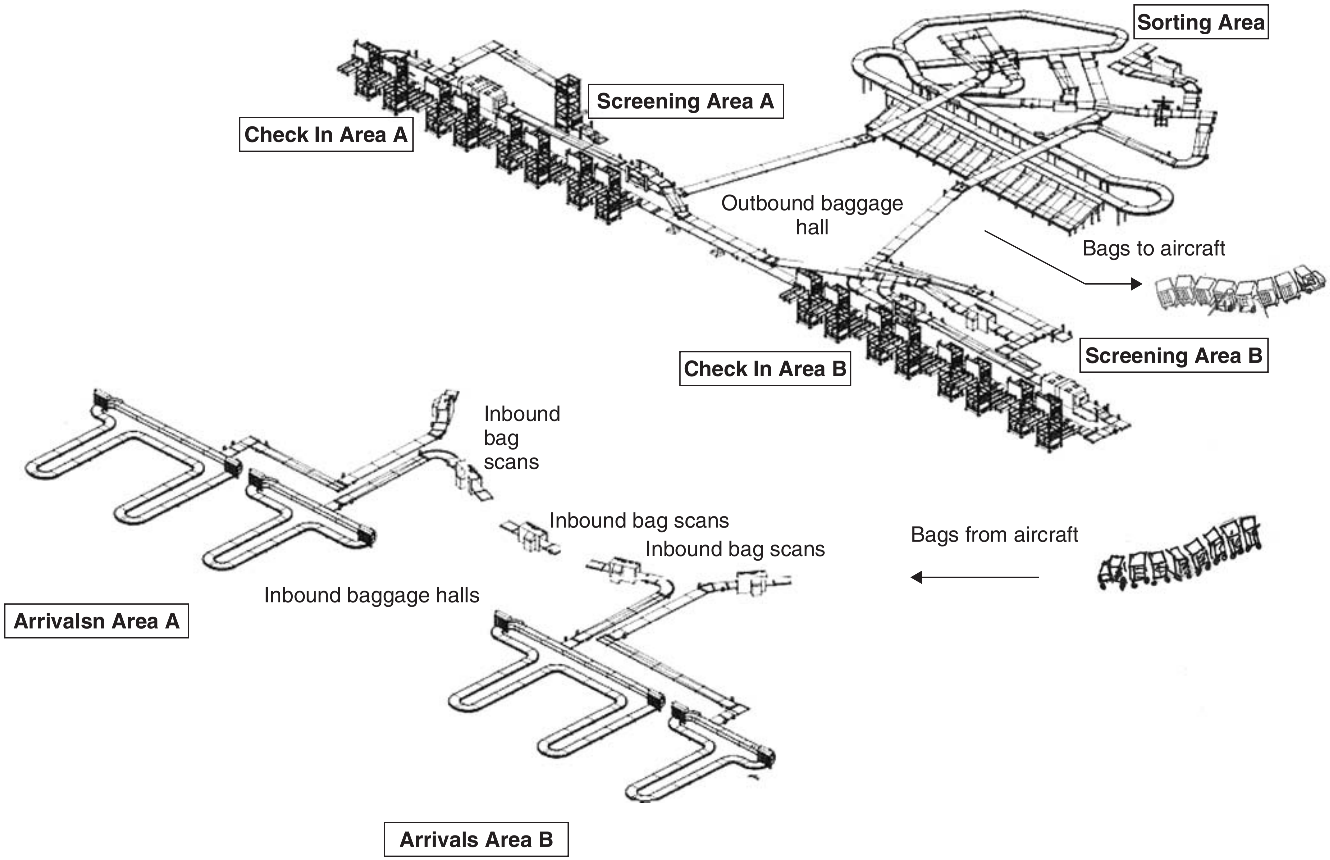
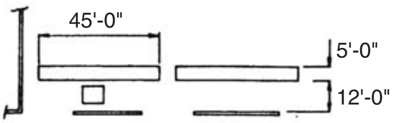
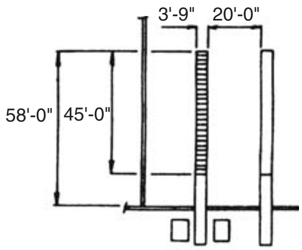


Figure 10.13 Automated outbound baggage system. (Courtesy of Vanderlande Industries.)



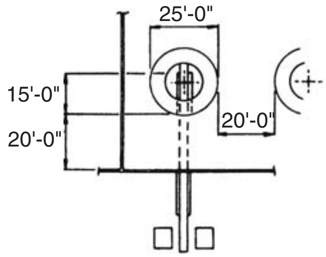
Claim length available 45'-0"
Area per unit: 225 ft^2
Max. bags per unit: 69(at 1'-4" per 2 bags)
Alternate: 2-level counters at single depth.

Linear Counter



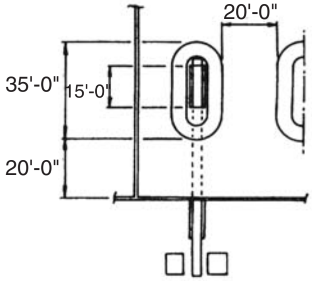
Claim length available 45'-0"
Area per unit: 218 ft^2
Max. bags per unit: 36(at 2'-6" per 2 bags)
presented lengthwise)

Linear Track



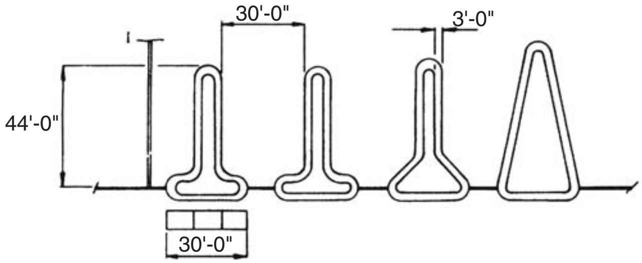
Claim length available : 78'-6"
Area per unit: 491 ft^2
Max. bags per unit: 60(at 1'-4" per bags)

Carousel



Claim length available : 90'-0"
Area per unit: 547 ft^2
Max. bags per unit: 69(at 1'-4" per bags)

Oval Carousel/Racetrack



Claim length available : 115'-0"
Area per unit: 576–1020 ft^2
Max. bags per unit: 120(at 1'-4" per bags) 88 bags on track, 32 bags inside track.

Figure 10.14 Examples of five different baggage delivery systems.

carousel and racetrack designs are necessary to handle the volume of baggage delivered by the large, wide-bodied aircraft.

Where local security regulations require baggage inspection on arrival, this is normally supplied by X-ray and inspection machines after baggage delivery to the passengers and prior to customs inspection.

10.12 TERMINALS FOR LOW-COST CARRIERS

With the widespread introduction of LCCs many airports have built special terminals for these carriers with their special needs, for example, Lisbon and Kuala Lumpur. Other airports have accommodated the carriers with separate piers where the service provision to the low-cost traveler is quite different from that for travelers on conventional airlines, for example, Schiphol Amsterdam. The passenger terminals for both conventional and LCC service must have the same essential functions, but there are significant differences:

1. The areas of terminal supplied per passenger are considerably less for the LCC operation. More than occasional crowding is acceptable to the airline and LOS D is used for a great part of the time that the space is occupied.
2. Less seating is provided in the waiting areas to reduce the space required for passengers
3. There is a less generous provision of commercial space and often retail, food, and drink operations are basic
4. There is no need for provision for business class passengers
5. With the universal use of e-ticketing and on-line check-in the check-in operation is fast.
6. Most bag drop operations are fast; some airlines have automated bag drops that require no staff.
7. Turn-around times of the aircraft on the apron are fast, typically 20 min. Boarding and disembarking are consequently very rapid and passenger waiting time in the terminal is brief.

Table 10.4 shows a breakdown of the terminal areas allotted to the various facilities in the Kuala Lumpur LCC terminal. The terminal is designed to accommodate 10 mppa in a gross terminal area of approximately 35,000 m^2. A conventional design would be expected to have an area in the region of 100,000 m^2. Figure 10.15 illustrates the basic nature of the layout of a LCC passenger terminal.

10.13 EXPANDABILITY, MODULARITY, AND FLEXIBILITY

Because in the medium and long term air transport is generally expected to continue to grow at a steady rate in the region of 5% per annum, it must be recognized that airport passenger terminals are subject to continual change. Some authorities plan on minor renovations to terminals every 5 years and on major reconstructions every 15 years. At the rate that air transport is growing, the average terminal faces a doubling of volume over a 15-year period and a quadrupling over 30 years. Designers must therefore take

Table 10.4 Space Allocation in a LCC Terminal

KLIA LCC terminal capacity 10 mppa	
Cost RM108 million (US$30 million)	
Function	(m^2)
Check-in	2650
International departure hall	3240
International arrival hall	4340
Domestic departure hall	4430
Domestic arrival hall	1900
Public concourse main area	4355
Public concourse international arrival area	325
Common ramp and circulation	6760
Offices, administration, storage, other nonpublic space	7290

Source: Kuala Lumpur International Airport (KLIA).

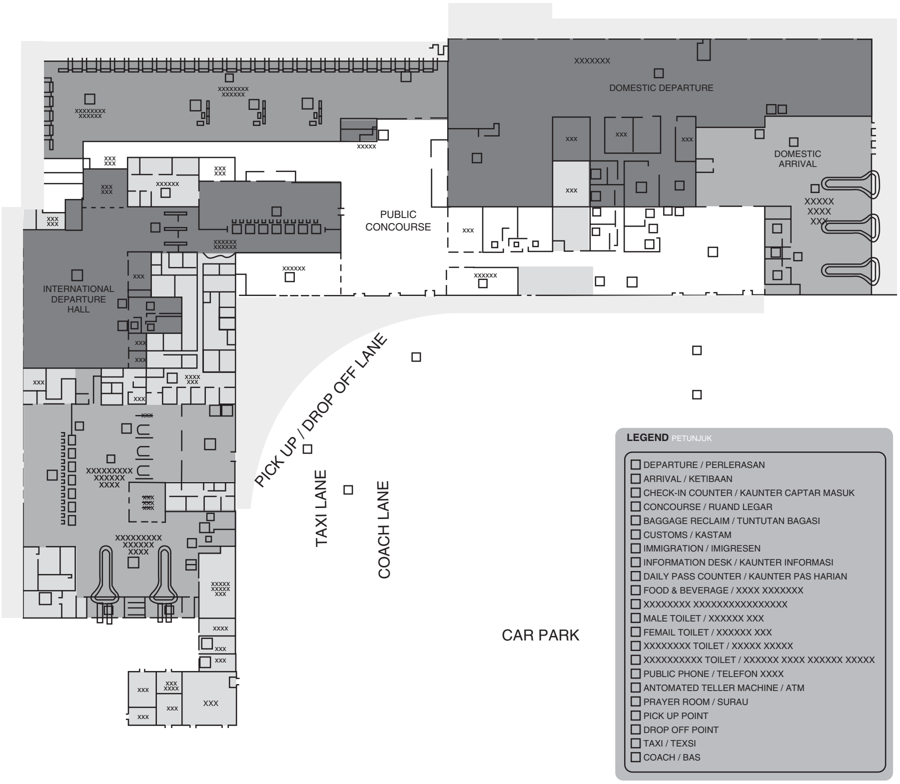


Figure 10.15 Layout of an LCC terminal serving both domestic and international passengers.

into account the requirement of *expandability* when initiating a design and must look at methods of expanding existing facilities without disrupting operations too seriously. The original design proposal for the new airport for Oslo, shown in Figure 10.16, is an example of a midfield terminal designed to operate on commissioning with 51 gates on two piers, one of which is remote. The ultimate design showed 120–140 gates on

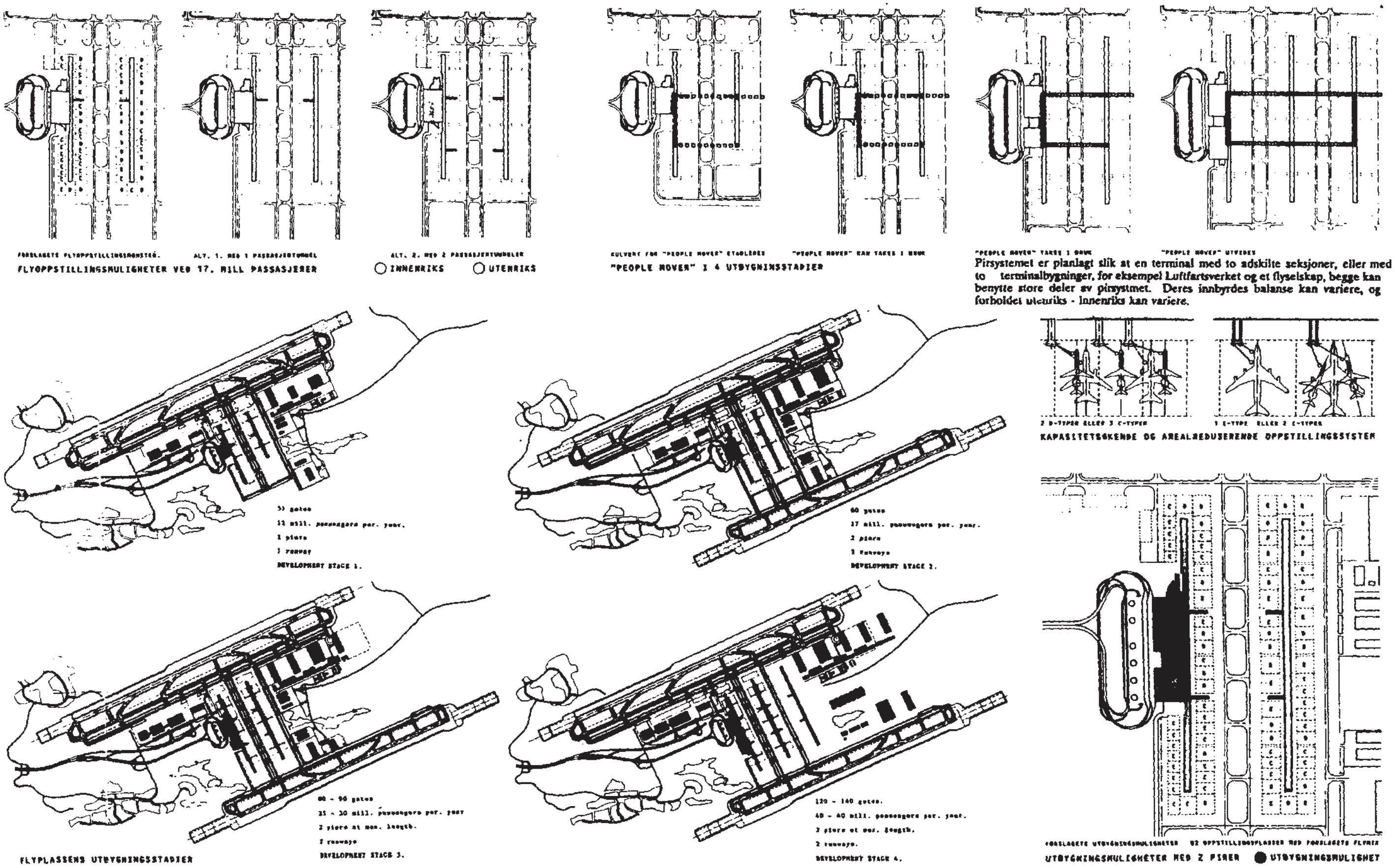


Figure 10.16 Example of an expandable terminal: New Oslo Airport competition entry 1990. (Courtesy of Hjellnes, Oslo.)

three expanded length piers, two of which were remote. This design was to be reached in at least three expansion phases. The third pier was planned to replace a number of limited life buildings constructed in the early life of the airport.

One way of adding to capacity is to build an initial terminal, which is replicated with additional identical units as demand grows, to require greater capacity. This can be achieved by adding additional modular bays to a main building or by adding additional replica unit terminals. A number of designs have used the second approach in their original master plans: Toronto Lester Pearson, Paris Charles de Gaulle, Houston, and Dallas-Fort Worth. Whereas in their original concept they exemplified modularity, in the manner in which they have developed, they have also demonstrated flexibility in that, after the initial construction stage at commissioning, future development has either been carried out or is planned in a different form. Figures 10.17(a) and (b), which show Houston International Airport, exemplify this well.

In the original master plan, terminals C and D were planned to replicate the two original terminals, A and B. Terminal C, however, was constructed to give a more efficient linear management of aircraft on the apron, and terminal D was planned for an even higher intensity of linear apron development. Expansion in the form of a planned duplication of an earlier building has taken place at some terminals, for example, Rio de Janeiro Gallẽo and São Paulo Guarulhos.

When a terminal is being designed, the concept of *flexibility* is also important. A flexible design is one which can easily adapt to a traffic which is different in nature from that for which the original design was made. Flexibility is especially useful if an airline decides, at some later date, to initiate hubbing operations at an airport, causing substantial changes in aircraft fleet mix, proportion of interlining passengers, and total traffic demand. With a flexible design, space in an existing terminal can be fairly easily changed from its original use to a totally different use in the expanded terminal. Schiphol Amsterdam has used flexible design to accommodate LCCs, which want no-frills space for no- frills service.

Figure 10.18 is an example of an existing small terminal which in its original design stage was inflexible, no consideration being given then to expansion at some later date. Expansion to its ultimate capacity would require costly sequenced construction in order to ensure minimum level of passenger service during the expansion phase. It is not unusual for renovation costs of existing terminal space to be more costly than completely new construction. It should also be understood that converting a single-level terminal to a two-level operation is likely to be infeasible unless this eventuality was envisaged in the original design. Modification will be necessary to columns, foundations, and roofs causing great disruption to continued operation.

Modular and flexible designs frequently increase initial construction costs, but in the long term they can be extremely cost effective in an industry where complete obsolescence of terminal infrastructure is common over a 20-year period.

10.14 NUMBER OF AIRCRAFT GATES

The final configuration of the airside interface depends largely on the number of aircraft gates. First principles would lead the designer to the conclusion that the number of gates is a function of the design peak-hour aircraft movements, the length of time that the individual aircraft spend at the gates, and some utilization factor to account for the

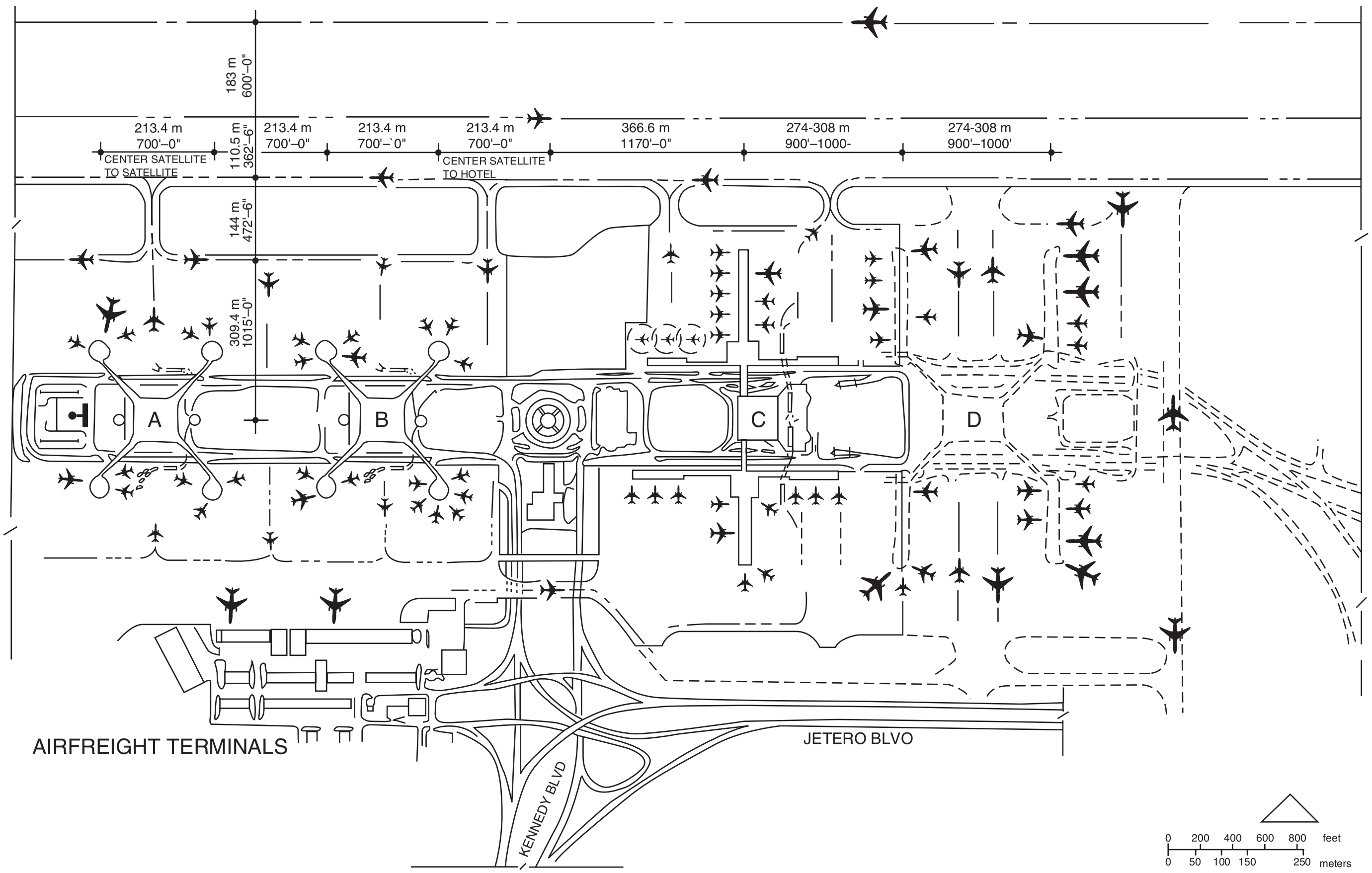


Figure 10.17(a) Apron–terminal complex at Houston Intercontinental Airport. (Adapted from Hart, W., *The Airport Passenger Terminal*, New York: Wiley Interscience, 1985.)

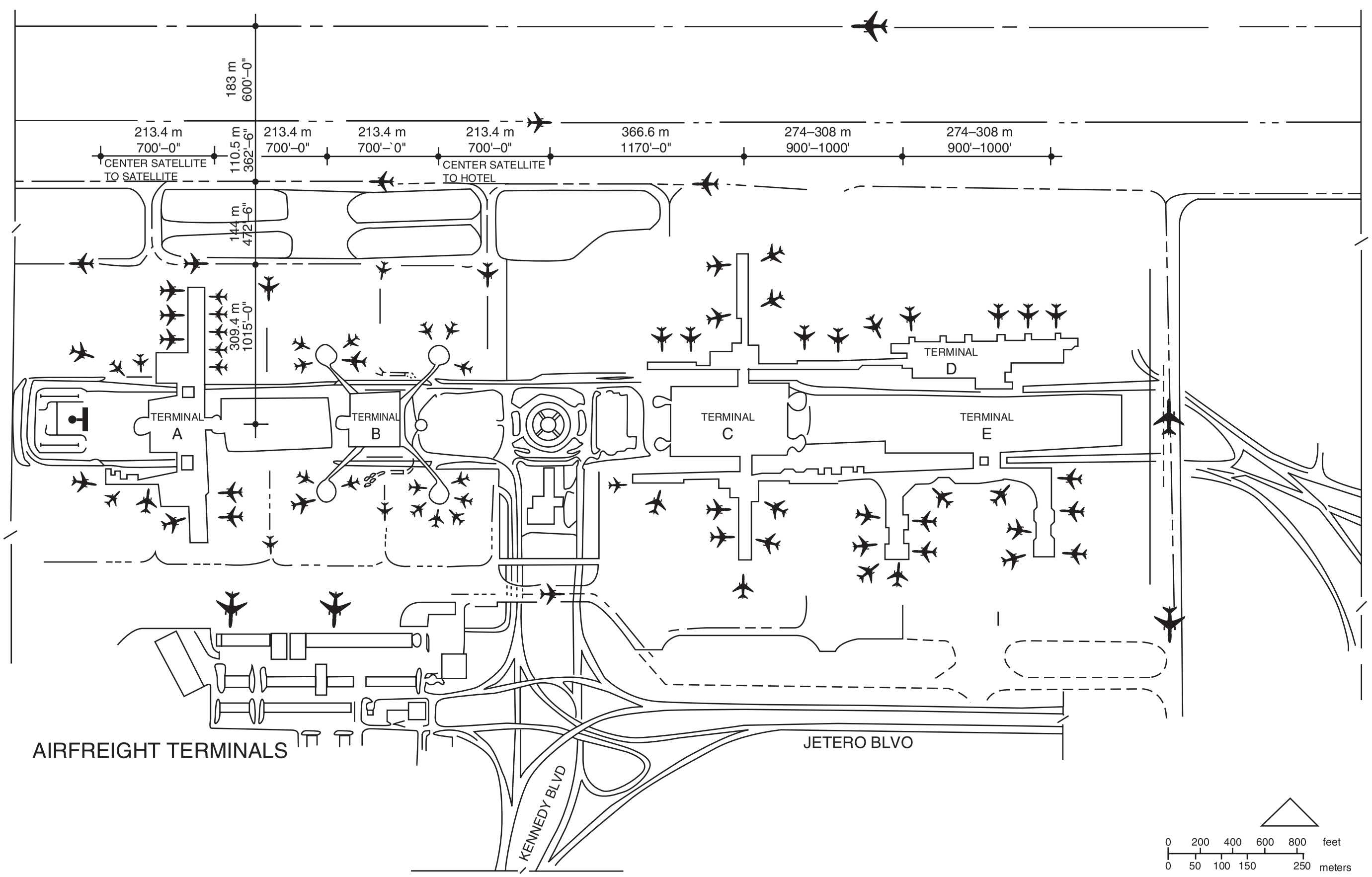


Figure 10.17(b) Apron-terminal complex at Houston International Airport as built, circa 2011.

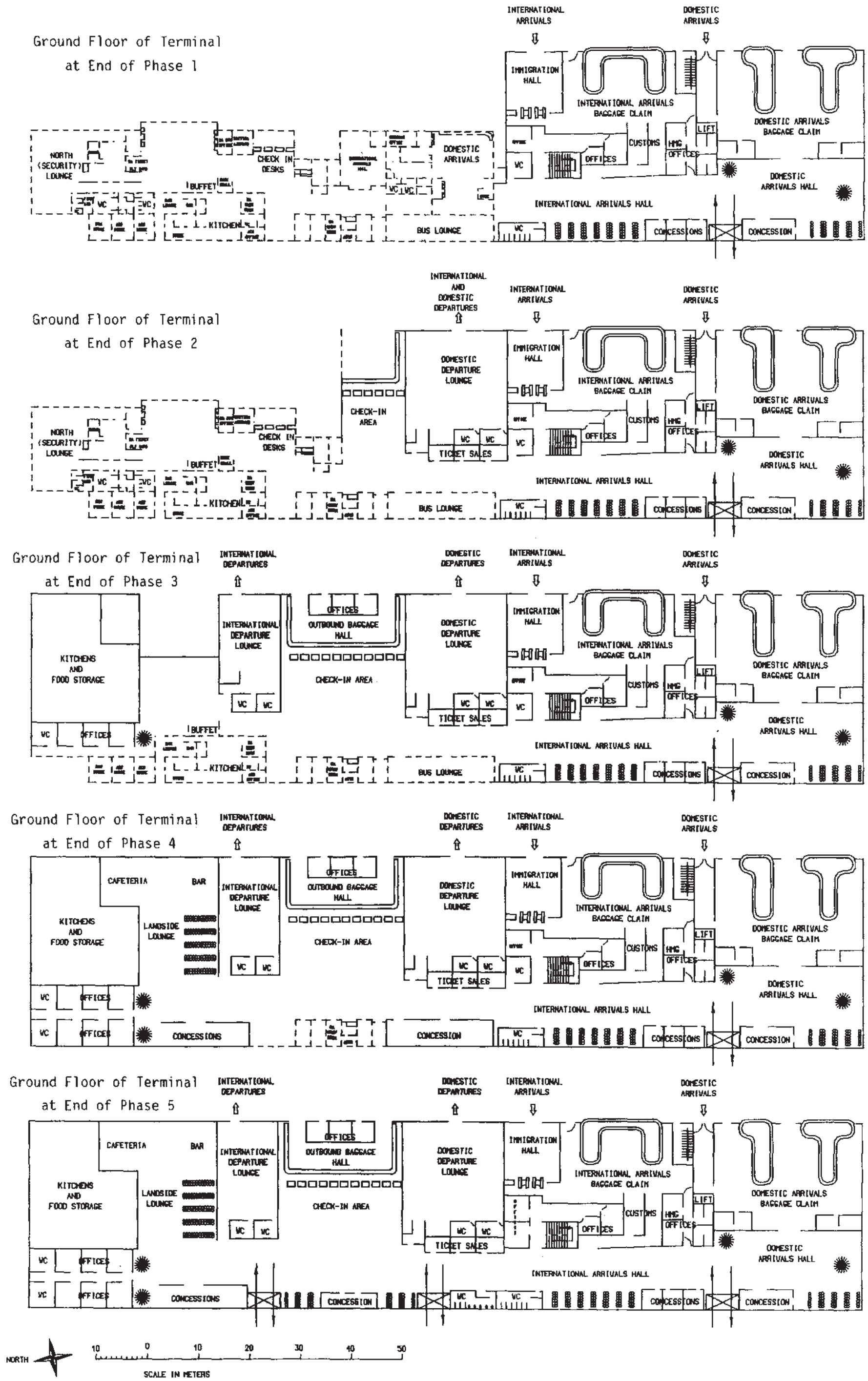


Figure 10.18 Proposed expansion of Inverness Airport passenger terminal,. (*Source:* Norman Ashford, Consultant Engineers Ltd., Loughborough, UK, 1989.)

impossibility of filling all gates for 100% of the peak time because of maneuvering and taxiing.

The output of the gate demand model of the ACRP spreadsheet in EQA and NBEG, while useful for the calculation of the elements of the passenger terminal, is unlikely to be satisfactory for the determination of the design number of aircraft gates or stands.*

A number of models have been proposed using variants of these variables; they do not necessarily lead to the same answers. The reason for the difference appears to be the location of the calibration of the models. U.S. and European turnaround practice at airports is different, and there are even wide variations within Europe. The following are presented with the advice that the designer should select the model which is calibrated on the apron practice that is most appropriate.

Horonjeff (United States)

$$n = \frac{vt}{u}$$

where

v = design hour volume for arrivals or departures (aircraft/hr)
t = weighted mean stand occupancy (hr)
u = utilization factor, suggested to be 0.6–0.8 where gates are shared

Piper (West Germany) (13)

$$n = mqt$$

where

m = design hour volume for arrivals and departures (aircraft/hr)
q = proportion of arrivals (total movements)
t = mean stand occupancy (hr)

Six Frederick Snow and Partners (United Kingdom)

$$n = 1.1\,m$$

where

m = design hour volume for arrivals and departures (aircraft/hr)

Loughborough (United Kingdom)

$$n = vt$$

where

v = design hour volume for arrivals or departures (aircraft per hour)
t = weighted mean stand occupancy time according to route type
= 0.90 hr for domestic
= 1.1 hr for short-haul international
= 3.8 hr for long-haul international.

Three different methods have been used by U.S. airlines (1):

Hart Method I (Hourly Method) (United States)

$$n = \frac{m}{2r}$$

*There is a divergence of usage between North America and elsewhere of the word “gates.” All stands tend to be called gates in the United States. Elsewhere, the gates are the assembly areas in the terminal where passengers board contact-stand aircraft directly or board buses to remote stands.

where

m = total number of peak-hour aircraft movements
r = movement factor = 0.9–1.1, originating or terminating
1.2–1.4, transfer
1.5–2.0,) through

Hart Method II (Daily Method) (United States)

1. Compute current average daily departures/gate (= q'): less than 5 is low; 10 considered the maximum.
2. Estimate future average daily departures/gate (q).
3. Divide future daily departures (d) by future average daily departures per gate (q).

Hart Method III (Annual Method) (United States)

1. Determine current annual utilization per gate.

   Annual enplanements < 15,000 per gate considered low.
   Annual enplanements > 150,000 per gate considered high.

2. Determine number of gates by estimating number of enplanements per gate (see nomographs in reference 3in).
3. Divide future enplanements by enplanements per gate.

While the above methods are satisfactory for preliminary sizing of gate requirement, calculation of apron gate requirements is also amenable to simulation; microcomputer software for modeling these requirements is now widely available. Most larger airports have computerized gate management systems (GMSs) which can be used for computing gate demand by aircraft type for any input schedule. The GMS can also be adopted for design purposes.

10.15 PARKING CONFIGURATIONS AND APRON LAYOUT

The aircraft is unloaded, loaded, and serviced in the terminal apron, which is usually in close proximity to the passenger airside gates. The spacing of aircraft on the apron, and therefore the layout of the apron itself, is determined by the physical characteristics of the aircraft, the choice of parking configuration, the effect of jet blast, and the manner in which aircraft will maneuver into parking position.

The form of the airside interface and the design dimensions of the apron depend on the number of gates and the parking configuration chosen. At most large airports, the majority of aircraft come to the nose-in parking position immediately next to the terminal under their own power and are pushed out by tugs. The two principal advantages to this arrangement are that passenger loading can be carried out by loading bridges, thereby protecting passengers from the elements, and apron dimensions can be minimized. The main disadvantage of power-in, push-out designs is the added manpower and equipment requirement (i.e., the tractor and its driver).

At some airports, power-out operations are permitted with aircraft using reverse thrust, principally from tail-mounted engines. Many airports, however, do not favor

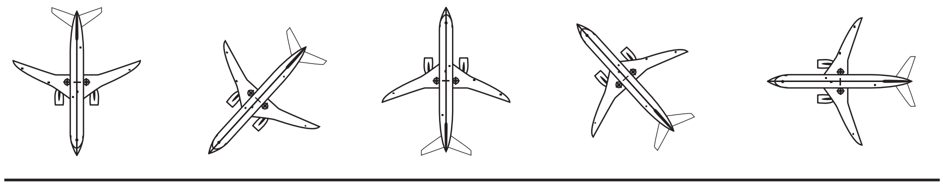


Figure 10.19 Five aircraft parking configurations at terminals.

this because of the effect of jet blast on the terminal and apron safety considerations; similarly, most airlines reject this type of maneuver, fearing there will be engine damage from foreign objects and dirt on the apron. This practice has been less common with the passing of rear-engine aircraft.

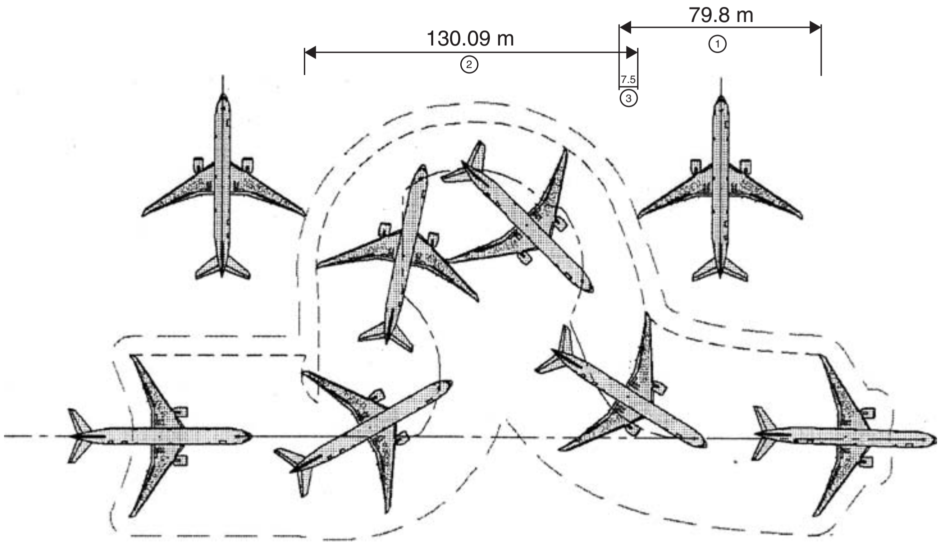
Power-in, power-out designs have four basic configurations (Figure 10.19), with the nose-in position reserved for power-in, push-out operations. Power-in, power-out operation, though requiring no special equipment or apron personnel to move the aircraft out, fails to place the nose of the aircraft in the most desirable position, since it does not permit the loading and unloading of passengers with air bridges.

Usually the choice of any of the configurations without air bridges means exposure of passengers to the weather conditions on the apron. The main difference between the nose-in and nose-out configurations is that, with the former, there is the convenience of having the main passenger doors near the terminal, whereas the latter configuration normally minimizes noise and jet blast, because the aircraft is lighter and has more momentum when turning immediately after taxiing. Because air bridges are needed only at the largest facilities, most airports, which are still small facilities, are designed without them; their aprons and gate positions must have dimensions that permit the aircraft to maneuver with adequate clearances (14).

For passenger flow, under power-in, power-out conditions, the best position is the parallel parking configuration, but this requires the greatest apron space, and blast and high-frequency noise are directed at adjacent gate positions at breakaway. The increase in terminal apron frontage required for self-maneuvring operations is indicated by Figure 10.20, which shows the 60% increase of apron frontage required for a Boeing 777. For detailed discussion of apron design dimensions, see Sections 8.12 and 8.13 and other standard references (14–16). When detailed geometrics are not necessary—in master planning, for example—the following apron areas are suggested for various aircraft classes:

Aircraft	Self Maneuvering space (m^2)	Power In/Push Out (m^2)
Super jumbo (e.g., A380)	13,800	8,640
Jumbo (e.g., Boeing 747)	8,720	5,450
Smaller wide bodied (e.g,. Boeing 767)	4,000	3,500
Two-engine narrow body (e.g., Boeing 737)	3,000	2,178

Source: M. Makariou and Associates.



1. Distance required for nose-in parking position
2. Distance required for parallel parking position
3. ICAO minimum wing-tip clearance

Figure 10.20 Comparison of terminal frontage required for parking a Boeing 777 in nose-in (power in–push out) and parallel (power in/power out) configurations. (Courtesy of Halcrow Airports Group.)

In determining apron dimensions, it is customary to predict the aircraft mix for the peak design hour. There must be enough gates to accommodate the number of aircraft expected and at least as many gates capable of parking the longest aircraft as there are expected aircraft in this category in the design hour. If gates are permanently assigned to individual airlines, the requirement for maximum-sized gates is larger than if there is a nondesignated system of gate assignment. Pavement markings on the apron furnish guidance to maneuvering aircraft. A yellow guideline traces out the track to be followed by the nosewheel of the largest aircraft that can use the gate position. Since this is the critical vehicle, smaller aircraft can follow the pavement marking while maintaining adequate clearance from other parked aircraft and buildings.

10.16 APRON FACILITIES AND REQUIREMENTS

The apron serves two functions: for parking airplanes and for performing servicing and minor maintenance work. The dimensions and strength of the apron are determined by the first function. The facilities supplied on the apron and their location are set by the servicing function. The principal services to be supplied are:

- Aircraft fueling facilities
- Electrical supply
- Aircraft grounding facilities
- Apron roadways

Fueling Facilities

There are three methods by which aircraft are refueled: from an apron hydrant system, from fuel pits, and by mobile fuel trucks.

In the hydrant system, pipes beneath the apron are connected to a central fuel storage. Flush-mounted hydrant valves are provided at the gate positions. The aircraft is refueled using small mobile hydrant dispensers, each equipped with a pump filter, an air eliminator, and a meter. Fuel can be rapidly pumped into the parked airplane by attaching the dispenser to the closest hydrant valve.

A variation on the hydrant system is the fueling pit, which is similarly connected to a central fuel storage. But since each pit is fitted with hose, reel, filter, and air eliminator, there is no need for mobile dispensers on the apron. However, the fuel pits must be much larger than hydrant boxes, as well as more substantial, to withstand rolling apron wheel loads. Additionally, there is an inevitable redundancy of refueling equipment, which is avoided by the hydrant valve system.

At most small airports, the conventional system of refueling is by fueling trucks, which carry their own pumps, reels, meters, filters, and air eliminators. These trucks, carrying very large fuel loads (up to 8000 U.S. gal), are specially designed for operation on the apron. They are low-slung vehicles with very high axle loadings and thus are unsuitable in most countries for operation on highways.

Opinions on the best system of refueling are sharply divided. Apron operators have conflicting views on the relative suitability of mobile and fixed systems. The disadvantages of using fueling trucks are obvious. Very large aircraft, such as the Boeing 747, can require four large tankers for a complete fuel load. At a large airport, the apron traffic generated by fuel trucks alone can be unacceptably high and a potential source of accidents. Moreover, aircraft may be delayed if fuel trucks are not available because of insufficient supply or industrial strike action. Consequently, many of the new major airports in the United States have installed hydrant systems.

In the past, however, hydrant systems have been found to lack flexibility in adapting to new airlines. With the introduction of wide-bodied large aircraft, for example, it became apparent that hydrant valves located for smaller aircraft were unsuitably positioned for the new aircraft. Where gates were not exclusively used by one airline but must accommodate a number of airlines and a range or aircraft, hydrant positions could present large operational problems. The IATA recommends modular apron design, which permits acceptance of both conventional and wide-bodied aircraft (4). Therefore, many European airport operators still use fueling trucks extensively.

Electrical Supply

Electricity must be supplied to the aircraft during the period that its engines are shut off, to run lighting and other equipment, and, frequently, to start the engines. Supply can be arranged either by flush-mounted supply points from subapron conduits, sufficiently separated from any fuel hydrant valves, or by mobile units. In the United States, power usually comes from apron supply points. This arrangement may be less successful where the range of aircraft types to be accommodated is very wide because requirements for voltages, and even for alternating or direct current, may be different.

Grounding Facilities

Grounding facilities must be supplied to prevent fire hazard on the apron. Aircraft undergoing high-speed refueling are especially likely to generate high static charges, which could cause explosion and fire in the presence of volatile aviation fuels.

Airside Roadways

Airside roadways are necessary to permit the servicing, cleaning, and refueling of aircraft. As the size of aprons increases, the number of potential conflicts between surface apron vehicles becomes very large, requiring careful layout of airside surface routes to ensure reasonable safety for personnel walking on the apron. If passenger access to aircraft is permitted across the apron, the layout becomes even more critical

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11

Air Cargo Facilities

11.1 IMPORTANCE OF AIR CARGO

During the 1970s and the 1980s, the cargo sector of air transport underwent fast technological change and remarkable growth development in the following 30 years. Modern airports often require designs that accommodate both cargo and passenger operations, providing desirable proximity on the airside while separating passenger landside automobile and bus traffic from cargo-related heavy truck and commercial vehicle traffic. Air cargo is a strong component of air transport that tends to be concentrated at cargo hubs, rather than being equally spread across the airport network. Until the deep recession that started in 2008, air cargo had been generally regarded as a major contributor of profit to the airlines. During periods of recession, cargo revenues and cargo traffic are found to contract disproportionately in comparison with passenger revenues and traffic. However, passenger airlines which also concentrate on carrying cargo claim that cargo operations are competitively profitable even when fully allocated costs are considered but especially profitable on a marginal-cost basis.

Since 1970, cargo operations and traffic have been influenced by a number of factors:

1. The freight industry itself underwent a conversion to the use of unitized loads (containerization).
2. Many firms integrated their production and transport functions using the newly developing tools of physical distribution management (PDM).
3. Highly efficient, low-cost, just-in-time (JIT) techniques were adopted into manufacturing, wholesale, and retail businesses.
4. There was a rapid and widespread introduction and adoption of wide-bodied aircraft capable of accepting large unit loads.

Although the overall air cargo industry is generally considered to have settled into a period of more stable growth, it still presents an image of rapid change and flux, and at individual airports demand variations can be dramatic. Consequently, the design of air cargo terminals is susceptible to rapid modification of parameters due to demand and technological changes. Design flexibility, therefore, is generally felt to be imperative. An industry forecast is shown in Figure 11.1.

11.2 FUNCTIONS OF CARGO TERMINAL

In many ways, the functions performed by the cargo terminal are very similar to those that take place in the passenger terminal, even though the aspects of the two areas

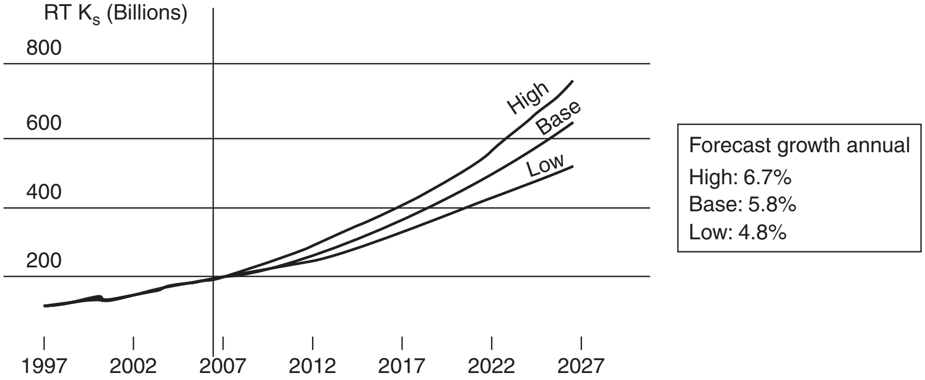


Figure 11.1 World air freight forecast (1).

are strikingly different. The cargo terminal serves four principal functions: *conversion, sorting, storage*, and *facilitation and documentation.*

In *conversion*, the size of a load is changed by combining a number of small loads into a larger unit, such as a pallet or container, which can be more easily handled airside. A conversion also almost certainly takes place in flow patterns. The landside flow is characterized by the continual arrivals or departures of small loads, which may form either the entire load or part of the load of a truck. These loads are batched into individual aircraft loads.

The *sorting* function occurs as the terminal accepts loads consisting of cargo bound for a number of different destinations, combines them, and forms aircraft loads for individual destinations.

Storage is necessary to permit load assembly by conversion and sorting, since flow rates and patterns on the landside and airside are quite dissimilar.

Finally, *facilitation and documentation* are conveniently carried out at the cargo terminal, where frequently a physical transfer takes place between the surface and air carriers and such governmental controls as customs are normally performed. The efficient operation of a large, modern cargo terminal is vitally dependent on modern documentation procedures. The application of electronic computer data processing techniques to a large cargo terminal is described in Section 11.7.

11.3 FACTORS AFFECTING SIZE AND FORM OF CARGO TERMINAL

Although most airports are capable of handling air freight in some capacity, the size and form of the cargo terminal facilities vary substantially. The degree of sophistication provided depends on the following factors:

Mix and flow characteristics of the cargo
Characteristics of the surface and air vehicles
Materials handling, documentation, and communication techniques
Degree of mechanization

Mix and Flow Characteristics of Cargo

Air cargo can arrive at the terminal in two forms: as a large number of small consignments that require sorting, storing, and batching before transfer to the aircraft or as containerized large unit loads, requiring far less handling at the cargo terminal itself. The mix of large and small consignments has strong design implications. Now, almost all air freight arrives at the freight terminal already in unit loads, some shipments arriving as prepack air freight containers.

Some of the early major cargo terminals of the 1960s were designed to mechanize and automate the handling of numerous small consignments. However, starting in the late 1960s, there was a rapid move toward containerization. By 2010, more than 98% of all air freight was containerized in a variety of standard air cargo containers. It seems unlikely that bulk or loose cargo which is manually loaded will entirely disappear. There are many airports with short runways incapable of accepting the large aircraft required for containerized freight.

Intermodal containers, suitable for conventional road transport, have not made significant penetration into the air freight market; the tare weight of these containers is usually too great to make their usage economic.

Automation and mechanization in the freight terminal have been introduced successfully with the development of transfer vehicles (TVs) and elevated transfer vehicles (ETVs). TVs move freight on one level, while ETVs move containers both horizontally and vertically into storage racks. Modern ETV systems can produce very efficient utilization of terminal floor area by the use of multilevel container storage and can also dramatically decrease expensive container damage that inevitably results from handling with mobile units such as forklift trucks. Figure 11.2 shows a modern ETV system in place.

In addition to the mix, the planner must consider the total volume and peaking characteristics of the flow that can occur. The total annual volume of cargo moved is the determinant of revenues, which will influence strongly the level of investment that can be made in facilities. Peak figures, however, influence the design of the various system elements that must accommodate anticipated traffic flows. Unlike the passenger

Figure 11.2 Modern ETV system. (Courtesy of ICM Airport Technics.)

terminal, the airside and landside peaks of a freight terminal do not necessarily coincide. Airside peaks are closely related to the schedules of aircraft, particularly passenger aircraft, which carry the majority of air freight. Landside peaks are related to the practices and working hours of shippers and receivers. The storage areas within the freight terminal provide the balancing effect between airside and landside peaking. Figures 11.3(a), (b), and (c) plot examples of the peaking of cargo flows on an annual, daily, and hourly basis.

It is very important to be aware that each terminal will have its own characteristic peaking graphs. Variations will depend on seasonal variations of commodities carried and industrial output. Daily variations relate to shipper and receiver preferences on clearing and receiving material. Hourly variations of throughput depend on the sector of the freight operation considered (landside reception, landside dispatch, airside outbound, airside inbound). These, in turn, are affected by shipper and receiver operating preferences, location of airport relative to eastbound and westbound traffic flows, aircraft schedules, noise curfews in situ and at destination airports, and the proportion of freight carried on passenger aircraft.

Although the designer can expect to spread the peaks by the use of terminal storage, prudence must be exerted in the choice of storage time. If system throughput is too slow and cargo is delayed too long in storage, the premium level of service supplied by the air cargo mode is vulnerable to severe deterioration, certainly in the short haul. Typically, dwell time will be less than one day outbound and less than four days inbound. It may, on the other hand, be necessary for the operator to set storage charges at a punitive level beyond 48 or 72 hr to encourage rapid clearance of inbound freight, preventing the use of the facility as the receiver's warehouse.

Cargo is normally categorized into three groups: *emergency demand*, where speed is essential to the usefulness of the commodity (e.g., blood plasma); *regular demand*, where the commodity has limited commercial life (e.g., flowers or newspapers); and *planned demand*, where air freight is selected after analysis of distribution costs. Each may require different treatment within the terminal.

Aircraft and Surface Vehicle Characteristics

The size and type of anticipated aircraft will affect the materials handling procedures adopted in the cargo terminal; the various aircraft types have differing requirements of standard containers, low containers, igloos, and pallets. Aircraft of the same family have strikingly different requirements when used as all-freight or mixed-payload craft. The most successful terminal design is that which is best adapted to the mix of aircraft it receives over its working life. This implies a level of optimal fit and a degree of flexibility to adapt to technological change in the short and long term.

Degree of Mechanization

Potentially heavy capitalization of air freight terminals seems like a highly attractive way to decrease labor costs, which can form a major portion of terminal handling costs. However, high capitalization and automation are economic only at relatively high load factors (i.e., when throughput is sustained at a reasonably high level) and the traffic mix conforms to expectations. If either of these conditions is not met, overmechanization can lead to poor economic performances and unsatisfactory operation. Equally

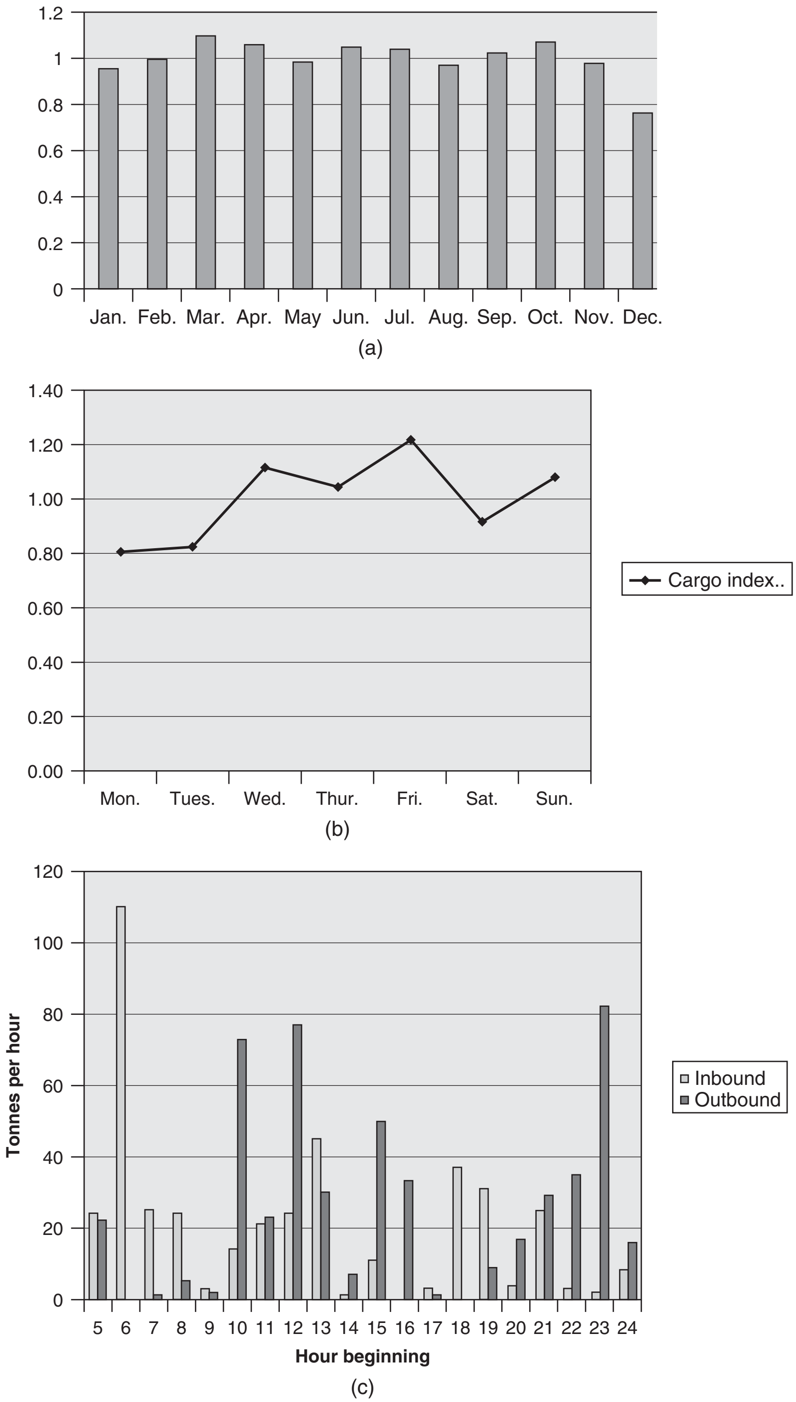


Figure 11.3 Peaking characteristics of air freight flows: (a) annual peaking characteristics: (b) daily peaking characteristics: (c) hourly peaking characteristics. (Courtesy of FRAPORT, Frankfort Airport.)

necessary is the ability to eliminate labor on the scale anticipated, which requires both union cooperation and a precise knowledge of what is feasible in the area of industrial relations.

Three basically different types of freight terminals can be identified: low technology, medium technology, and high technology.

Low Technology. These are often, but not necessarily, low-volume terminals. Where manpower is both available and cheap, freight is moved by manhandling over extensive layouts of roller beds and transfer tables. Such terminals are also desirable when there are problems with the supply of hard currency to purchase equipment and spares and where there is a lack of skilled labor for equipment maintenance.

Medium Technology. Containers are moved by mobile lifting and transfer equipment, for example, forklift trucks. The vast majority of existing medium- and high-volume facilities still operate with this level of sophistication.

High Technology. Involving TVs and ETVs, these facilities use single- or multiple-level storage of containers, which are moved within the terminal mainly by the railed transfer vehicles. ETV operations produce high throughputs per square meter, with minimum container damage and minimum labor requirements. There is, however, a very high level of capitalization required.

Figures 11.4 and 11.5 show two modern freight terminals that have extensive container storage areas served by ETVs.

Materials Handling, Documentation, and Communications

Although automated cargo handling had a disappointing early history due to an undue concentration on uncontainerized bulk cargo, modern terminals successfully combine automated and mechanized techniques for the handling, retrieval, and storage of less than container shipments.

Automation of documentation through the application of electronic computer data processing (ECDP) has proved remarkably successful since the development and widespread use of microcomputers. Since cargo cannot move without its documentation, the use of on-line computers to pinpoint the progress of a shipment through the complex cargo handling process has offered substantial benefits to shippers, forwarders, carriers, and customs. Shipment tracking and the movement of documentation by electronic means have become greatly simplified over the last 30 years (2).

11.4 FLOW THROUGH AIRPORT CARGO TERMINAL

Figure 11.6 illustrates how import and export flows of cargo move through the airport terminal (3). Incoming cargo for export passes through the reception area, is moved through the documentation area (where it undergoes count checks, weighing, measuring, and labeling), and either is passed directly into a preflight assembly lineup or is placed in a short-term storage area, from which is eventually transfers into preflight assembly. Next, the cargo is moved into the flight assembly area, the nature of which depends on whether the freight is to be carried by a passenger–cargo or by all-cargo aircraft.

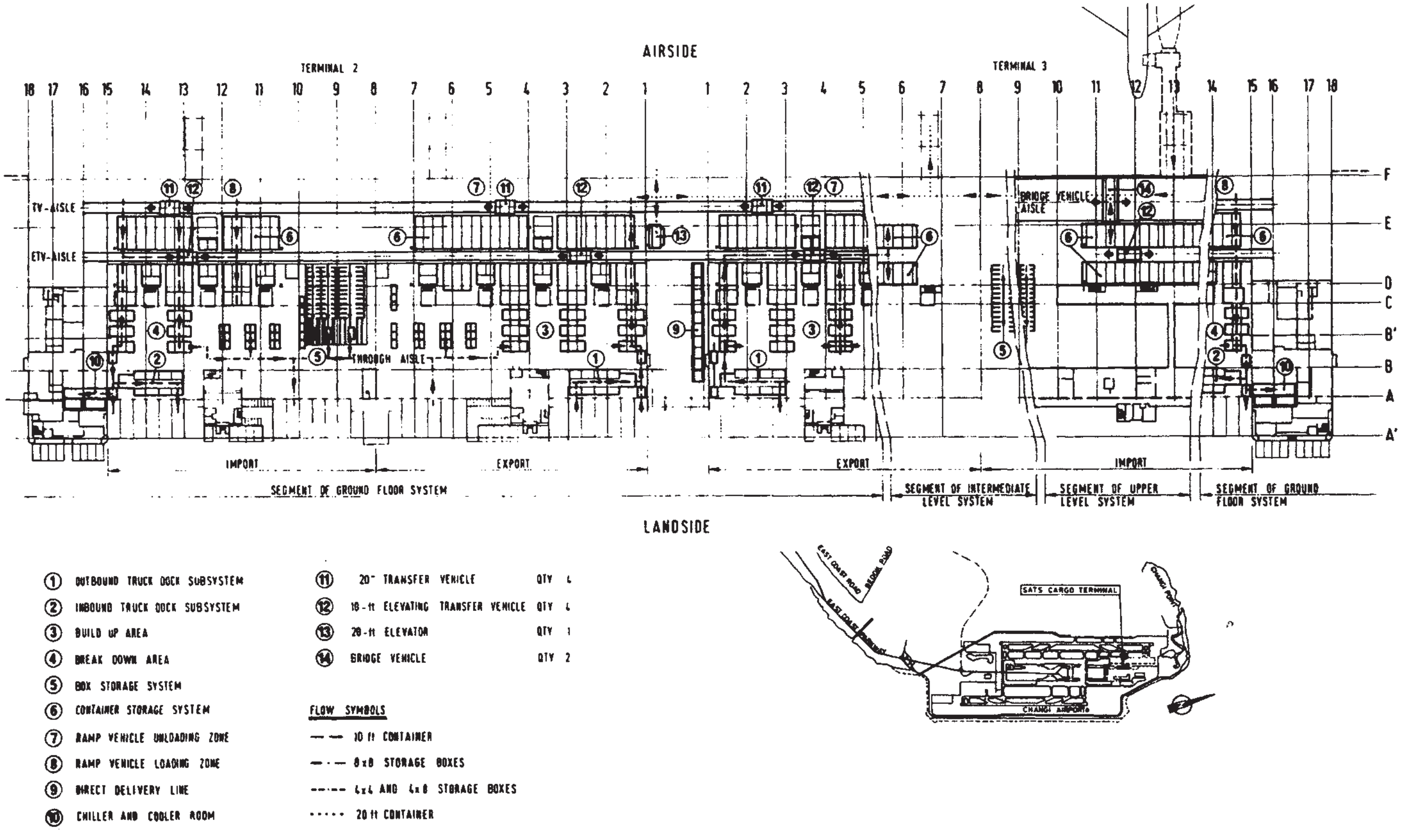


Figure 11.4 SATS air cargo terminal, Changi International Airport, Singapore. (Courtesy of Agusta Westland.)

Figure 11.5 Lufthansa cargo center Frankfurt. (Courtesy of Lufthansa German Airlines.)

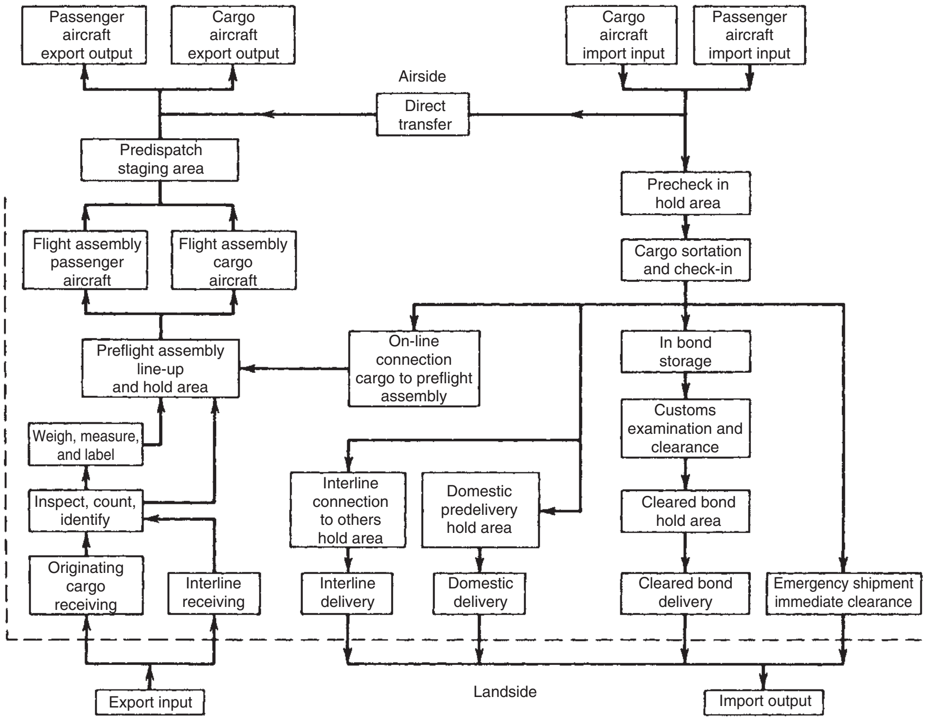


Figure 11.6 Flow through cargo terminal (3).

From the flight assembly area, flight loads of freight move to the final staging area and then across the cargo or passenger apron to their outbound flight.

Incoming or import cargo can similarly arrive on mixed-payload or all-cargo flights. On arrival, it passes through an initial holding area before sorting and check-in. After sorting, cargo requiring customs clearance goes to in-bond storage, from there by way of customs clearance to a cleared bond storage area, and eventually to the receiver via import delivery. Domestic cargo, on the other hand, requires no customs clearance and proceeds directly from the check-in area to a predelivery hold area, where it remains pending arrangement of delivery.

Figure 11.6 also points up the need for interline transfers to other carriers and across the apron movements for intracarrier transfers between flights. The latter type of movement is extremely important in some European cargo gate airports, where transfer freight can account for a large proportion of the incoming traffic. At some hub airports, more than half of all incoming freight is transferred to outgoing flights; the terminal designs reflect these specialized needs.

11.5 PALLETS, CONTAINERS, IGLOOS, AND OTHER UNITIZED SYSTEMS

Until the early 1960s, air cargo was generally loose loaded into combination and freight aircraft. As freight traffic increased, paralleling growth in aircraft size, economic operation could be maintained only by limiting the turn-around time of freight-carrying aircraft on the apron. Rapid loading and unloading can now be achieved by unitizing loads. Various unit-load devices are currently in use: containers, pallets, and igloos (4).

Containers

Rigid-bodied *containers* are used to protect air cargo and to ease the handling of numerous small, individual consignments of air cargo. Wide-bodied freight aircraft, such as the Boeing 747F, are capable of taking modular International Organization for Standardization (ISO) 8 × 8-ft containers in 10-, 20-, and 40-ft lengths. These containers are not intermodal, however, since tare weight considerations limit their structural strength; ISO aircraft containers can be rolled but not lifted. Special low-height containers are built for the lower holds of wide-bodied freight and combination aircraft. Figure 11.7 shows the container loading arrangements. Typically, lower hold containers are contoured and have maximum dimensions of 64 × 92 in. and 64 × 186 in.

Pallets

Pallets are devices providing a rigid base, suitable for forklifting, on which cargo can be loaded. The load is held in place by nets, and the complete load can be manhandled, forklifted, or moved mechanically as a unit [see Figures 11.8(a) and (b)]. For narrow-bodied aircraft, standard pallet dimensions are 88 × 125 × 64 in. for all-freight craft and 88 × 108 × 64 in. where there is necessity to move through the cargo hold for access to passenger areas. Wide-bodied craft also can accept pallets to 96 × 125 × 64 in. within the upper hold. In the lower hold, 96 × 125 × 64-in. pallets can be accommodated as well as the pallets normally taken by narrow-bodied craft.

Igloos

Igloos are rigid-bodied pallets used primarily to prevent damage to cargo or to the inside of the aircraft, where passenger cabins are converted to freight usage. A *structual igloo* is a fully enclosed shell constructed integrally with a pallet to ensure that cargo conforms to required contours. The shell and the pallet of the igloo form a single structural unit. A *nonstructural igloo* is a bottomless shell that fits over the pallet to give a shape to loaded cargo. The shell is used in conjunction with the pallet but adds no structural strength.

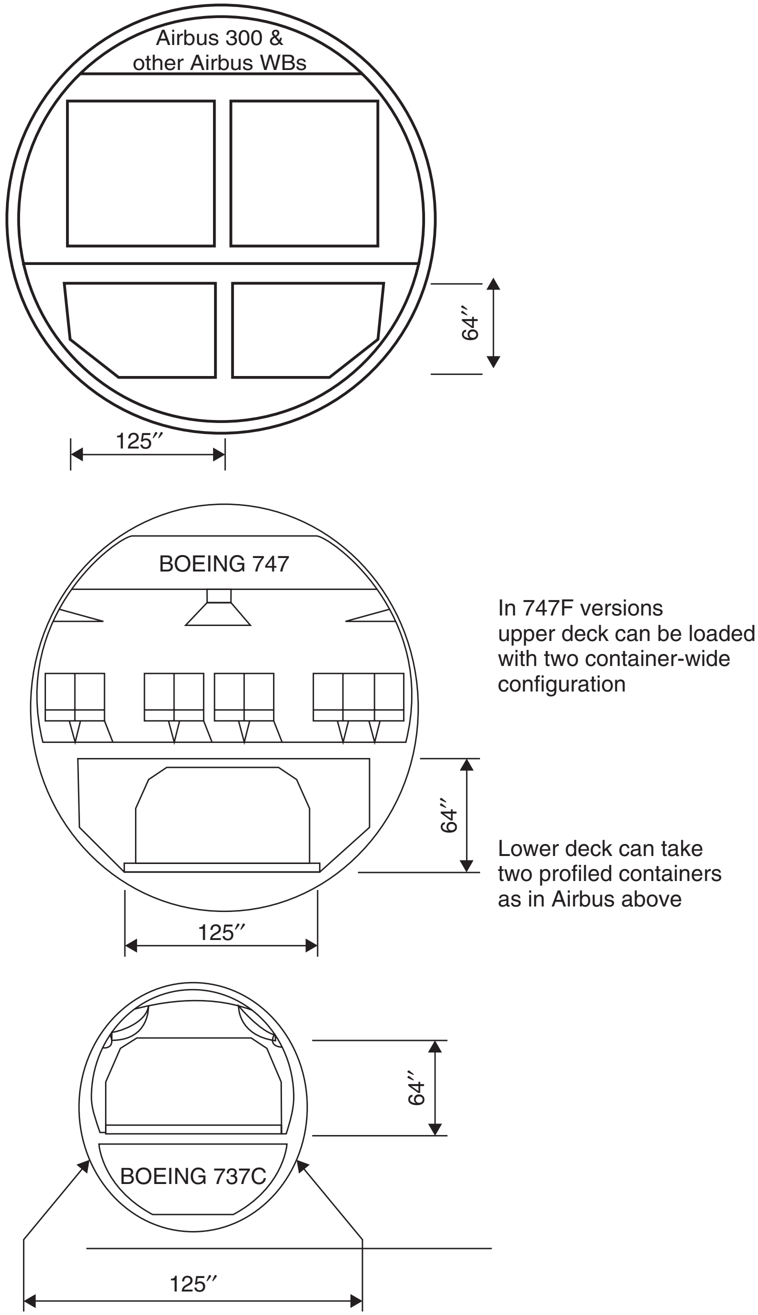


Figure 11.7 Container arrangements in wide- and narrow-bodied aircraft.

(a)

Figure 11.8(a) Palletized unit being transferred to a wide bodied combi aircraft.

(b)

Figure 11.8(b) Palletized unit being transferred to a cargo train.

IATA Unit-Load Devices (ULDs)

The IATA system of classifying ULDs is shown in part in Figure 11.9. Each container type is identified by a multialphanumeric code, in which each alphanumeric identifies a particular category:

Alphanumeric position 1 includes:

A. Certified container
B.D Noncertified container

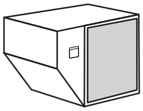
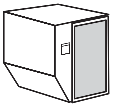
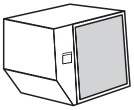
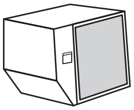
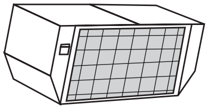
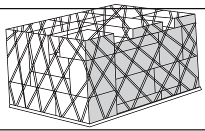
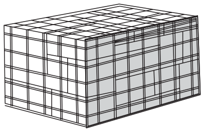
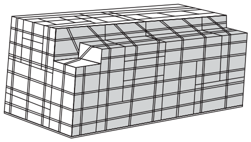
IATA Container Classification, (USA Code)		Cubic Capacity	External Dimensions (cm)	Maximum Gross Weight Capacity
AKC (LD1)	 Contoured half width	169 ft^3, 4.8 m^3,	234 × 152 × 162 92 × 60.4 × 64	1588 kg/3500 lb
DPE (LD2)	 Contoured half width	120 ft^3, 3.4 m^3	155 × 152 × 162 61.5 × 60.4 × 64	1225 kg/2700 lb
AKE (LD3)	 Contoured half width	153 ft^3, 4.3 m^3	200 × 152 × 162 79 × 60.4 × 64	1588 kg/3500 lb
RKN (LD-3 refrigerating container or LD-3 reefer)	 Contoured half width	95 ft^3, 2.7 m^3	200 × 152 × 163 79 × 60.4 × 64	1338 kg/2950 lb
ALF (LD6)		310 ft^3, 8.8 m^3	407 × 153 × 163 160 × 60.4 × 64	3170 kg/6985 lb
PIP (LD7) flat pallet with net		360 ft^3, 10.2 m^3,	318 × 224 × 163 125 × 88 × 64	4626 kg/10198 lb
AAP (LD9)		320 ft^3, 9.0 m^3,	318 × 224 × 163 122 × 88 × 64	6000 kg/13227 lb main deck 4625 kg/10194 lb Lower deck
PGA (M-6)	 Flat pallet with net	1195 ft^3, 33 m^3,	600 × 242 × 242 236 × 95.3 × 95.3	11340 kg/25,000 lb

Figure 11.9 Air freight unit-load devices. (*Source*: Adapted from Reference 4.)

P. Aircraft pallet
R. Thermal certified aircraft container
U. Nonstructural igloo container

Alphanumeric position 2: base dimensions

Alphanumeric position 3: contour, fork lift capability, and aircraft compatibility restraint system

11.6 FREIGHT-CARRYING AIRCRAFT

Freight can be carried by aircraft in a number of ways: in the lower compartments of narrow-bodied aircraft, in the lower holds of wide-bodied aircraft, or in all-freight aircraft; containerized freight can be carried on the upper decks of narrow-bodied aircraft and on both upper and lower decks of wide-bodied aircraft. The lower holds of narrow-bodied aircraft and the main decks of commuter-sized aircraft can be used for loose freight. Because of the handling costs without containerization, loose freight is often uneconomic and is used only where there are constraints on the size of the aircraft that can use the airport or where the freight flows are too low to warrant containerization.

Until the early 1970s, there was an increasing trend to use all-freight aircraft, including passenger aircraft that could be converted rapidly from passenger use—the so-called QC (quick-change) models. The introduction of wide-bodied aircraft in the early 1970s altered this pattern in some market areas (4). The cargo hold capacity of the 747 is very large (6190 ft^3), even when compared with the all-freight narrow bodies. The rapid introduction of wide-bodied aircraft over many long-distance routes made spare cargo capacity available. This space could utilize reasonably large containers, thus affording to the carrier the advantages of modern materials handling in the terminal. The use of the wide-bodied belly compartments for freight therefore is economic, and this option has been extensively chosen. By the year 2010, almost half of all freight was still carried in the bellies of passenger aircraft.

All-freight aircraft continue to be in use by a number of specialized air freight airlines. Some passenger airlines, such as Lufthansa, Cathay Pacific, and JAL, also operate all-cargo aircraft, but it is likely that in the foreseeable future a large proportion of air freight will continue to be carried on passenger aircraft. In this context, the “combination” configuration for passenger aircraft is increasingly popular in some parts of the world. In this configuration, part of the main passenger deck, usually of a narrow-bodied aircraft, is used to carry freight containers. Table 11.1 shows the freight capacities of a selection of freight and combination aircraft.

11.7 DOCUMENTATION AND CONTROL

Since cargo cannot move without documentation, the rapid movement of large volumes of cargo requires the rapid processing of large amounts of documentation with a high level of accuracy and reliability. In addition, the documentation must be available to a large number of persons who are separated in the system, both spatially and temporally. Figure 11.10 outlines in simplified form a typical documentation and flow control system for the export side of an air cargo terminal.

Table 11.1 Freight Capacities of Typical Freight and Combination Aircraft

Aircraft model	Maximum freight payload (kg)	Maximum freight payload (lb)
B-747-200F	115,503	254,640
B-747-400F	122,685	270,474
B-777F	103,000	226,800
B-757-200PF	22,680	50,000
B-747-200C	107,551	237,110
A300-400F		
A300-600F	48,067	105,970
A310F	34,901	76,943
B-737-200QC	15,590	34,371
B-737-200C	15,874	34,996
DC-10 (Series 30F)	70,624	155,700
MD-11F	55,656	122,700
MD-DC10 30F	80,282	176,991

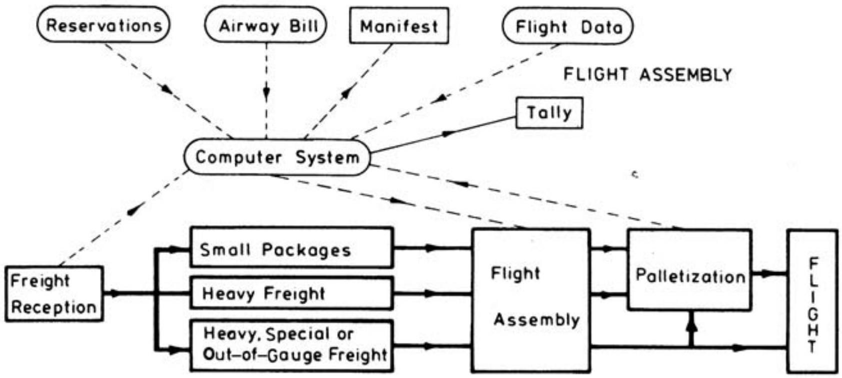


Figure 11.10 Idealized cargo data processing system for an export operation.

Space is reserved on a particular flight on a space-available basis. Scheduled to arrive at cargo reception in time for the outgoing flight, the freight is weighed and checked against an electronic airway bill. The loading manifests are produced in conjunction with the flight tally and individual consignment information.

The freight is sorted at reception into small, heavy, and special or out-of-gauge freight and may be temporarily stored in the terminal bin racks. Cargo is moved into the flight assembly area in accordance with the flight tally. Pallets and containers are packed after the freight has passed through the live lanes in the flight assembly area; data on pallet contents are computerized for tracking until final delivery.

In 2005 the IATA started vigorously to promote e-freight, with the aim of very significant reduction of the amount of documentation required. In the middle part of the decade, each cargo shipment could involve up to 30 paper documents; by 2010 these were reduced to 10, the remainder being converted to standardized electronic messages. The move to fully electronic data was generally supported by customs authorities and resulted in faster, cheaper, and more reliable air freight transport.

11.8 APRON CARGO HANDLING

Unlike the passenger apron, where the passenger payload can move itself, the cargo apron must be highly mechanized to carry out the transfer of the freight from the terminal to the aircraft. Since short aircraft turnaround time is essential to profitability, apron cargo handling systems should be capable of rapid unloading and loading while achieving high payload densities. The type of equipment used depends on the exact nature of the cargo. Care is to be exercised in using aircraft manufacturers' estimates of minimum unloading and loading times for aircraft. In many cases, these times can be achieved under ideal conditions only, which are not likely to occur on a working cargo apron.

Palletized units comprise the most common cargo form. After the pallets have been assembled and sent to the preflight holding area in the terminal, they must be transferred across the apron. This is frequently achieved by transferring the pallets to roller mat dollies, which are pulled to the aircraft by a ramp tractor. The pallets are rolled onto a cargo lift that raises them to the level of the aircraft floor, onto which they are rolled. Movement along the aircraft can be by simple manhandling or, in the case of large aircraft, by powered floor roller mats. At some airports, ramp transporters are used instead of tractor and dolly systems. This is usually when the distance from the cargo terminal to the aircraft is considerable and a higher transfer speed is required.

Some freight terminals have nose-dock loading systems. These allow nose-loading aircraft to load directly from the ETV system through the open nose of the aircraft, which is parked immediately adjacent to the system. Figure 11.11 shows a terminal arrangement in which two aircraft can be loaded simultaneously at nose-dock parking positions while other aircraft at noncontact stands are loaded from tractor and dolly trains. Nose loading can also be carried out at noncontact stands using conventional

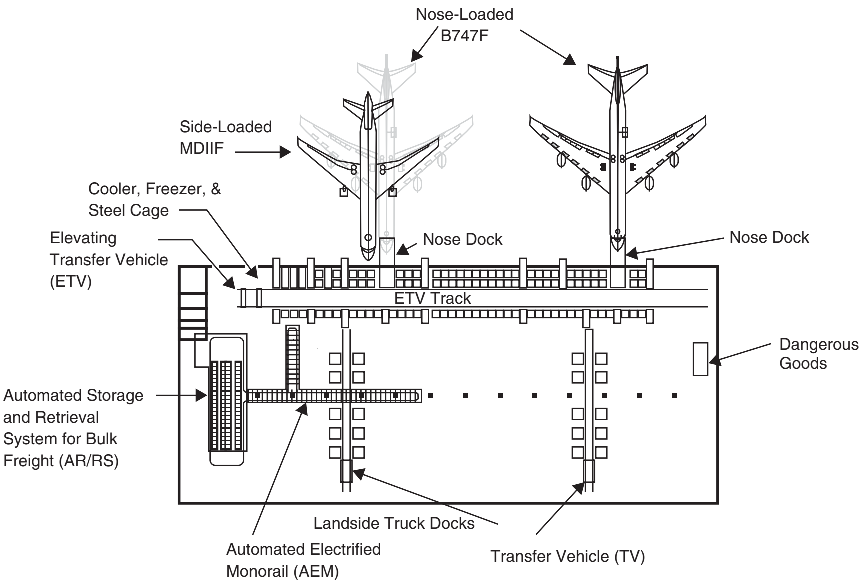


Figure 11.11 Terminal with two nose-dock systems. (Courtesy of Korean Air Terminal, JFK.)

Figure 11.12 Unloading U.S. Aid cargo from B747 in Utapao, Thailand. (Courtesy of Bombardier Aerospace Commercial Aircraft)

devices, such as are shown in Figure 11.12. Nose loading requires considerable space at the head of the stand to accommodate the loaders.

Loose cargo can be transferred across the apron by dollies and loaded by either cargo lift or small cargo conveyors, which handle light loads. Out-of-gauge and non-palletized cargo can be handled in this way, but this can become uneconomic in large volumes due to poor aircraft turnaround time at the cargo apron. Freight rates for unpalletized and uncontainerized cargo are frequently very high

The choice of apron handling devices depends chiefly on the air vehicle to be loaded. Combination wide-bodied aircraft and narrow-bodied cargo aircraft can take igloos, pallets, and low containers. They are normally side loaded using cargo lifts and transporters or dollies. Wide-bodied all-cargo craft can take large 8×8-ft containers in modular lengths up to 40 ft. The largest can be loaded by nose docks; others are side door loaded. Narrow-bodied combination aircraft, which have low cargo capacity, must be loose loaded in the belly holds.

11.9 ELEMENTS TO BE CONSIDERED IN DESIGN OF AIR FREIGHT TERMINALS

1. Market demand forecast
   Domestic/international volumes
   Inbound/outbound transfer volumes
   Cargo/mail
   Bypass traffic (freight already containerized in flight-ready containers)
   Nature and amount of material requiring special handling
      Heavy/oversized freight

  - Perishables
  - Very great urgency material
  - High value
  - Dangerous goods
  - Livestock
- Seasonal, daily, and hourly fluctuations of flows

2. Forecast of aircraft fleet and flight activity
- Fleet mix
- Type of operation: all cargo, combination, belly loads only
- Frequency of operations
- Number of aircraft to be handled simultaneously on the apron
- Air vehicle type: 747-200F, 747-400F, 777F, 757-200, A300-400F, A300-600F, A310F, 737-200, DC10-30F, MD11F, etc.

3. Main capacity-constrained elements of design
- Overall area
- Buildup positions
- Pallet and container storage area
- Bins
- Airside and landside doors

4. Cargo handling concept choice
- Low mechanization, high manpower
- Low manpower, mobile lifting, and loading equipment
- High mechanization with TVs and ETVs

5. Site selection factors
- Dimensions of terminal, apron, and landside access areas
- Layout of road access and degree of separation of commercial freight vehicles from passenger terminal traffic
- Proximity and ease of airside access to the passenger apron
- Layout and capacity of airside service roads
- Availability of utilities

6. Architectural decisions
- Main floor level
- Landside and airside dock levels
- Clear height (later installation of ETVs should be considered)
- Construction materials
- Expandability for future traffic growth
- Flexibility for changes of freight type and handling methods
- Floor pits for self-leveling buildup/breakdown areas

7. Other areas to be included
In all cases, the dimensions of the space allotted, as well as of the doors, must be suitable for the function of the area:

Maintenance and Support Facilities. For the maintenance and repair of ULDs and their handling devices. Space will include facilities for washing and welding, compressor and vehicle hoist.

Customs. Inspection areas, offices, toilets, secure storage areas.

Livestock: Storage areas, cages, feeding, watering, and cleaning facilities. Environmental control.

Dangerous Goods. Facilities dependent on nature of goods; secure storage.

Cold Room. Areas for high-value and fragile cargo, human remains, and radioactive material.

8. General design considerations
Security. Ease of general access into the freight terminal area, location of space for security personnel, use of closed circuit TV.

Health and Safety. Design to observe local and national industrial health and safety laws that govern workers and working conditions. Noise levels, operating procedures predicted by design and surface finishes.

Insurance. Sprinkler systems, smoke detectors, fire ratings of building materials.

Suitability of Building Materials. Material used must reflect the handling methods within the terminal. Potential damage should be minimized and its repair should be easy.

11.10 EXAMPLE OF DESIGN OF MIDDLE-TECHNOLOGY FREIGHT TERMINAL

Example 11.1 To design the layout and areal requirements for a freight terminal to meet the following annual demand profile:

	Total	Percent received at terminal already containerized and therefore bypassable
Domestic		
In (×1000 kg)	18,000	40
Out (×1000 kg)	18,000	20
Export (×1000 kg)	8,000	NIL
Import (×1000 kg)	16,000	NIL

Peak-month domestic: 10% annual domestic traffic

Peak-month import: 15% annual import traffic

Peak-month export: 12% annual export traffic

Peak-day traffic = 0.05 × peak-month traffic

Bypass peak-hour traffic = 30% peak-day traffic
Non-bypass peak-hour traffic = 25% peak-day traffic
Import peak-hour traffic = 20% peak-day traffic
Dwell times:

Domestic out and export: 1 1/2 days
Domestic in and import: 6 days

A. Assumptions

Extensive containerization:
Containers and loose bulk freight moved by mobile lifting equipment, for example, forklift trucks.
No fixed transfer vehicles (TVs and ETVs).

B. Design criteria

	Domestic and Export	Import
Throughput per unit floor area (kg/m^2/yr)	13,500–22,500 (use 13,500)	5,500
Landside truck loading and unloading doors (kg/door/hr)	2,500–4,500 (use 3,500)	1,800
Airside door capacity:		
Bypass pallets/door/hr	15	—
Processed pallets/door/hr	20	20
Average pallet/container weight (kg)	1,800	1,800
Average bin weight (kg)	225	225
Build-up/breakdown floor area (kg/building unit/hr)	2,000	1,800

C. Traffic structure

	Total (kg × 1000)	Bypass (kg × 1000)	Processed (kg × 1000)
Domestic			
In	18,000	7,200	10,800
Out	18,000	3,600	14,400
Subtotal	36,000	10,800	25,200
Export	12,000	—	12,000
Import	16.000	—	16,000
Total	64,000	10,800	53,200
	Bypass	Nonbypass	Import
Peak month	1,080	3,480	2,400
Peak-day traffic = 0.05 × peak month	54	174	120
Peak-hour traffic	16.2	43.5	24

**Source*: R. Brawner, formerly Flying Tiger Airlines.

D. Facility requirements

1. Bypass facilities

$$\text{Pallets processed} = \frac{\text{peak-hour flow (kg)}}{1800\ \text{kg/pallet}} = \frac{16{,}200}{1800}$$

$$= 9\ \text{pallets/peak-hour or 1 by pass door}$$

2. Domestic and export nonbypass facilities

a. $$\text{Gross m}^2\ \text{required} = \frac{\text{Annual Volume}}{13{,}500\ \text{kg/m}^2\text{/yr}} = \frac{33.2\ \text{mill. kg}}{13{,}500} = 2459\ \text{m}^2$$

b. $$\text{Landside truck doors} = \frac{\text{peak-hour flow (kg)}}{3500\ \text{kg/door/hr}} = \frac{43{,}500\ \text{kg}}{3500}$$

$$= 12.4,\ \text{say 13 truck doors}$$

c. $$\text{Build-up/breakdown positions} = \frac{\text{peak-hour flow}}{2000} = \frac{43{,}500}{2000}$$

$$= 21.75,\ \text{say 22 positions}$$

d. Assuming 70% of peak-day flow loaded on to pallets and staged,

$$\text{Pallet staging racks} = \frac{\text{peak-day flow} \times 70\%}{1800\ \text{kg/pallet}} = \frac{174{,}000 \times 0.7}{1800}$$

$$= 68\ \text{racks}$$

e. Assuming 30% of peak-day flow to go to bin storage,

$$\text{Bins} = \frac{\text{peak-day flow} \times 30\%}{225\ \text{kg/bin}} = \frac{174{,}000 \times .30}{225} = 232\ \text{bins}$$

f. Airside doors:

$$\frac{\text{peak-hour flow}}{\text{Pallet wt} \times \text{pallets/door/hr}} = \frac{43{,}500}{1800 \times 20} = 1.2 \text{(not critical)}$$

3. Import Facilities

a. $$\text{Gross m}^2\ \text{required} = \frac{\text{annual volume}}{5500} = \frac{16\ \text{mill. kg}}{5500} = 2910\ \text{m}^2$$

b. $$\text{Landside truck doors} = \frac{\text{peak-hour flow (kg)}}{1800\ \text{kg/door/hr}} = \frac{24{,}000}{1800}$$

$$= 13.3,\ \text{say 14 truck doors}$$

c. $$\text{Build - up/breakdown positions} = \frac{\text{peak-hour flow}}{1800\ \text{kg/hr}} = \frac{24{,}000}{1800} = 13.3, \text{say 14 positions}$$

d. Pallet staging racks (75% of flow into pallet racks): assume pallet positions required in-bond and customs cleared. This will give a duplication factor between 1 and 2. Allow 1.5.

$$\text{Pallet staging racks} = \frac{\text{peak-day flow (kg)} \times 1.5 \times 0.75}{1800\ \text{kg/pallet}}$$
$$= \frac{120{,}000 \times 1.5 \times 0.75}{1800} = 75\ \text{racks}$$

e. Bins: Assume 25% of flow into bin racks with duplication of in-bond and custom cleared racks. This will give a duplication factor of between 1 and 2. In this case, allow 2.

$$\text{Bins} = \frac{\text{peak-day flow (kg)} \times 2 \times 0.25}{225}$$
$$= \frac{120{,}000 \times 2 \times 0.25}{225}$$
$$= 267$$
$$= 267\ \text{bins}$$

f. Airside doors: not critical.

E. Summary design requirements

1. Overall requirements

	Domestic/Export	Import	Total
a. Total area (m^2)	2459	2910	5666
b. Landside truck doors	13	14	27
c. Build-up/breakdown positions	22	14	36
d. Pallet staging rack	68	75	143
e. Bins	232	267	499
f. Bypass doors	1	—	1

2. Space Breakdown

Facility	Area (m^2)
a. Cold room	20
b. Strong room	20

Facility	Area (m^2)
c. Radioactive	20
d. Human remains	20
e. Toilets	20
f. Changing rooms/staff facilities	40
g. Fragile cage	50
h. Reception and dispatch/office	450 $\simeq$ 8% total
i. Customs clearance	450
j. ULD breakdown and buildup	900
k. Maintenance	300 $\simeq$ 5% total
l. Circulation and storage	3460
	5700

A typical layout of the above areas is shown in Figure 11.13.

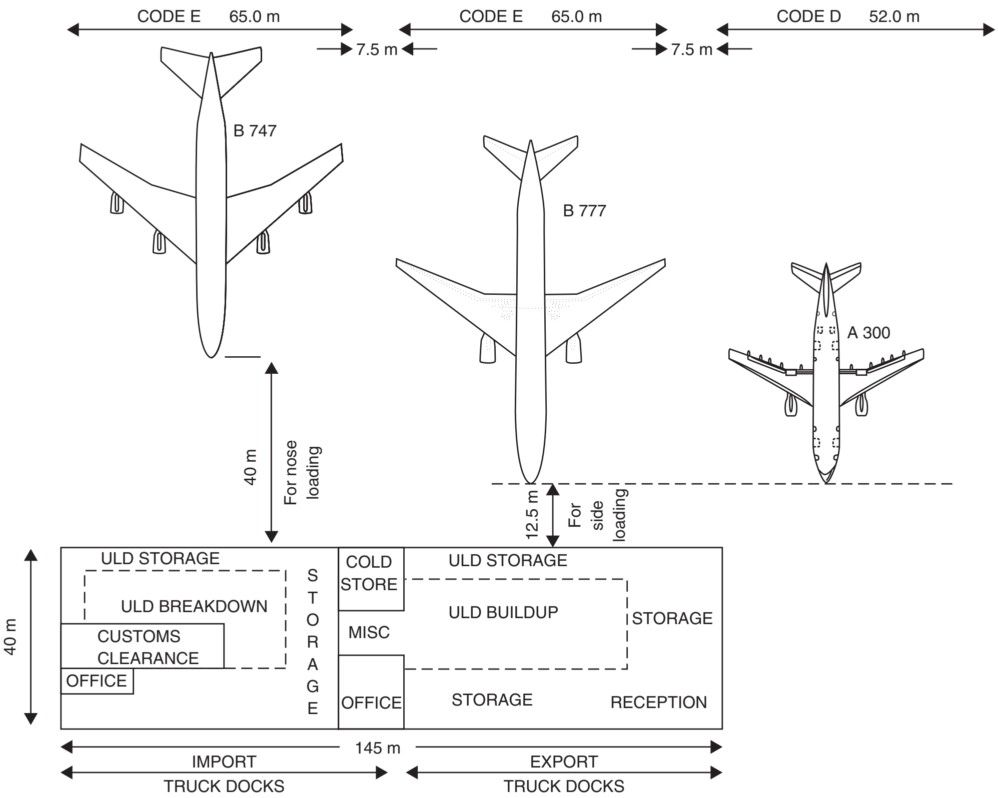


Figure 11.13 Example layout of cargo apron and terminal.

F. Comparison with industrywide standards

For master planning, less rigorous methods of cargo terminal sizing are often used, with the overall area being computed from annual tonnage throughout. Formerly, the IATA recommended using 1.0 ft^2 per ton per year for the outbound area and 1.1 ft^2 per ton per year for the inbound area calculations. General experience indicates now that those figures which approximate to 0.1 m^2 per tonne per year may underestimate the space requirements.

The IATA now recommends the following space planning ratios if no site-specific data are available:

Low automation (mostly manual)	5 tonnes/m^2/yr
Automated (average)	10 tonnes/m^2/yr
Highly automated	17 tonnes/m^2/yr

Using the flows in the preceding example, the average IATA space requirement criterion of 10 tonnes/m^2/year would give the following:

Outbound: 26,000 tonnes = 28,636 tons	Requires 2600
Inbound: 34,000 tonnes = 37,478 tons	Requires 3400
Total area required:	6000 m^2

11.11 DESIGN OF HIGHLY MECHANIZED CARGO TERMINAL WITH CONTAINER STACKS AND ETV*

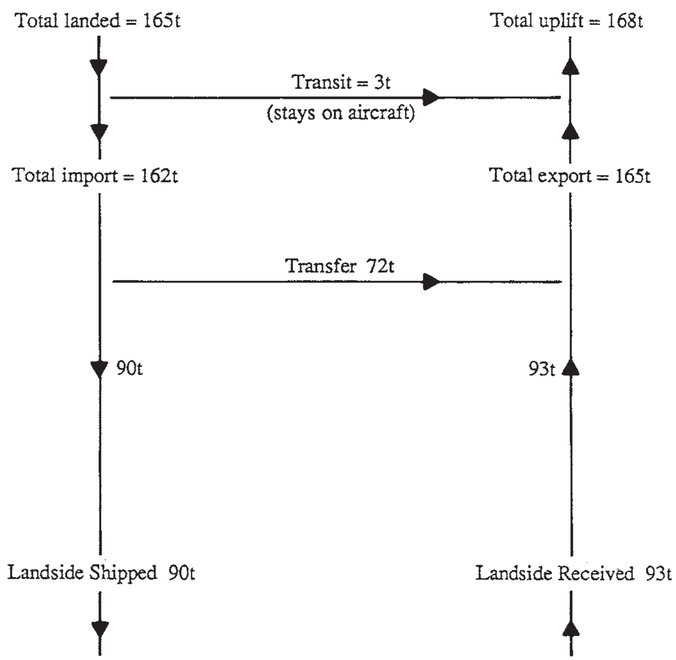
Example 11.2 Figures in the calculations on pp. 480–485 are rounded for simplicity.

Assumptions and Data

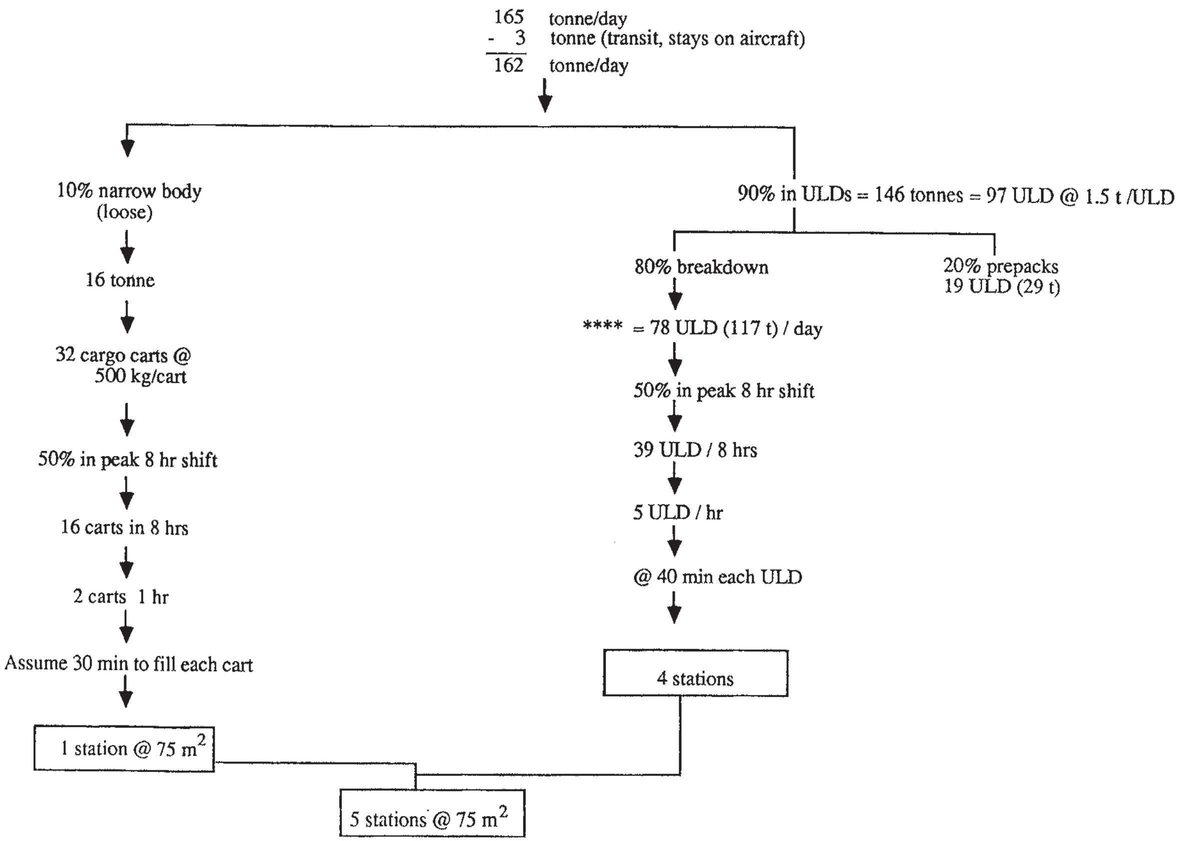
- Annual tonnage uplifted and landed
- Peak-day/annual tonnage ratio = 0.00333
- % transit on peak day = 0.9%
- % transfer on peak day = 21.62%
- Buildup–breakdown areas: 75 m^2 per station
- Truck docks: 4 m wide with 15 m deep inside building and 4 m wide outside building on ramp
- ULD dimensions: 2.5 × 3 m; capacity 1.5 tonnes
- Cargo carts for loose cargo, capacity 500 kg. Each cart requires 30 min to fill or unload
- ULD breakdown 40 min, buildup 45 min
- Inbound ULDs 20% prepacks
- Outbound ULDs 20% prepacks

*Example by kind permission of Hans Marx, Airport Consultant, Frankfurt.

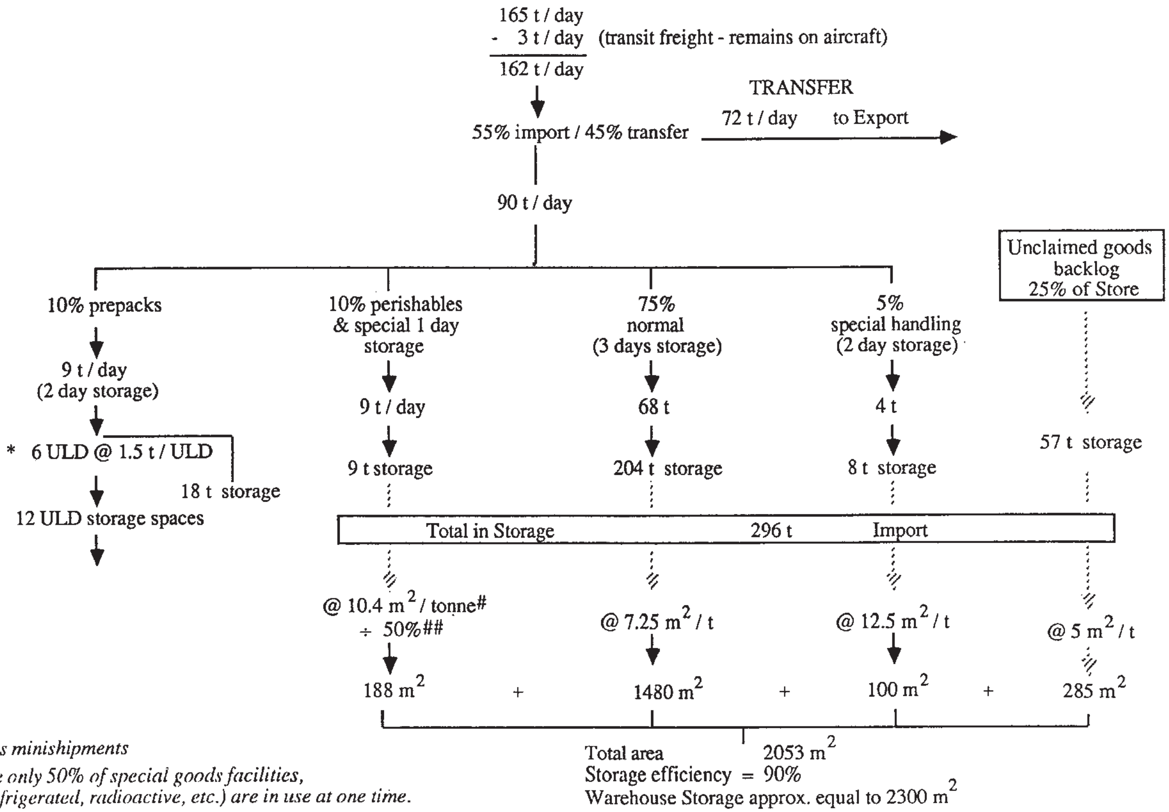
- Inbound storage times:
  Prepacks, two days
  Perishables and special freight, one day
  Normal, three days
  Special handling, two days
- Storage efficiency 90%
- Storage areas
  Perishables and special freight 10.4 m^2/tonne
  Normal 7.25 m^2/tonne
  Special handling 12.5 m^2/tonne
  Unclaimed goods 5 m^2/tonne
- Only 50% of special goods facilities (e.g., refrigerated, radioactive, etc.) are in use at one time
- Export storage: 1 day at 12.5 m^2/tonne
- No physical separation of inbound or outbound freight for customs purposes
- Allowance of 50% of space for empty containers and pallet stacks
- Floor area per ULD with three-level storage = 5.6 m^2
- Average delivery or pick up per truck landside = 1 tonne
- Average landside dwell time per truck = 30 min



INBOUND BREAKDOWN



IMPORT WAREHOUSE

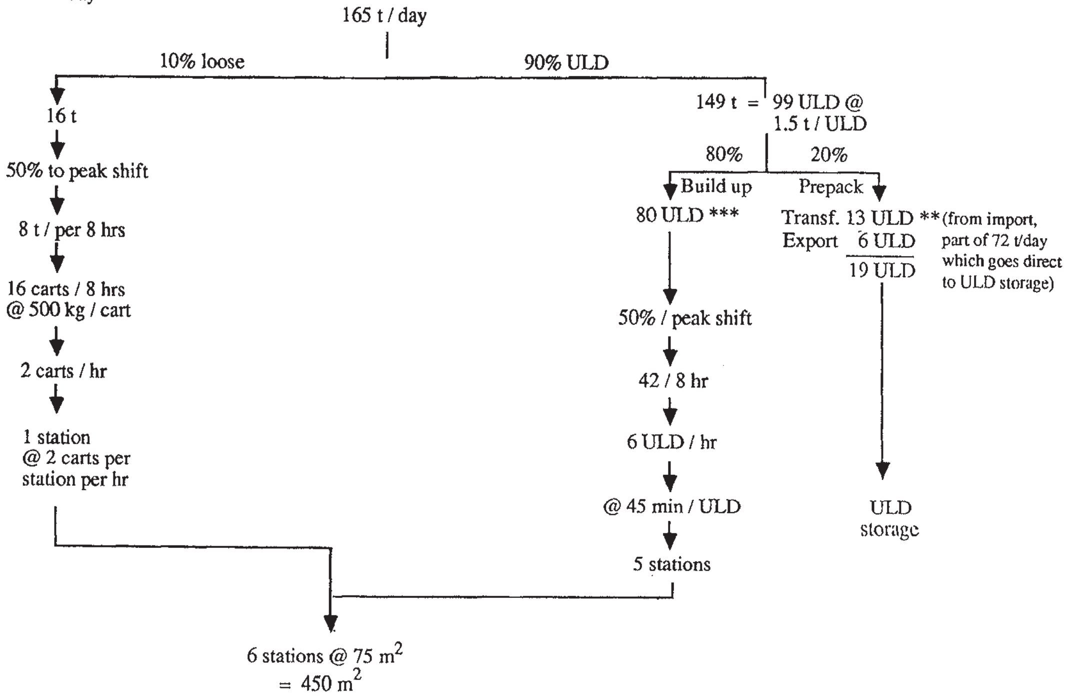


\# *same as minishipments*

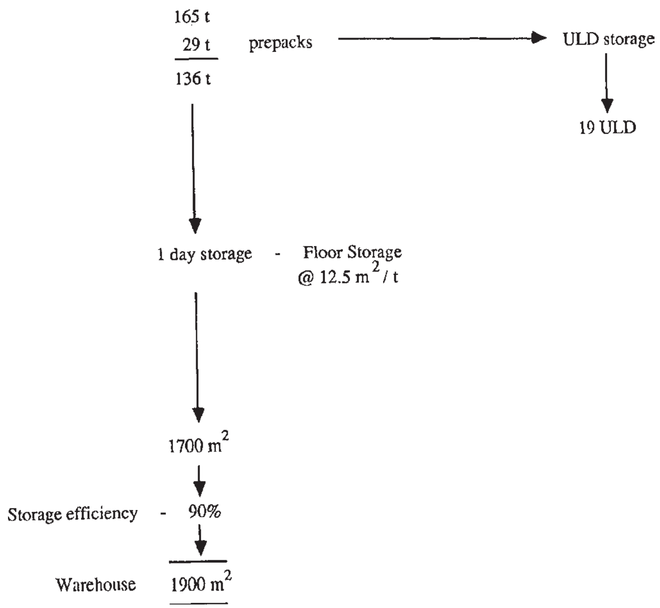
\#\# *assume only 50% of special goods facilities, (e.g. refrigerated, radioactive, etc.) are in use at one time.*

EXPORT BUILD-UP

Landside received	93 t / day
Transfer	72 t / day
Total export	165 t / day



EXPORT WAREHOUSE



ULD System Sizing

Assume no physical separation of inbound or outbound

*	(see p. 482)	6 = Import prepacks (2 days storage)	=	12
**	(see p. 482)	13 = Transfer prepacks (1 day storage)	=	13
***	(see p. 483)	80 × 50% of daily buildup	=	40
****	(see p. 481)	78 × 50% of daily inbound awaiting breakdown	=	39
		Total full ULD		104
		Empty containers/pallet stacks at 50%		52
		Total storage spaces		156
		At 3 high system 5.6 m^2/ULD	=	873.6 = (say) 900 m^2

LANDSIDE CAPACITY

Import

Daily flow	=	90 tonnes
Hourly flow	=	15 tonnes
At 1 tonne/truck (including small goods)	=	15 trucks/hr
At $\frac{1}{2}$ hr/truck	=	8 truck docks
Width = 8 × 4 m	=	32 m
Area = 32 m × 15 m approx.	=	500 m^2
Import inspection (+100%)	=	500 m^2
		1000 m^2

Export

Daily flow	=	93 tonnes
Landside requirements about the same as for import	=	500 m^2

SUMMARY OF SPACE DEMAND

Import					
	Breakdown		375 m^2		
	Storage		2300 m^2		
	Landside				
		Customs	500 m^2		
		Truck area	500 m^2		
			3675 m^2		3675 m
Export					
	Landside		500 m^2		
	Storage		1900 m^2		
	Buildup		375 m^2		
			2775 m^2		2775 m
ULD System			1000 m^2		1000 m
SUBTOTAL					7450 m
Aisles, equipment, storage, repair, etc. (add 50%)			3725 m^2	approx.	4000 m
Airside staging area			2000 m^2		2000 m
Offices/staff facilities			500 m^2		500 m
				approx.	14,000 m
Truck ramp at 7 m					1500 m
					15,500 m

Overall check of requirements:

$$\frac{100{,}000 \text{ tonnes/yr}}{15{,}500 \text{ m}^2} = 6.45 \text{ tonnes/m}^2\text{/yr (cf. Table 11.2)}$$

11.12 MAIL AND EXPRESS PARCELS FACILITIES

One area of air freight which grew very rapidly from a modest start was the transport of express or small-parcel freight, usually guaranteed for overnight delivery domestically and everywhere on a rapid door-to-door basis. Sometimes the operators are called freight integrators, in whose operation the freight is handled on the integrator's aircraft,

Table 11.2 Typical Throughputs at Various Air Cargo Terminals

	Annual tonnes/m^2
Frankfurt (Lufthansa)	8
Frankfurt (FAG)	6.5–7
London Heathrow (British Airways)	8
London Gatwick (British Airways)	12–15
Katmandu	3
São Paulo (Viracopas)	3
General industry figure	6

processed through the company's freight warehouses and both picked up and delivered by the integrator's trucks. Such freight is often processed through a centralized hub, for example, the Federal Express hubs at Memphis and the DHL hub at Nottingham, and is carried by dedicated all-cargo aircraft fleets. Characteristically, this freight differs from conventional freight in that movement is overnight, causing peak terminal flows at night through the specialized terminals. In that there is virtually no terminal dwell time, express freight flows in some ways resemble passenger flows where inbound and outbound freight cause linked peaks on both the airside and landside. There is little available literature on the design of such facilities.

The IATA recommends the following space provision for express cargo facility design (3):

Regional hub/gateway	7 tonnes/m^2/yr
Reliever hub	5 tonnes/m^2/yr

The following, taken from a recent European design, are useful parameters for estimating the size of express freight facilities:

Throughput per meters square of gross warehouse floor space: 8 tonnes/m^2/yr

Average shipment weight: 15 kg

Average annual number of shipments per square meter of gross warehouse space: 533

Average dwell time per outbound shipment: 1.1 hr

Average dwell time of inbound shipment: 1.35 hr

Average dwell time of shipment in transit: 55 min

At one smaller European hub, approximately 30% of all movements are transit, 77% of transit operations are made across the apron, and 23% of transit are made through the freight warehouse. Because the balance of transit and OD movements will vary greatly from one integrator to another, depending on the nature of the integrator's operation, the design of the hubs will also vary greatly.

Figures 11.14(a) and (b) indicate the differences between a small spoke express terminal and a major transfer hub. At the spoke facility, the overall dwell time is small and the integration of landside delivery is critical to the operation. At the major hub facility, the emphasis is on the rapid transfer of freight both through the terminal building and across the apron. Figure 11.15 is a sketch of the massive FedEx terminal at Memphis, which indicates the small landside requirement of a major express hub operation as contrasted with the major airside requirements, especially the aircraft aprons.

11.13 CONCLUSION

The planning of a high-volume special-purpose air cargo terminals is a complex procedure. Because such facilities are often owned and operated by individual airlines, the design of these terminals may well be carried out internally within the airline organization. The most accurate design procedure is likely to be derived from a simulation

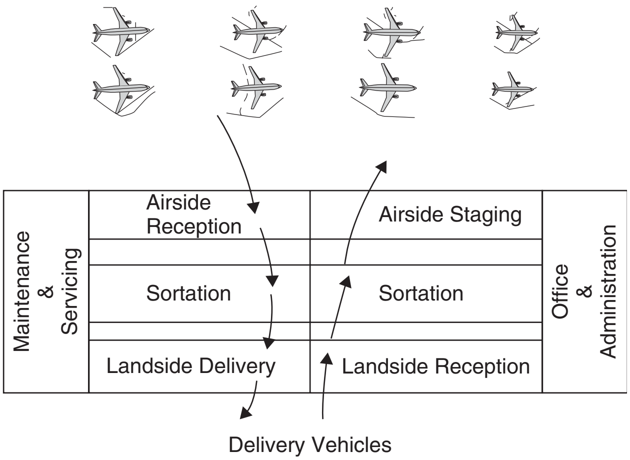


Figure 11.14(a) Schematic of flows in spoke terminal of integrated freight carrier.

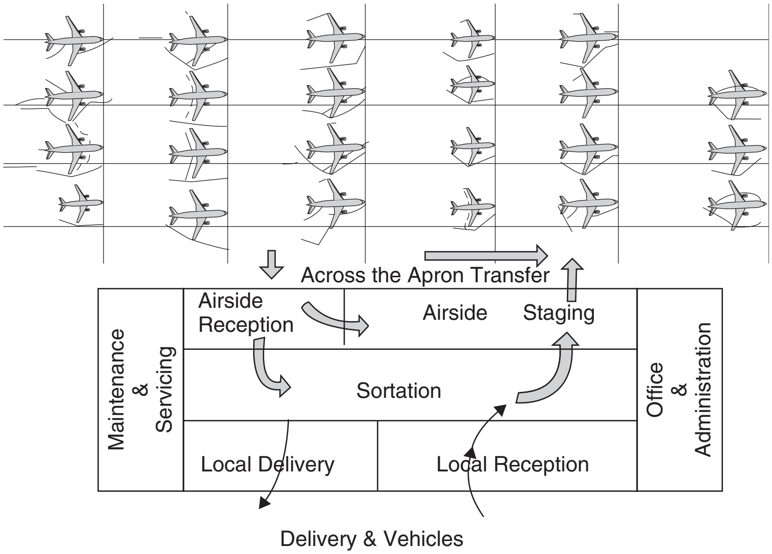


Figure 11.14(b) Schematic of flows in integrated freight carrier's hub terminal.

based on knowledge of the mix and flow characteristics of the cargo, the predicted aircraft fleet mix, handling practice, and surface transport characteristics. Such studies, even with modern simulation software, are expensive and are liable to lead to significantly incorrect conclusions when unexpected changes occur in technology or handling procedures. Less precise methods, such as those shown in Sections 11.10 and 11.11, are therefore likely to be sufficiently accurate for planning purposes. For the foreseeable future, design of cargo facilities should provide a large degree of flexibility, recognizing that the industry is still in development and is, therefore, still subject to large changes in both traffic and technology (2).

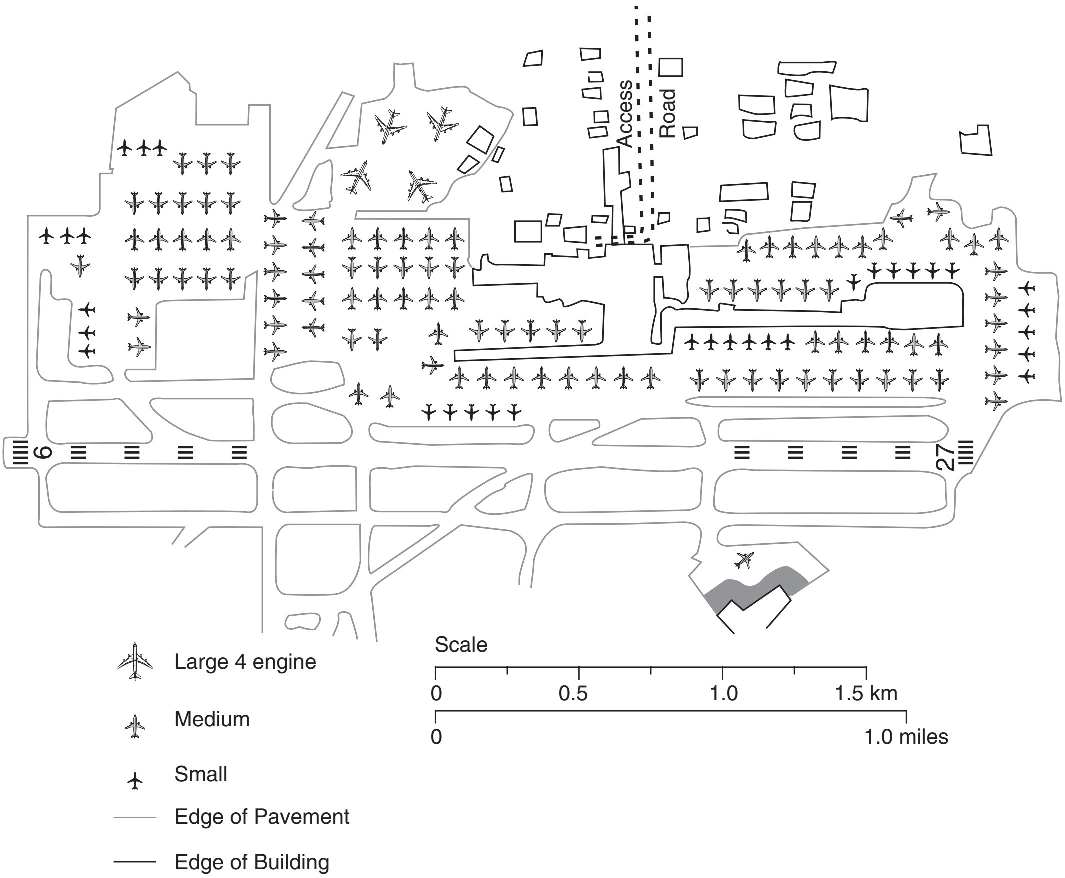


Figure 11.15 Sketch of layout of FedEx hub terminal at Memphis International Airport, 2010.

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2. Ashford, N. J., H. M. Stanton, and C.E. Moore, *Airport Operations*, New York: McGraw Hill, 1996.
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12

Airport Drainage and Pavement Design

This chapter discusses two subjects of fundamental importance to the airport engineer: airport drainage and structural pavement design.

Airport Drainage

12.1 INTRODUCTION

A well-designed airport drainage system is a prime requisite for operational safety and efficiency as well as pavement durability. Inadequate drainage facilities may result in costly damage due to flooding as well as constituting a source of serious hazards to air traffic. Furthermore, inadequate drainage systems may cause unsightly erosion of slopes and saturated and weakened pavement foundations.

In many respects, the design of an airport drainage system is similar to street and highway drainage design. However, airports often have special drainage problems and challenges. Characterized by vast expanses of relatively flat areas and a critical need for the prompt removal of surface and subsurface water, airports usually require an integrated drainage system. Such a system must provide for the removal of surface water from runways, taxiways, aprons, automobile parking lots, and access roads. The runoff then must be removed from the airport by means of surface ditches, inlets, and an underground storm drainage system. Some of the more important drainage design principles and procedures, described in the following sections, are as follows:

1. Estimation of runoff
2. Design of a basic system for collection and disposal of runoff
3. Provision for adequate subsurface drainage

For a more complete treatment of this important subject, the reader is referred to the FAA advisory circular *Surface Drainage Design* (1) and the other references listed at the end of this chapter.

12.2 ESTIMATION OF RUNOFF

A number of formulas and analytical procedures have been developed for the estimation of surface runoff. However, all the available estimation techniques are fraught with imprecision and require the judicious employment of engineering judgment. The method most commonly used for airport drainage design is the rational method. To introduce this technique, we describe briefly the factors that influence the magnitude of surface runoff.

Coefficient of Runoff

Only a part of the precipitation that falls on a watershed flows off as free water. Some of the precipitation evaporates, and some of it may be intercepted by vegetation. A portion of the precipitation may infiltrate the ground or fill small depressions or irregularities in the ground surface. Therefore, the storm runoff, for which airport drainage channels and structures must be designed, is the precipitation minus the various losses that occur.

These losses are strongly related to the various characteristics of the watershed, such as the slope, soil condition, vegetation, and land use. The designer should keep in mind that certain of these factors, especially vegetation and land use, are likely to change with time. It is especially important to consider possible effects of planned future airport development on the quantity of runoff from the airport area.

Most analytical procedures for estimating runoff involve the use of a coefficient of runoff or factor to account for the hydrologic nature of the drainage area. As used in the rational method, the coefficient of runoff is the ratio of the quantity of runoff to the total precipitation that falls on the drainage area. Table 12.1 gives recommended values of the runoff coefficient C for use in the rational formula. If the drainage area under consideration consists of several land use types, for which different runoff coefficients must be assigned, the runoff coefficient for the entire area should be a weighted average of the coefficients of the individual areas. For example, if a drainage area consists of 2 acres of concrete pavement having a runoff coefficient of 0.8 and 5 acres of impervious soil with turf with a coefficient of 0.4, the weighted average coefficient for the overall area is $[(2 \times 0.80 + (5 \times 0.4)] \div (2 + 5)$, or 0.51.

Table 12.1 Values of Factor *C*

Type of surface	Factor *C*
For all watertight roof surfaces	0.75–0.95
For asphalt runway pavements	0.80–0.95
For concrete runway pavements	0.70–0.90
For gravel or macadam pavements	0.35–0.70
For impervious soils (heavy)[a]	0.40–0.65
For impervious soils, with turf[a]	0.30–0.55
For slightly pervious soils[a]	0.15–0.40
For slightly pervious soils, with turf[a]	0.10–0.30
For moderately pervious soils[a]	0.05–0.20
For moderately pervious soils, with turf[a]	0–0.10

[a]For slopes from 1 to 2%.

Rainfall Intensity, Duration, and Frequency

Rainfall intensity is the rate at which rain falls, typically expressed in inches per hour. Because of the probabilistic nature of weather, the intensity of rainfall must be discussed in the context of its frequency and duration.

For many years, the National Weather Service (formerly U.S. Weather Bureau), the Department of Agriculture,* and other agencies have collected rainfall data in the United States. Based on these data, the National Weather Service has published a series of technical papers that contain rainfall frequency (isopluvial) maps and empirical relationships that are useful in airport drainage design. Technical Paper No. 40 (2) gives such data for the coterminous United States. Similar data can be obtained for Puerto Rico, the Virgin Islands, Hawaii, and Alaska. Local rainfall data may also be available from the National Weather Service, the City Engineer's Office, the State Department of Transportation, and possibly drainage districts or utility companies.

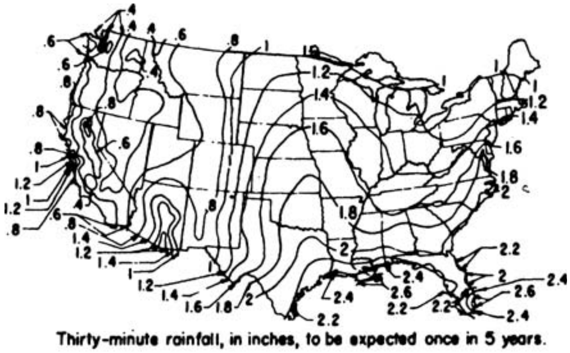
Procedures for the construction of rainfall intensity–duration curves have been published by the FAA (1). Suppose we want to construct a rainfall intensity–duration curve for a storm frequency of five years. By spotting the airport location on charts such as those of Figure 12.1, we can determine the amount of rainfall that can be expected once every five years for rainfalls lasting 30 min, 1 hr, and 2 hr. For example, Figure 12.1(a) indicates that a 30-min, 1.37-in. rainfall can be expected to occur in Chicago once every five years. Similarly, rainfalls of 1.73 and 2.10 in. would be expected with durations of 1 and 2 hr, respectively. To plot a rainfall intensity–duration curve in terms of inches per hour, these values must be expressed on a 1-hr basis; conversion is achieved by multiplying the scaled values by the ratio between 1 hr and the durations shown on the chart. Thus, for example, the rainfall intensities are as follows:

Duration (min)	Chart Value	Intensity (in./hr)
30	$1.37 \text{ in.} \times \frac{60}{30}$	$= 2.74$
60	$1.73 \text{ in.} \times \frac{60}{60}$	$= 1.73$
120	$2.10 \text{ in.} \times \frac{60}{120}$	$= 1.05$

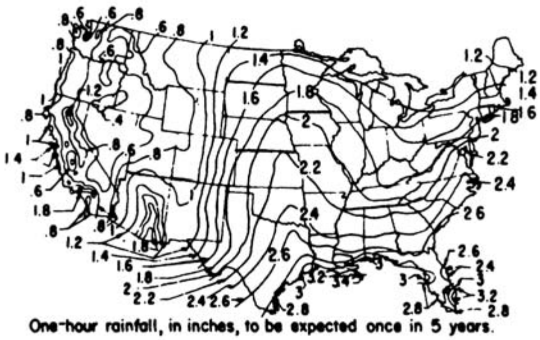
To obtain values for short-duration rainfalls, the following relationships between a 30-min rainfall and 5-, 10-, 15-min amounts may be used:

Duration (min)	Ratio
5	0.37
10	0.57
15	0.72

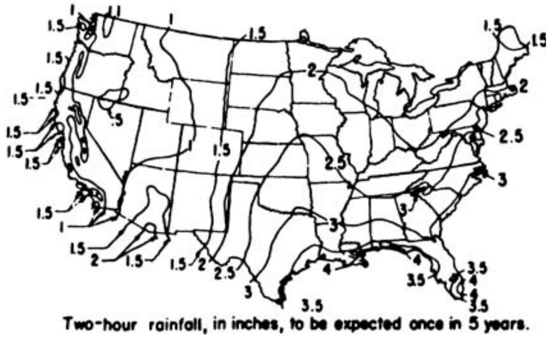
*The National Resources Conservation Service (NRCS) is an agency of the Department of Agriculture.



(a)



(b)



(c)

Figure 12.1 Rainfall frequency maps (2).

In the Chicago example, the 30-min rainfall of 1.37 in. would be multiplied by the ratios given, yielding rainfalls of:

0.51 in.	in 5 min
0.78 in.	in 10 min
0.99 in.	in 15 min

These values must be converted to inches per hour for curve-plotting purposes:

Duration (min)	Chart value	Intensity (in./hr)
5	$0.15 \text{ in.} \times \frac{60}{5}$	$= 6.12$
10	$0.78 \text{ in.} \times \frac{60}{10}$	$= 4.68$
15	$0.99 \text{ in.} \times \frac{60}{15}$	$= 3.96$

These six values may now be used to plot a 5-year rainfall intensity–duration curve (Figure 12.2). Similar curves for 2 years, 10 years, and other return periods may be plotted by referring to appropriate isopluvial maps published by the National Weather Service (2).

To use a tool like Figure 12.2, the designer must choose the right curve, which involves weighing the physical and social damages that might result from a flood of a given frequency against the additional costs of designing a drainage system to decrease the risk of such damages. As Figure 12.2 discloses, the choice of the 10-year curve instead of the 5-year curve would mean designing for a more severe storm but at a higher cost. On the other hand, the choice of a 2-year frequency would result in a less costly drainage system but would involve the risk of more frequent runoffs exceeding the capacity of the system.

A return period of 5 years is commonly used for the design of drainage systems at civil airports. However, the design should be checked to determine the consequences of less frequent but more severe storms.

As Figure 12.2 indicates, rainfall intensity decreases nonlinearly with increases in the rainfall duration.

Time of Concentration

In the design of airport drainage facilities, a rainfall duration equal to the *time of concentration* is chosen. The time of concentration is the maximum time runoff from any point in a drainage area can take to flow to the outlet. It consists of two components: the time of surface flow (sometimes referred to as the "inlet time" or time of overland flow) and the time of flow within the structural drainage system.

The surface flow time varies with land slope, type of surface, size and shape of the drainage area, and other characteristics of the watershed. Many empirical studies have been made relating the time of surface flow to the slope, dimensions, and other characteristics of a drainage area.

Figure 12.3 plots some values found using the following formula, recommended by the FAA (1):

$$T \approx \frac{1.8(1.1 - C)(D)^{1/2}}{(S)^{1/3}} \tag{12.1}$$

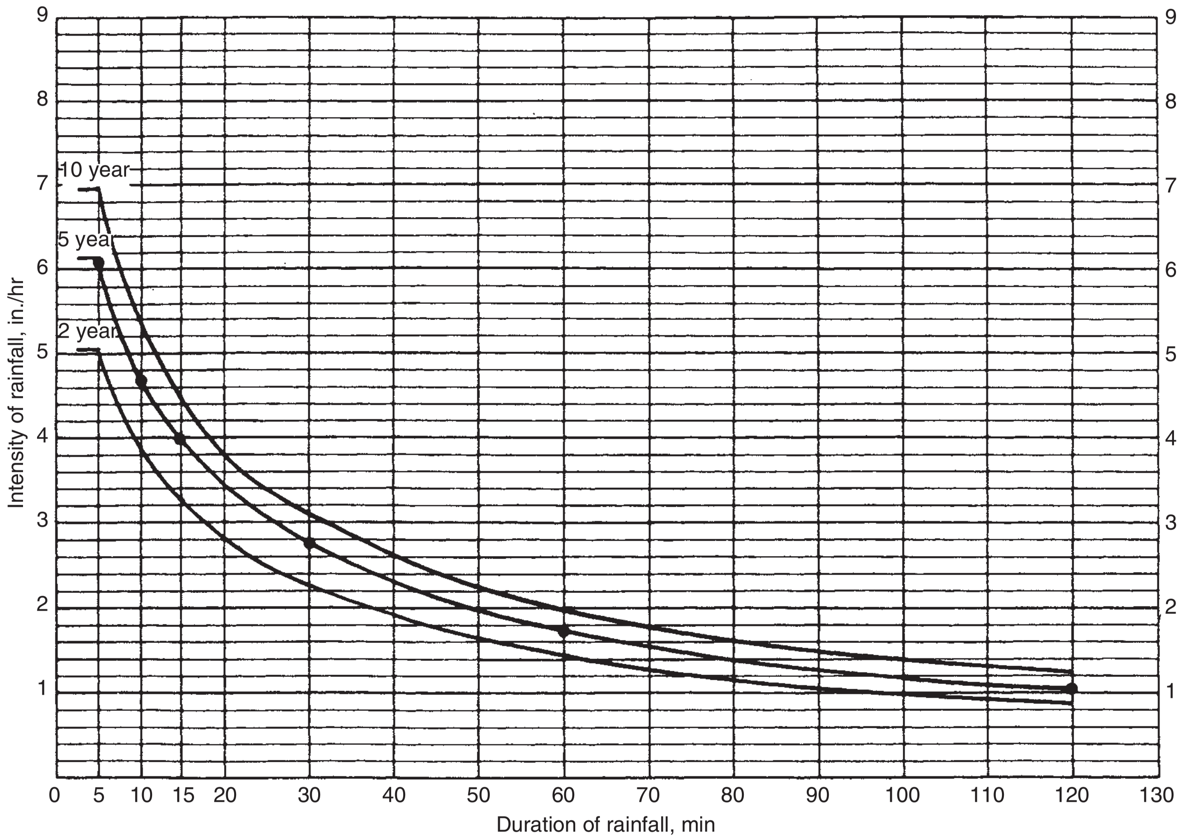


Figure 12.2 Intensity–duration curves for storms in vicinity of example site (1).

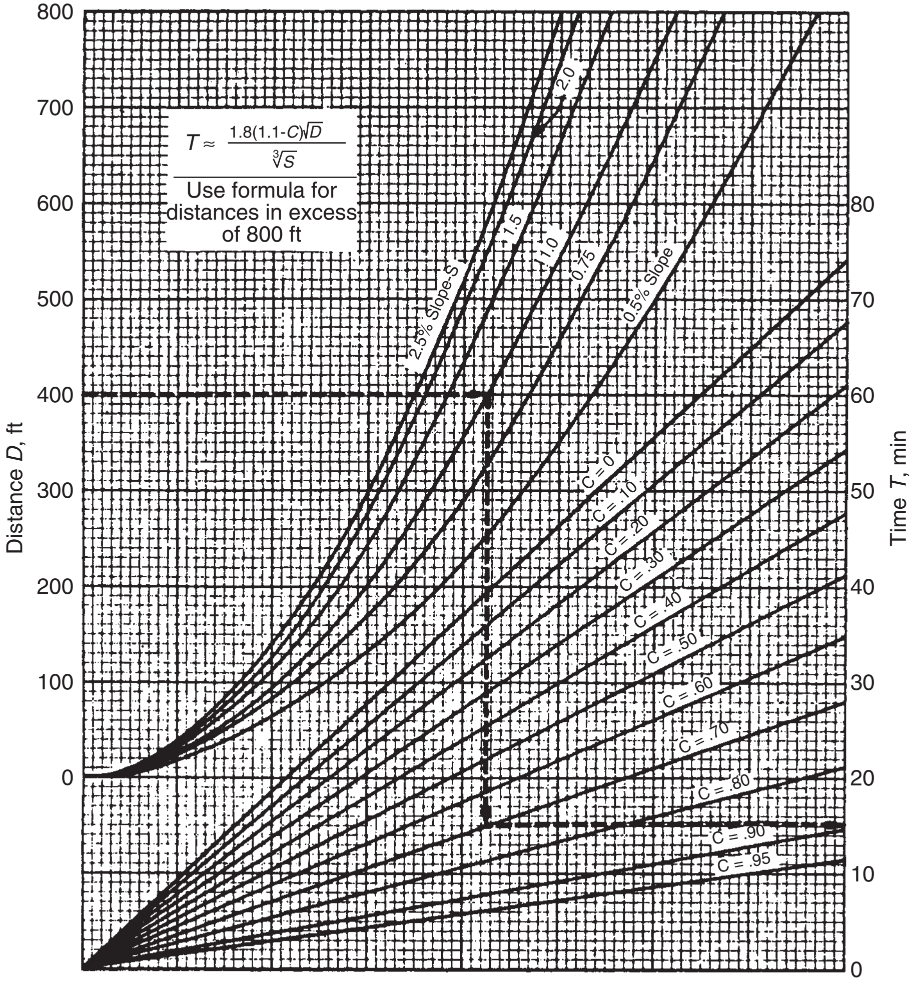


Figure 12.3 Surface flow time curves (1).

where

T = surface flow time (min)
C = runoff coefficient
S = slope (%)
D = distance to most remote point (ft)

The time of flow within the structural system can be determined by dividing the structure length (in feet) by the velocity of flow (in feet per minute).

Maximum flow through a given section of an airport drainage system should occur when the duration of rainfall equals the time of concentration for the tributary area. Although rainfalls of greater intensity than that corresponding to the time of concentration can be expected to occur, these rainfalls will be of such short duration that only a portion of the tributary area will contribute to the flow.

Rational Method

The rational method is recommended for the calculation of runoff from airport surfaces, especially for drainage areas of less than 200 acres.* The method is expressed by the equation

$$Q = CIA \tag{12.2}$$

where

Q = runoff (cfs)
C = runoff coefficient (typical values are given in Table 12.1)
I = intensity of rainfall (in./hr for estimated time of concentration)
A = drainage area (acres); area may be determined from field surveys, topographical maps, or aerial photographs

Example 12.1, which follows the section on underground pipes, illustrates the use of the rational method.

12.3 COLLECTION AND DISPOSAL OF RUNOFF

The hydraulic design of a system for the collection and disposal of surface runoff is discussed in the framework of four subtopics:

1. Layout of drainage system
2. Design of underground pipe system
3. Design of open channels
4. Design of inlets, manholes, and other appurtenances

Layout of Drainage System

As a first step in the layout and design of the drainage system, a generalized topographical map showing existing 2-ft ground contours should be obtained or prepared. This map should show all the natural and man-made features that could affect (or be affected by) the overall layout and design of the drainage system (e.g., existing watercourses and outfalls, canals, irrigation ditches, drainage structures, railroads, highways, and developed areas).

In addition, a more detailed map or grading and drainage plan, which shows the runway–taxiway system and other proposed airport features, should be prepared. This plan, which normally indicates the finished grading surfaces by 1-ft-interval contours, can serve as a working drawing for the proposed drainage system. Each drainage subarea should be outlined on the plan, and pipe sizes, lengths, and slopes should be shown. It is customary to identify drainage structures and pipelines by numbers or letters for easy reference in design computations. Figure 12.4 is an example of a portion of a grading and drainage plan.

*In the United States, the soil conservation service method is growing in prominence. It can be used for larger drainage areas (3.4).

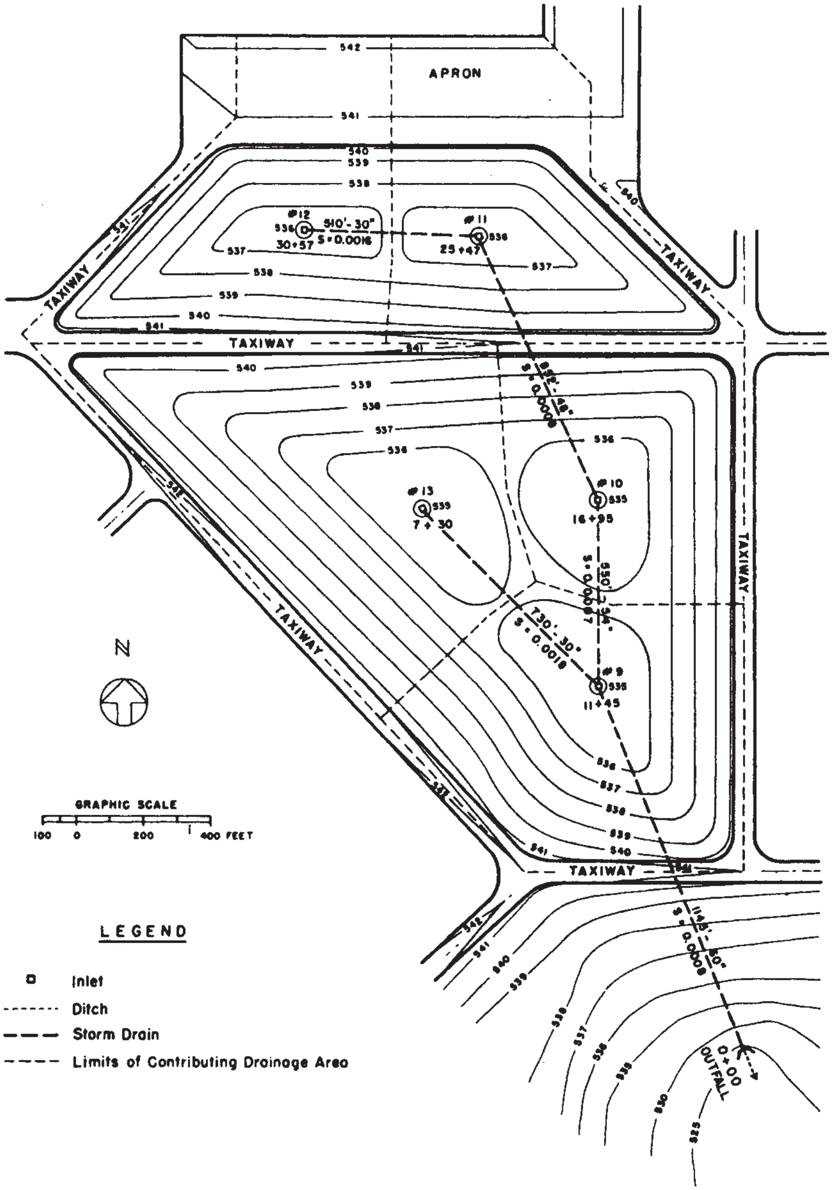


Figure 12.4 Portion of airport showing drainage design (1).

The grading plan makes it possible to select appropriate locations for drainage ditches, inlets, and manholes. Storm drain inlets are placed as needed at low points and are typically spaced 200–400 ft on tangents. The FAA (1) recommends that inlets be located laterally at least 75 ft from the edge of pavements at air carrier airports and 25 ft from the edge at general aviation airports. The designer should avoid placing inlets close to pavement edges; otherwise ponding may cause pavement flooding or saturation of the subgrade.

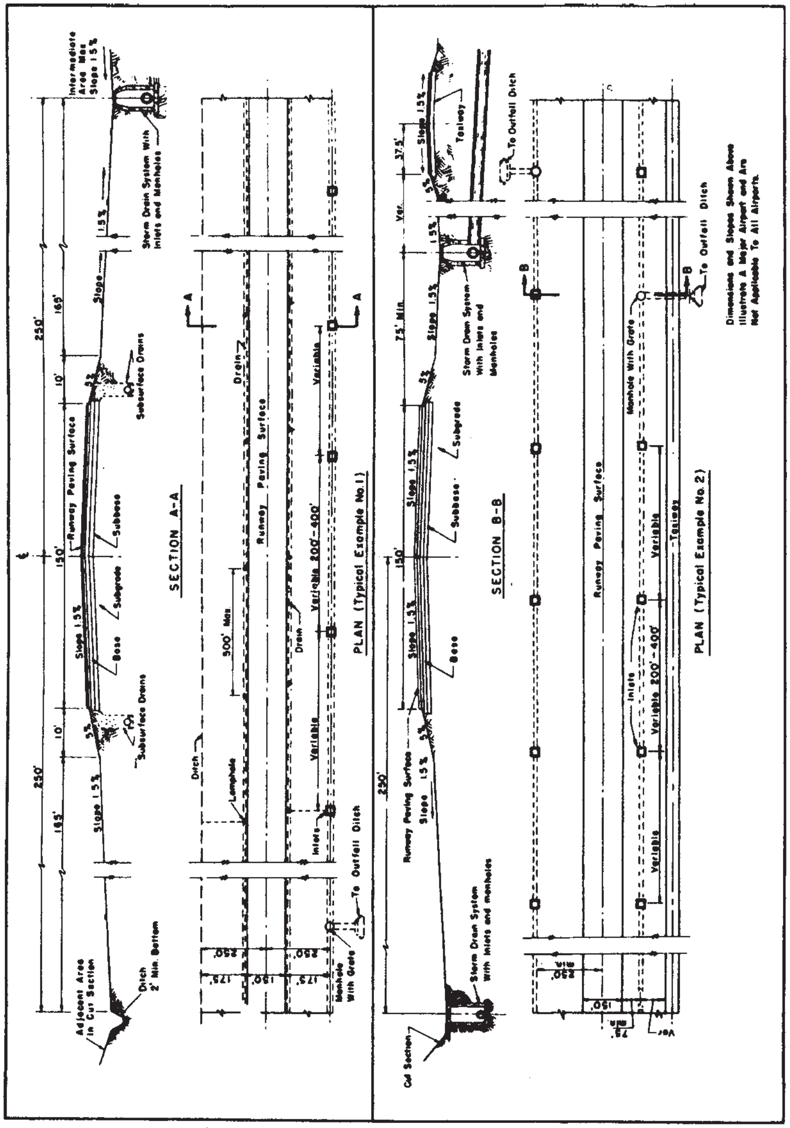


Figure 12.5 Ttypical runway safety area and runway drainage cross section (1).

Manholes permit workers to inspect and maintain the underground system. Normally, manholes are placed at all changes in direction, grade, and pipe sizes and approximately every 300–500 ft on straight segments. A typical runway safety area and runway drainage plan appears in Figure 12.5.

Design of Underground Pipe System

Alter the ditches, pipes, inlets, and manholes have been generally located on the drainage plan, the size and gradient of the pipes must be determined. The underground conduits are design to operate with open-channel flow, and because pipe sections in the system are long, uniform flow can be assumed.

The Manning equation is the most popular formula for determination of the flow characteristics in pipes. Its use is recommended by the FAA (1) in the design of underground airport pipe systems. The equation is

$$Q = \frac{1.486AR^{2/3}S^{1/2}}{n} \tag{12.3}$$

where

Q = discharge (cfs)
A = cross-sectional area of flow (ft^2)
R = hydraulic radius (ft: area of section/wetted perimeter)
S = slope of pipe invert (ft/ft)
n = coefficient of roughness of pipe

A number of agencies have prepared nomographs and charts for the solution of the Manning equation (1, 5, 6); Figure 12.6 is representative of this material. The FAA, for example, has nomographs for circular pipes flowing full with Manning roughness coefficients ranging from 0.012 to 0.031. The roughness coefficient for clay, concrete, and asbestos cement is 0.012, whereas those for corrugated metal pipes range from

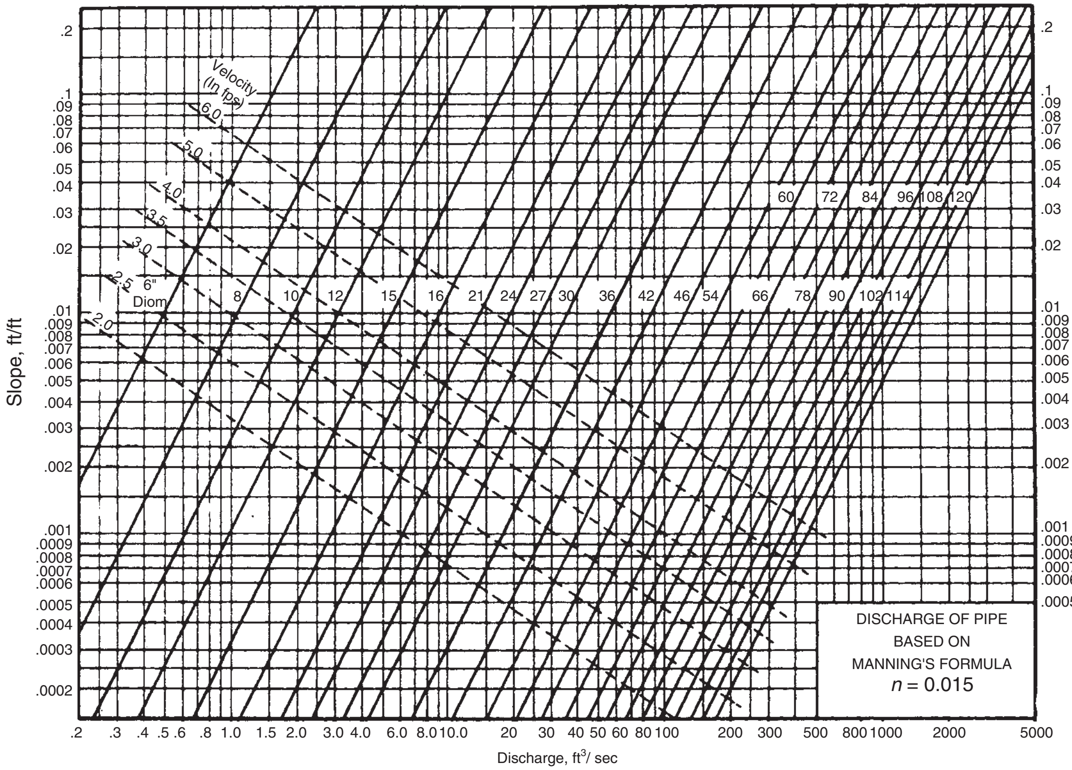


Figure 12.6 Design chart for uniform flow (1).

0.012 to 0.031, depending on the pipe size, wall configuration, and whether the wall is paved or unpaved.

It is important that sufficient velocities be maintained to prevent the deposition and accumulation of suspended matter within the pipes.

Past experience shows that a mean velocity of 2.5 ft/sec will normally prevent the depositing of suspended matter in the pipes. When lower velocities are used, special care should be taken in the construction of the system to assure good alignment, straight grades, smooth, well-constructed joints, and proper installation of structures. The pipelines and slopes should be designed, wherever possible and when topographical conditions permit, so that the velocity of flow will increase progressively or be maintained uniformly from inlets to outfall (1).

Example 12.1 Drainage Design without Ponding Consider, for example, the portion of an airport shown in Figure 12.4.* Given the following information, determine the size, capacity, and slope of pipe and the invert elevation at the outer end for line segment 13-9. The 21.5-acre drainage area (approximately 9% of which is paved and the remainder turfed) has a weighted average runoff coefficient of 0.35. The distances and slopes to the most remote point from the inlet (scaled from the sketch) are:

Area	Distance (ft)	Slope (%)
Over pavement	110	1
Over turf	1140	0.6

Use the five-year curve in Figure 12.2 to determine rainfall intensity and assume a Manning roughness coefficient $n = 0.015$. The invert elevation at the inlet end is 530.38.

Solution

The time of surface flow is the sum of surface flow time over pavement, which from Figure 10.3 is 4 min, and the surface flow time over turf,

$$T_t \approx \frac{1.8(1.1 - 0.3)(1140)^{1/2}}{(0.6)^{1/3}} = 58 \text{ min}$$

The total time of surface flow is 62 min.

Since inlet 13 is at the upper end of a drainage line, the time of surface flow is the time of concentration. Entering Figure 12.2 with a duration of rainfall of 62 min, the rainfall intensity $I = 1.76$ in./hr. The runoff $Q = (0.35)(1.76)(211.5) = 13.24$ cfs.

From Figure 12.6, we find that a 30-in. pipe will be suitable and, if installed on a 0.0018 slope, will result in a mean velocity of 3.1 ft/sec. The capacity of the pipe will be 15 cfs.

The elevation of the invert at the outlet end of line segment 13-9 will be

$$530.38 - (0.0018 \times 730) = 529.07\text{ft}$$

*This example constitutes a portion of an example published in reference 1, to which the reader is referred for more detail.

Example 12.2 Drainage Design with Ponding When the rate of runoff inflow at a drainage inlet exceeds the capacity of the drainage structure to remove it, temporary storage or ponding occurs in the vicinity of the inlet. Excessive or prolonged this may create operational hazards, damage pavement subgrades, and kill grass. It is therefore wise to undertake special studies in suspected ponding areas to determine the probability of a ponding problem and its likely magnitude. Such a study involves the computation of the total volume of runoff that flows into a ponding basin over a period of time and, similarly, the volume that can be removed by the drainage system.

The volume of runoff flowing into a drainage area, V_{in}, is the product of the runoff (as determined by the rational equation) and time:

$$V_{\text{in}} = Qt = CIAt \tag{12.4}$$

Note that the rainfall intensity is a function of time. The volume of runoff that can be removed from the ponding basin, V_{out}, is a product of the capacity of the drainage structure (as determined by the Manning equation) and time:

$$V_{\text{out}} = q_{\text{cap}}t \tag{12.5}$$

where

q_{cap} = the capacity of the drainage structure (cfs)

Since the capacity is independent of time, V_{out} varies linearly with time. When plots of those relationships are made, as Figure 12.7 illustrates, it is possible to determine the amount of ponding that occurs at various times and thus the maximum ponding. From such a graph, one can also determine the length of time that ponding will occur for the assumed conditions. Cumulative runoff graphs can be used to evaluate the ponding effects of various sizes and slopes of culverts and of different flood frequencies. An illustrative example of a ponding problem, omitted here because of limitations of space, is given in reference 1.

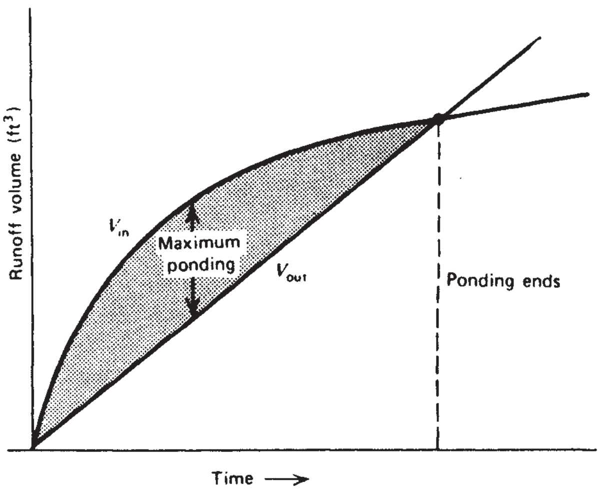


Figure 12.7 Cumulative runoff graph.

Design of Open Channels

Open waterways or ditches generally constitute an important part of an airport's overall drainage system. The size, shape, and slope of these channels must be carefully determined to avoid possible overflow, flooding, erosion, and siltation. As is the case with underground conduits, flow in long, open channels may be assumed to be uniform, and the Manning equation (equation 12.3) may be applied. In uniform flow, a state of equilibrium exists in which the energy losses due to friction are counterbalanced by the gain in energy due to slope.

To solve the Manning equation directly, the depth and cross-sectional area of flow and the slope, shape, and frictional characteristics of the channel must be known. The more common problem of determining the depth and velocity of flow corresponding to a known discharge must be solved by repeated trials. Once the depth of flow is known for a given channel cross section, the mean velocity V can be easily calculated by the continuity equation $Q = AV$. Fortunately, a wide variety of nomographs and charts for different sizes and shapes of channel cross sections have been published (1, 5, 6), making direct and repeated solution of the Manning equation unnecessary. Table 12.2 gives values of Manning's roughness coefficients for various types of channel lining.

Generally, wide, rounded, and shallow open channels are preferred. To facilitate mowing and other maintenance operations and to enhance safety and appearance, cross-sectional channel slopes should not be steeper than 2.5:1 (horizontal to vertical). To prevent offensive and costly erosion, flow velocities should not exceed the maximum values given in Table 12.2. Where velocities greater than about 6.0 ft/sec are expected, special treatment of the ditch lining, such as soil cement or paving with asphalt or Portland cement concrete, may be required.

Table 12.2 Maximum Permissible Velocities and Manning Coefficients for Various Open-Channel Linings

Type of lining	Maximum velocity (ft/sec)	Manning coefficient, n
Paved		
Concrete	20–30+	0.011–0.020
Asphalt	12–15+	0.013–0.017
Rubble or riprap	20–25	0.017–0.030
Earth		
Bare, sandy silt, weathered	2.0	0.020
Silt clay or soft shale	3.5	0.020
Clay	6.0	0.020
Soft sandstone	8.0	0.020
Clean gravelly soil	6.0	0.025
Natural earth, with vegetation	6.0	0.030–0.150[a]
Turf		
Shallow flow	6.0	0.06–0.08
Depth of flow over 1 ft	6.0	0.04–0.06

[a] Will vary with straightness of alignment, smoothness of bed and side slopes, and whether channel has light vegetation or is choked with weeds and brush.

Source: Airport Drainage, Advisory Circular AC 150/5320-5B, Washington, DC: Federal Aviation Administration, July 1970.

Design of Inlets, Manholes, and Headwalls

Space limitations preclude the inclusion of a thorough discussion of the principles of design of inlets, manholes, and headwalls. Some of the most important considerations in the design of such structures are briefly treated in the following paragraphs.

Where high heads are permissible, the capacity of an inlet grating can be determined by the orifice formula:

$$Q = cA(2gH)^{1/2} \tag{12.6}$$

where

$c = 0.6$
$A =$ waterway opening (ft^2)
$g =$ acceleration of gravity (ft/sec^2)
$H =$ head (ft)

For low heads, the discharge conforms to the general weir equation:

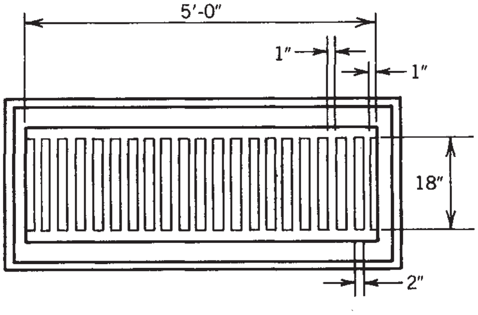
$$Q = CLH^{3/2} \tag{12.7}$$

where

$C = 3.0$
$L =$ gross perimeter of grate opening, omitting bars (ft)
$H =$ head (ft)

With these equations, the number and size of grates needed to accommodate a given runoff and allowable headwater conditions can be readily determined. The general weir formula should be applied for aircraft servicing aprons and other areas where significant ponding depths would be unacceptable. The orifice formula normally applies to grates in turfed areas. When employing these formulas, the FAA (1) recommends using a safety factor of 1.25 for paved areas and 1.5–2.0 for turfed areas to allow for partial obstruction of the grating area with debris. The FAA coefficients are based on a model test of similar grates, with a 2:3 ratio of net width of grate opening to gross width.

Example 12.3 Capacity of a Double-Inlet Grating A double-inlet grating like the one illustrated in the accompanying sketch is used to drain a paved apron area. Determine the capacity of the inlet: (a) with a head of 1.6 feet and (b) with a head of 0.4 ft.



PLAN OF DOUBLE INLET GRATING

Solution to Part a

Equation 12.6 applies for the high-head situation, with $H = 1.6$ ft. There are 20 grate openings, each 2 in. by 18 in. The total area of the opening is

$$A = 20 \times \frac{2}{12} \times \frac{18}{12} = 5.0\,\text{ft}^2$$

$$Q = cA(2gH)^{1/2} = (0.6)(5)(2 \times 32.2 \times 1.6)^{1/2} = 30.4\,\text{ft}^3/\text{sec}$$

Applying a safety factor of 1.25, the capacity is 24.4 ft^3/sec.

Solution to Part b

For a low head $H = 0.4$ ft, equation 12.7 applies. The gross perimeter of the grate opening is

$$L = (2 \times 5) + (2 \times 1.5) = 13\ \text{ft}$$

$$Q = CLH^{3/2} = 3.0(13)(0.4)^{3/2} = 9.9\ \text{ft}^3/\text{sec}$$

$$\text{The Capacity is } \frac{9.9}{\text{safety factor}} = \frac{9.9}{1.25} = 7.9\ \text{ft}^3/\text{sec}$$

Inlet grates and frames, such as those used for municipal storm drainage systems, generally are suitable for airports in the utility and basic transport categories. At larger airports, the design of inlet structures in aircraft traffic areas should be based on a careful analysis of probable aircraft loadings. As a rule, the structural strength of inlet frames and grates can be certified by the supplier. Of course, the inlet structure proper, which is normally constructed of reinforced concrete, brick, concrete blocks, and the like, must also be strong enough to support the anticipated loads. Figure 12.8 presents a typical drainage inlet (1):

> Manholes . . . are usually made of reinforced concrete, brick, concrete block, precast concrete, corrugated metal, or precast pipe sections [Figure 12.9]. The design will depend on the stresses to which they will be subjected. Adequate unobstructed space must be provided within the manhole to enable workmen to clean out the line when necessary. Inside barrel dimensions equivalent to a diameter of 3 1/2 ft and a height of 4 ft are usually considered sufficient, but they can be varied to suit particular situations.

Suggested standard designs for headwalls have been developed by the FAA, state departments of transportation, and other public agencies. However, designers should be aware that headwalls may constitute a fixed object hazard to errant aircraft or motor vehicle traffic, and where such potential exists, the possibility of an alternative treatment should be explored.

12.4 SUBSURFACE DRAINAGE

Special drainage systems may be required to control and avoid the undesirable effects of subsurface moisture. Such systems are usually installed to avoid saturation and

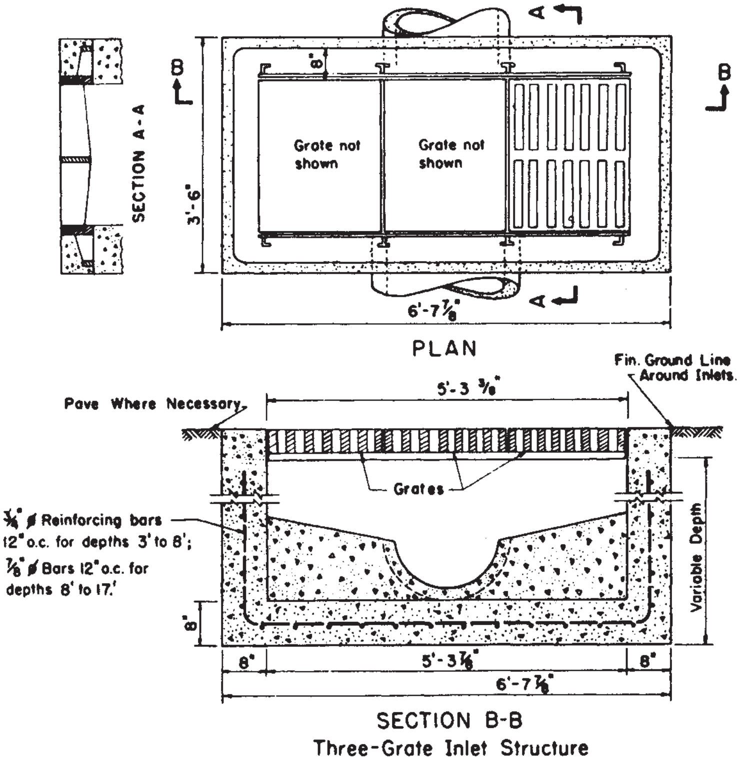


Figure 12.8 Ttypical three-grate inlet structure (1).

weakening of pavement foundation layers and to control or prevent damaging frost heave.*

Subsurface drainage has at least three functions: (a) to drain and upgrade wet soil masses, (b) to intercept and divert subsurface flows, and (c) to lower and control the water table.

Subsurface drains consist of small pipes (typically 6–8 in. in diameter) which are laid in trenches approximately 1.5–2.0 wide and backfilled with a pervious filter material. The pipes should be bedded in a minimum thickness of filter material. Vitrified clay, concrete, asbestos cement, bituminous fiber, corrugated steel, and corrugated aluminum alloy pipes have been used for subdrains. To allow water to enter, the pipes are normally either manufactured with gaps, slots, or perforations or laid with open joints.

Subsurface drainage systems are most likely to be effective in sandy clays, clay silts, and sandy silts. The finer grained materials (predominantly silts and clays) are much more difficult to drain, whereas the coarser grainer materials (gravels and sands) tend to be self-draining.

*In cold climates, frost action will occur in certain subgrade soils if precautions are not taken. Interstitial water freezes in the upper soil layers, and the small ice crystals develop into large ice lenses as water is attracted upward from voids in lower strata. The resulting nonuniform "heave" of the supporting soil can be extremely harmful to the pavement structure. This phenomenon is discussed further in Section 12.6.

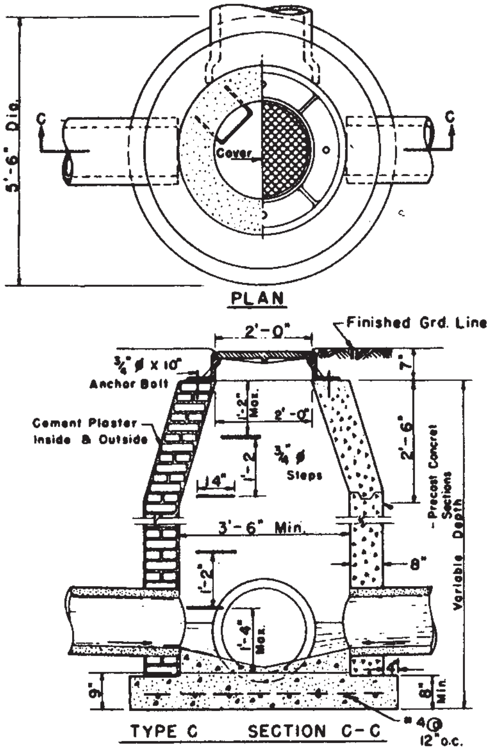


Figure 12.9 Suggested manhole design (adapted from Ref. 1).

Careful studies of soil and water conditions are a prerequisite to the design of a subsurface drainage system. Data are available from a variety of sources, including field borings and laboratory tests, topographic maps, agricultural soil surveys, and aerial photographs.

Subsurface drainage systems fall into two general classes: base and subgrade drains and intercepting drains.

Base and Subgrade Drainage

Normally, a single line of subsurface drains installed along the edges of runways and taxiways gives adequate base and subgrade drainage (see Figure 12.5). Additional drainage lines may be required under expanses of pavement (e.g., aprons) that are wider than 75 ft (1).

The maximum rate of discharge from a saturated base course may be estimated by the following equation:

$$q = \frac{kHS}{60} \tag{12.8}$$

where

q = peak discharge (cfs/lineal ft of drain)
k = coefficient of horizontal permeability (ft/min)

H = base thickness (ft)
S = slope (ft/ft)

A similar but slightly more complicated formula has been published (7) for the estimation of flow from subgrades. Experience has shown that, under normal conditions, a pipe 6 or 8 in. in diameter is large enough for base and subgrade drains.

Intercepting Drainage

An intercepting drainage system intercepts and diverts groundwater flowing in a pervious shallow stratum. Although the quantity of water collected cannot be precisely computed, it depends on the amount of precipitation, the type of ground cover, the permeability of the soil, and the depth and spacing of the drain pipes. As a rule of thumb, the FAA (1) recommends that a rate of infiltration for subdrainage of 0.25–0.50 in./acre in 24 hr be used. With appropriate unit conversion, this corresponds to a flow rate of 0.0105–0.021 cfs/acre. On the basis of the estimated flow rate, the proper size of pipe can be determined from Manning curves or nomographs. The U.S. Army Corps of Engineers (7) has indicated that a 6-in. intercepting drain pipe not longer than 1000 ft generally has adequate capacity.

Slopes and Backfill

It is recommended that subsurface drains be laid on a slope of at least 0.15 ft/100 ft. To be effective, the drain pipes must be backfilled with a carefully graded filter material. The backfill material must be pervious enough to allow free water to enter the pipe but impervious enough to prevent the pipe from becoming clogged with fine particles of soil. Specific details on the recommended gradation and permeability of backfill filter material are given in references 1 and 7.

Manholes and Risers

Subsurface drainage systems must be inspected and maintained. To allow for this, the army recommends (6) that manholes be placed at intervals of not more than 1000 ft and at principal junction points in base and subgrade drainage systems. Inspection and flushing holes (risers) are normally placed between manholes and at dead ends. These holes are usually constructed of the same type and size of pipe as the subdrain and have a grate or cover at the surface (1).

Design Software

The equations, graphs, and example in earlier sections of this chapter show the underlying analytic and empiric methods of design that underlie the design of drainage infrastructure. For many years, this methodology has been adapted into computer software which now is very widely used to solve drainage calculations. Two stormwater management programs designed for urban areas are useful for airports: STORM, developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, and SWMM, developed for the U.S. Environmental Protection Agency (EPA). Furthermore, the Federal Highway Administration (FHWA) has a Windows®-based program for subsurface drainage, DRAINAGE REQUIREMENT IN PAVEMENTS (DRIP). By 2011 there were numerous private and public domain software products for drainage. The software-versus-capabilities matrix indicates some of those available in the public domain which may be freely downloaded. The reader is referred to FAA Advisory Circular AC 150/5320, Surface Drainage Design, as updated, for descriptions of the content of these software programs (1).

Software-versus-Capabilities Matrix

	Storm drains	Hydrology	Water surface profiles	Culverts	Channels	Water quality	Pavement drainage	pond routing	BMP evaluation	Metric version
HYDRAIN	•	•	•	•	•		•	•		•
TR-55		•								
TR-20		•						•		
HMS		•						•		•
SWMM	•	•				•	•	•	•	•
PRSM-QUAL	•	•				•	•	•		
DR3M	•						•	•		
HY-TB	•				•		•	•		
Urban drainage	•				•		•	•		•
Evaluation of water quality									•	

Structural Pavement Design

12.5 INTRODUCTION

An airfield pavement must be able to support loads imposed by aircraft without excessive distortion or failure. It should be smooth, firm, stable, and free from dust or other particles that might be blown or pushed up by propeller wash or jet blast (8). It must be usable in all seasons and in all weather conditions. The ability for a pavement to perform these functions for given aircraft traffic depends on the foundation or subgrade, the quality of construction materials and workmanship, the design or proportioning of the materials in the pavement mix, and the thickness of the layers of the pavement system. This section focuses on the structural design of the pavement, that is, the determination of the thickness of the various components or layers of the pavement system.

A pavement is a structure consisting of one or more layers of processed or unprocessed materials placed on a prepared subgrade. There are two general classes of pavements: flexible and rigid.

Flexible pavements typically consist of a bituminous "surface course," a "base course," and a "subbase course." These courses or layers are carefully placed and compacted on a prepared subgrade in an embankment or excavation.

The surface course* in a flexible pavement may be constructed of bituminous concrete, sand–bitumen mixtures, or sprayed bituminous surface treatments. Because it is the top layer, the surface course is subjected to the highest stresses and the most severe effects of weather and traffic. It must be able to do the following:

1. Withstand the effects of applied loads and distribute those loads to underlying layers
2. Resist deterioration due to the environment and abrasive effects of traffic
3. Provide a smooth, skid-resistant surface without causing unnecessary abrasion to the tires
4. Prevent penetration of water into the base course

The base course typically consists of crushed or uncrushed aggregates, which may be untreated or treated with Portland cement, asphalt, lime, or other stabilizing agents. This layer must be strong enough to fulfill its principal functions, namely, to support applied loads and to distribute the loads to the subbase or subgrade.

A subbase course is sometimes employed consisting of lower quality and less expensive material than that used in the base course. Subbases typically are composed of a stabilized or unstabilized granular material or a stabilized soil. Subbases distribute imposed loads to the subgrade and in certain instances may be used to facilitate subsurface drainage and prevent destructive frost action.

Rigid pavements consist of a slab of Portland cement concrete (PCC)† that rests on a prepared subgrade or subbase. Distributed steel or tiebars and dowels are used in Portland concrete pavements to control and minimize the harmful effects of cracking and to provide for load transfer between adjacent slabs. Relatively thin subbases (4–6 in.) may be placed under rigid pavements to prevent pumping. Subbases may also be used to improve a low-strength subgrade.

A large number of methods have been used for the structural design of airport pavements. Most are extensions of methods that have been employed in the design of highway pavements. These methods are more or less theoretically based; however, the procedures have been modified and refined through analyses of pavement performance under service conditions. The sections that follow briefly describe the design methods which have now been adopted by the FAA. First, we discuss some of the significant effects of various factors on pavement performance.

Pavement Performance

Airport pavements are complex structural systems, and their performance depends on a broad spectrum of variables. These variables may be classified into five groups, listed in Table 12.3.

The most important variables are those that relate to the imposed loadings. The load variables depend primarily on the sizes and numbers of airplanes that comprise

*In this chapter, the wearing course will be described as a hot-mix asphalt wearing course to conform with the terminology used in the FAA advisory circular. In many countries this course is termed a Marshal asphalt wearing course, having specifications for a dense special asphalt mix.

†In some countries, PCC is referred to as pavement quality concrete (PQC).

Table 12.3 Variables That Influence Pavement Performance (8)

Load variables
Aircraft gross load
Wheel load
Number and spacing of wheels
Tire contact pressures
Number of applications
Duration of load application
Distribution of lateral placement of loads
Type of load (static or dynamic)
Environmental variables
Amount and distribution of precipitation (especially rainfall)
Ambient temperatures
Aircraft blast and heat
Fuel spillage
Structural design variables
Number, thickness, and type of pavement layers
Strength of materials
Construction variables
Maintenance variables

the aircraft mix. The task of the pavement designer is complicated by the rapidly changing state of aircraft design technology. The introduction of larger and heavier aircraft as well as changes in wheel loads, gear configurations, tire pressures, and other load variables significantly affect the performance of airport pavements. A pavement's performance is especially sensitive to the frequency of loadings. Areas subjected to repeated loadings due to channelization or concentration of traffic must be designed to accommodate the stress from such loadings.

The environmental variables that affect the performance of a pavement include:

1. Amount and distribution of precipitation, which may weaken subgrades and contribute to pavement pumping and frost action
2. Ambient temperatures, which can cause excessive expansion of concrete slabs and asphalt softening and bleeding
3. Variables associated with the aircraft, such as jet blast, heat, and fuel spillage
4. Type of subgrade soil

The performance of a pavement is directly related to its structural design. Structural design variables include the number and thickness of the pavement layers and the strength and behavioral characteristics of the pavement materials. It should also be obvious that performance under service conditions depends on the quality of construction workmanship and the adequacy of maintenance during its service life. Therefore, the designer should make suitable allowances for probable inadequacies in quality control during construction and should consider the effects of the anticipated level of maintenance.

A further complication is the impossibility of giving a precise definition of functional pavement failure. Pavements seldom fail catastrophically; rather, they gradually wear out and suffer a loss of serviceability over time. This makes pavement performance evaluation very difficult.

Because of the complexity of the pavement structural design problem, there is no single analytical equation for its solution. Nor is it likely that such an equation will soon be developed. The modern methods of pavement design adopted by the FAA use layered elastic theory and finite-element analysis. However, there is a base of empiricism still underlying the design procedures due to the fact that soils and aggregates are not purely homogeneous materials. It still remains true that these methods "cannot be used with confidence when it becomes necessary to extrapolate the loading conditions, materials, environmental conditions, and so on, that are different from those used for the development of the methods" (9).

The FAA now provides software for the design of both flexible and rigid pavements through the Office of Airport Safety and Standards via a design program (FAARFIELD) (10). For flexible pavements, for a predicted pavement structural life this software provides the required thickness for the individual layers of flexible pavement to support a given airplane traffic mix over a particular subgrade. Layered elastic theory is the basis of the computations and the criteria of design are the maximum vertical strain at the top of the subgrade and the maximum horizontal strain at the bottom of the asphalt surface layer. The same software package uses finite-element analysis for calculating the required thickness of the rigid-pavement slab based on the calculation of the maximum horizontal stress at the bottom of the PCC slab as the predictor of pavement structural life. The maximum horizontal stress for design is an edge loading condition.

In summary, the factors which are found to influence the thickness of aircraft pavements are:

Magnitude and character of the pavement loads applied by the airplanes

Volume of traffic

Distribution of traffic across the pavement surface

Quality and strength of the materials used in pavement construction

Strength of the subgrade

Method of subgrade strength evaluation

The FAA methods (8) of pavement design calls for accurate identification and evaluation of pavement foundation (subgrade) conditions. The recommended method requires thorough investigations to determine the distribution and physical properties of pavement foundation soils. A soil survey should be made to describe the soils that comprise the soil profile and to indicate subsurface water conditions. It is recommended that representative samples of soil be taken by means of a soil auger. Generally, borings should be taken along runway and taxiway centerlines at 200-ft intervals. One boring for every 10,000 ft^2 should be made under other pavement areas. Such borings normally are made to a depth of 10 ft below the finished grade in cut areas and 10 ft below the existing ground surface in fill areas. Borrow areas should be adequately sampled to establish the physical characteristics of the borrow material.

The FAA (8) uses the USCS (USCS). This system, which was developed by the U.S. Army Corps of Engineers and is described in ASTM D-2487, classifies soils on the basis of grain size and then further subgroups them on the basis of the Atterberg limits (10); see Table 12.4. Specifically, the USCS is based primarily on the following soil characteristics:

1. Percentage of material retained on No. 200 sieve
2. Percentage of material retained on No. 4 sieve
3. Liquid limit
4. Plastic limit

Seventeen soil groups comprise the USCS as used by the FAA.* The system array of soil types ranges from clean gravels, the best pavement foundation material, to peat, muck, and other highly organic materials that are unsuitable as pavement foundations.

Table 12.4 gives the criteria for classifying soils into the major divisions for the purposes of pavement design. Additional criteria for determining the specific soil class are also given in Table 12.4. Coefficients of uniformity (C_u) and curvature (C_c) are used to judge the shape of the grain size distribution curve of a coarse-grained soil. These coefficients may be calculated by the following equations:

$$C_u = D_{60}/D_{10} \tag{12.9}$$

$$C_c = (D_{30})^2/(D_{10} \times D_{60}) \tag{12.10}$$

In these equations, the term D_{10} refers to the grain size (diameter) that corresponds to 10% on the grain size distribution curve. The terms D_{30} and D_{60} have similar meanings. The reader is referred to reference 8 for the effect of uniformity on the suitability of soils in the GU and SU classes.

Fine-grained soils are classified on the basis of liquid limit and plasticity index (see Figure 12.10).

A listing of the group symbols and an abbreviated description of each group reveals the general rationale for the USCS:

Gravels

GW—Well-graded gravels
GP—Poorly graded gravels
GU—Uniformly graded gravel or sandy gravel
GM—Silty gravels.
GC—Clayey gravels

Sands

SW—Well-graded sands
SP—Poorly graded sands
SU—Unsuitably graded sand or gravelly sand
SM—Silty sands
SC—Clayey sands

*In the USCS as set out by ASTM, there are only 15 classes of soil. The FAA adds the classes GU (uniformly graded gravel and sandy gravel) and SU (poorly uniform and unsuitably graded sand or gravelly sand).

Table 12.4 Soil Classification Based on USGS (As Modified for Airplane Pavements)

Major divisions		Letter	Name	Value as foundation when not subject to frost action	Value as base directly under wearing surface	Potential frost action	Compressibility and expansion	Drainage characteristic	Unit dry weight (pcf)	California bearing ratio	Subgrade modulus k (pci)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Coarse gravelly soils	Gravel and gravelly soils	GW	Gravel or sandy gravel, well graded	Excellent	Good	None to very slight	Almost none	Excellent	125–140	60–80	300 or more
		GP	Gravel or sandy gravel, poorly graded	Good	Poor to fair	None to very slight	Almost none	Excellent	120–130	35–60	300 or more
		GU	Gravel or sandy gravel, uniformly graded	Good to excellent	Poor	None to very slight	Almost none	Excellent	115–125	25–50	300 or more
		GM	Silty gravel or silty sandy gravel	Good	Fair to good	Slight to medium	Very slight	Fair to poor	130–145	40–80	300 or more
		GC	Clayey gravel or clayey sandy gravel	Good to excellent	Poor	Slight to medium	Slight	Poor to practically impervious	120–140	20–40	200–300
	Sand and sandy soils	SW	Sand or gravelly sand, well graded	Good	Poor to not suitable	None to very slight	Almost none	Excellent	110–130	20–40	200–300
		SP	Sand or gravelly sand, poorly graded	Fair to good	Not suitable	None to very slight	Almost none	Excellent	105–120	15–25	200–300
		SU	Sand or gravelly sand, poor uniformly, not suitably graded	Fair to good	Poor	None to very slight	Almost none	Excellent	100–115	10–20	200–300
		SM	Silty sand or silty gravelly sand	Good	Not suitable	Slight to high	Very slight	Fair to poor	120–135	20–40	200–300

(*continued overleaf*)

Table 12.4 (*Continued*)

Major divisions		Letter	Name	Value as foundation when not subject to frost action	Value as base directly under wearing surface	Potential frost action	Compressibility and expansion	Drainage characteristic	Unit dry weight (pcf)	California bearing ratio	Subgrade modulus k (pci)
		SC	Clayey sand or clayey gravelly sand	Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	105–130	10–20	200–300
Fine-grained soils	Low compressibility LL<50	ML	Silts, sandy silts, gravelly silts, or diatomaceous soils	Fair to good	Not suitable	Medium to very high	Slight to medium	Fair to poor	100–125	5–15	100–200
		CL	Lean clays, sandy clays, or gravelly clays	Fair to good	Not suitable	Medium to very high	Medium	Practically impervious	100–125	5–15	100–200
		OL	Organic silts or lean organic clays	Poor	Not suitable	Medium to very high	Medium to high	Poor	90–105	4–8	100–200
		MH	Micaceous clays or diatomaceous soils	Poor	Not suitable	Medium to very high	High	Fair to poor	80–100	4–8	100–200
	High compressibility LL<50	CH	Fat clays	Poor to very poor	Not suitable	Medium	High	Practically impervious	90–110	3–5	50–100
		OH	Fat organic clays	Poor to very poor	Not suitable	Medium	High	Practically impervious	80–105	3–5	50–100
Peat and other fibrous organic soils		Pt	Peat, humus, and other	Not suitable	Not suitable	Slight	Very high	Fair to poor	—	—	—

Source: Courtesy of American Society of Testing Materials (ASTM).

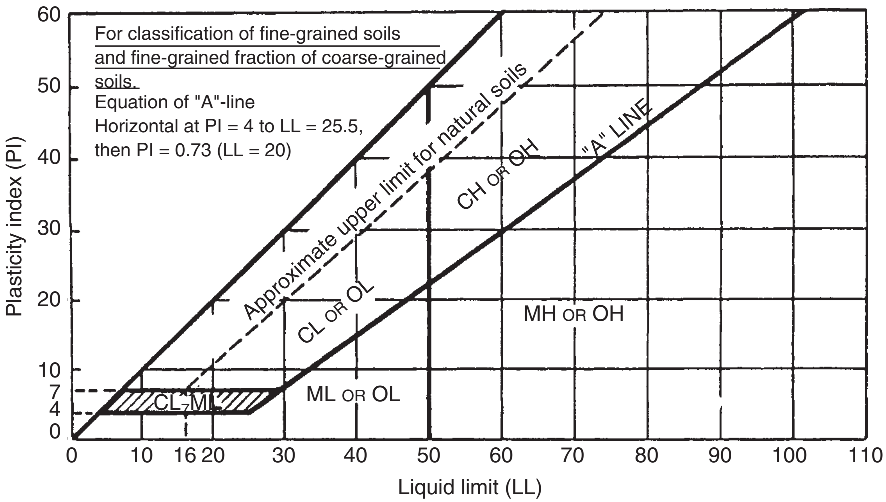


Figure 12.10 Graph for classification of fine-grained soils according to the USCS. (*Source*: *Standard Test Method for Classification of Soils for Engineering*, West Conshohocken, PA: American Society for Testing and Materials, 2008.)

Silts and Clays

ML—Inorganic silts with liquid limit less than 50

CL—Inorganic clays with liquid limit less than 50

OL—Organic silts and silty clays with liquid limit less than 50

MH—Inorganic silts with liquid limit higher than 50

CH—Inorganic clays with liquid limit higher than 50

OH—Organic clays with liquid limit higher than 50

Highly Organic Soils

PT—Peat, muck, and other highly organic soils

Experience has shown that organic soils containing more than 3% particles finer than 0.02 mm in diameter are subject to "frost action." The harmful effects of frost action may be manifested in frost heave, the distortion of the subgrade soil or base material when prolonged severe freezing temperatures prevail. Investigations have shown that, as the water in the upper soil layers of a pavement freezes, ice crystals are formed, and water may be drawn from a free water surface into the zone of subfreezing temperatures. This water then freezes, additional water may be drawn to this level, and this process continues until ice lenses of considerable thickness may be formed. The volume increase brought about by the formation of these layers of ice is the cause of frost heaving. The melting of these ice layers can result in a reduction in foundation support and even cause a failure of the pavement system.

Where the potential for damaging frost action exists, it may be necessary to include material that is not frost susceptible below the required base or subbase. The degree of frost protection required depends on the soil conditions and the usage the pavement will receive. Further guidance on the control of this problem is given in reference 8.

The reader is cautioned that the USCS may be only roughly indicative of the behavior of the soil as a pavement foundation. A more reliable approach to predicting foundation behavior is to directly measure soil strength by the California bearing ratio (CBR) or plate-bearing tests. For flexible pavements, the FAA recommends the use of CBR tests. The relationship between CBR values and the various Unified Soil Classes is given in Table 12.4.

California Bearing Ratio. The CBR method of pavement design was developed in the late 1920s by the California Division of Highways. It was modified and adopted for airfield pavement design by the Corps of Engineers at the beginning of World War II.

The CBR method of subgrade evaluation is based on a relatively simple test of the shear strength of the supporting soil (11):

> The CBR test is conducted by forcing a 2-inch diameter piston into the soil. The load required to force the piston into the soil 0.1 inch (sometimes 0.2 inch) is expressed as a percentage of the standard value for crushed stone . . . . The test can be performed on samples compacted in test molds, on undisturbed samples, or on material in place. The test must be made on material that represents the prototype condition that will be the most critical from a design viewpoint. For this reason, samples are generally subjected to a four-day soaking period. Experience during the past few years has shown that CBR tests on gravelly materials in the laboratory have tended to give CBR values higher than are obtained in tests in the field. The difference is attributed to the processing necessary to test the sample in the 6-inch mold, and to the confining effect of the mold. Therefore, the CBR test is supplemented by gradation and Atterberg limits requirements for subbases.

Subgrade soils are variable in character and the selection of the subgrade design CBR is an engineering judgment. The FAA suggests that the design value selected is equal to or less than 85% of all the subgrade CBR values from the soil tests, which corresponds to a design value of at least one standard deviation below the mean of the test results.

Once the strength of the subgrade has been established for design purposes, the overlaying pavement, either flexible or rigid, may be designed. The recommended requirements for subgrade compaction are shown in Table 12.5.

12.6 FLEXIBLE-PAVEMENT DESIGN METHODS (U.S. PRACTICE)

FAA Method of Flexible-Pavement Design

For many years, the FAA used a method of design for flexible pavements that was based on empirical research and field performance. Its design curves reflected the experience of thousands of pavements under a large range of service conditions. The administration had for some time been working on the development of a new design method that was able to address the impact of new landing gear configurations and increased pavement loads of future aircraft without modifying the underlying design procedures. Canceling the previous advisory circular on airport pavement design in 2009, the FAA produced a new procedure that utilizes layered elastic theory for flexible pavements (8) and

Table 12.5 Subgrade Compaction Requirements for Flexible Pavements (8)

		Noncohesive soils, Depth of compaction (in)				Cohesive soils, Depth of compaction (in)			
Gear type	Gross weight (lb)	100%	95%	90%	85%	95%	90%	85%	80%
S	30,000	8	8–18	18–32	32–44	6	6–9	9–12	12–17
	50,000	10	10–24	24–36	36–48	6	6–9	9–16	16–20
	75,000	12	12–30	30–40	40–52	6	6–12	12–19	19–25
D (incls. 2S)	50,000	12	12–28	28–38	38–50	6	6–10	10–17	17–22
	100,000	17	17–30	30–42	42–55	6	6–12	12–19	19–25
	150,000	19	19–32	32–46	46–60	7	7–14	14–21	21–28
	200,000	21	21–37	37–53	53–69	9	9–16	16–24	24–32
2D (incls. B757, B767, A300, DC-10-10, L10(1)	100,000	14	14–36	26–38	38–49	5	6–10	10–17	17–22
	200,000	17	17–30	30–43	43–56	5	6–12	12–18	18–26
	300,000	20	20–34	34–48	48–63	7	7–14	14–22	22–29
	400,000–600,000	23	23–41	41–59	59–76	9	9–18	18–27	27–36
2D/D1, 2D/2D1 (incls. MD11, A340, DC10-(30/40)	500,000–800,000	23	23–41	41–59	59–76	9	9–18	18–27	27–36
2D/2D2 (incls. B747 series)	800,000	23	23–41	41–59	59–76	9	9–18	18–27	27–36
	975,000	24	24–44	44–62	62–78	10	10–20	20–28	28–37
3D (incls. B777 series)	550,000	20	20–36	36–52	52–67	6	6–14	14–21	21–29
	650,000	22	22–39	39–56	56–70	7	7–16	16–22	22–30
	750,000	24	24–42	42–57	57–71	8	8–17	17–23	23–30
2D/3D2 (incls. A380 series)	1,250,000	24	24–42	42–61	61–78	9	9–18	18–27	27–36
	1,350,000	25	25–44	44–64	64–81	10	10–20	20–29	29–38

Notes:
[1]Noncohesive soils, for the purpose of determining compaction control, are those with a plasticity index of less than 3.
[2]Tabulated values denote depths below the finished subgrade above which densities should equal or exceed the indicated percentage of the maximum dry density as specified in Item P-132.
[3]The subgrade in cut areas should have natural densities shown or should (a) be compacted from the surface to achieve the required densities, (b) be removed and replaced at the densities shown, or (c) when economics and grades permit, be covered with sufficient select or subbase material so that the uncompacted subgrade is at a depth where the in-place densities are satisfactory.
[4]For intermediate airplane weights, use linear interpolation.
[5]For swelling soils, refer to paragraph 312.
[6]1 inch = 25.4 mm, 1 pound = 0.454 kg

at the same time introduced a new design procedure for rigid pavements based on finite-element analysis.

A flexible pavement is constructed of several layers of selected materials on the subgrade foundation. A typical construction would include:

Hot-mix asphalt wearing course

Base

Subbase (if required)

The function of the pavement is to carry the loads applied by the aircraft wheels down to the subgrade while at all depths incurring stresses that are sustained without damage to the pavement constituent materials.

The top or wearing course of a flexible pavement is a hot-mix asphalt wearing course* which has several functions: to prevent water penetration into the lower layers of the pavement, to provide a smooth well-bonded surface free of loose particle and strong enough to resist rutting, and to provide a surface that does not unduly damage the aircraft tires while offering good skid resistance. Hot-mix asphalt, best produced in a properly controlled central mixing plant, is a densely graded mixture of aggregates and bituminous binders that will produce a dense uniform surface possessing maximum durability and stability. Hot-mix asphalt must be protected from solvent spillage such as fuel and hydraulic fluids.

In a flexible pavement, the base course is the principal structural component of pavement strength, carrying and distributing the wheel loads down to the subgrade foundation. The spread of load through the base serves to prevent failure of the subgrade, resist deformation of the base itself due to vertical stress, and resist volume changes due to variation of the moisture content. Both stabilized and unstabilized materials are used for base construction including aggregate, crushed aggregate, lime rock, econocrete, and other materials; see Table 12.6 (8).

It is normal practice for a subbase to be supplied on all flexible pavements except those with a subgrade with a CBR in excess of 20. Subbase materials are of a lesser

Table 12.6 Materials Properties for Base Layers

Base layer	Modulus, psi (MPa)	Poisson's ratio
Stabilized (flexible)		
Variable minimum	150,000 (1035)	0.35
Variable maximum	400,000 (2760)	0.35
P-401/403 Asphalt	400,000 (2760)	0.35
Stabilized (rigid)		
Variable minimum	250,000 (1720)	0.20
Variable maximum	700,000 (4830)	0.20
P-304 Cement treated base	500,000 (3450)	0.20
P-306 Econocrete subbase	700,000 (4830)	0.20

Source: FAA.

*Specifications of materials suitable for flexible pavements are given in *Standards for Specifying Construction of Airports,* AC 150/5370-10 (12).

strength than those for bases. The FAA provides subbase course specifications for suitable subbase materials: caliche and shell base courses and sandy clay and soil cement base courses. Any material itself suitable for a base course is considered as also suitable for a subbase (8).

The program used for the FAA flexible-pavement design is FAARFIELD using the subprogram LEAF, which is a layered elastic computational design program implemented as a Microsoft Windows™ dynamic link library written in Visual Basic™ 2005.*

Traffic mix inputs required:

Aircraft model, annual departures of each model, annual percentage growth in traffic for each model

Design assumptions:

Design life of 20 years is standard condition but variations are possible.

The design method analyzes the damage to the pavement from the passage of each individual airplane and determines the pavement thickness from the total cumulative damage due to all aircraft.

Within the program, the pass-to-coverage ratio is modeled by a normal distribution to allow for the fact that aircraft wander from assumed paths.

Structure:Surfacing: hot-mix asphalt surfacing—minimum 4 in. (102 mm); fixed modulus value 200,000 psi

Base course: two types of stabilized base can be input:Stabilized (flexible): standard FAA P-401/403 and variable†

Stabilized (rigid): standard FAA cement treated base P-304, standard econocrete subbase P-306 and variable‡

Unstabilized base: crushed aggregate base course P-209

Minimum base course thickness: FAARFIELD by default computes the minimum thickness for the base course, assuming the subgrade has a minimum CBR of 20. Subgrade values of less than CBR 20 can be input with other data. When an aggregate base course is used:

Step 1. The aggregate base thickness is computed to protect a CBR 20 subgrade

Step 2. This is compared with the minimum base thickness requirements of Table 12.7 and the thicker of the two design values is selected.

Subbase Course

Design requires a minimum of depth 4 in. but more may be required for construction purposes.

Acceptable materials are defined by FAARFIELD; in areas subject to freeze thaw, frost-susceptible material may not be used.

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*http://www.faa.gov/airports_airtraffic/airports.

†Nonstandard bases are subject to maximum and minimum limits on the elastic modulus.

‡Nonstandard bases are subject to maximum and minimum limits on the elastic modulus.

Table 12.7 Minimum Aggregate Base Course Thickness

Gear type	Design load range lb	kg	in.	Minimum base course (P-209) thickness (mm)
S	30,000–50,000	13,600–27,700	4	100
	50,000–75,000	22,700–34,000	6	150
D	50,000–100,000	22,700–45400	6	150
	100,000–200,000[a]	45,400–90,700	8	200
2D	100,000–250,000[a]	45,400–113,400	6	150
	250,000–400,000[a]	113,400–181,000	8	200
2D(B757,B767	200,000–400,000[a]	90,700–181,000	6	150
2D or 2D/D1 (DC10,L1011)	400,000–600,000[a]	181,000–272,000	8	150
2D/2D2 (B747)	400,000–600,000[a]	181,000–272,000	6	150
	600,000–850,000[a]	272,000–385,600	8	200
2D/D1 or 2D/2D1(A340)	568,000–840,000	257640–381,200	10	250
2S(C130)	75,000–125,000	34,000–56,700	4	100
	125,000–175,000[a]	56,700–79,400	6	150
3D (B777)	537,000–777,000[a]	243,500–352,440	10	250
3D (A380)	1,239,000–1,305,125[a]	562,000–592,000	9	230

[a] Values are listed for reference. However, when the traffic mixture includes airplanes exceeding 100,000 lbs (45,400 kg) gross weight, a stabilized base is required.
Source: FAA.

Subbase may be layered; more than one material may be used but granular layers may not be sandwiched between stabilized layers.

Subgrade

The subgrade is assumed to be of infinite depth and characterized by a soil modulus or CBR. The subgrade compaction requirements for flexible pavements are shown in Table 12.7.

Example 12.4 Design of a Flexible Pavement (FAA)

Input Data

Design life: 20 years

Pavement Constituents

Surface course: P-401 / P403 HMA surface course
Base: P-401 / P-403 stabilized (flexible)
Subbase: P-208 crushed aggregate
Subgrade: CBR 8.0

Aircraft Mix

	Type	Annual departures	% Annual growth
1	A320-100	600	0.0
2	A340 600	1000	0.0
3	A380-800	300	0.0
4	B737-800	2000	0.0
5	B747-400 combi	400	0.0
6	B747-400ER passenger	300	0.0
7	B757-300	1200	0.0
8	B767-400 ER	800	0.0
9	B777-300 ER	1000	0.0
0	B787-8	600	0.0
1	A340-200	1200	0.0

Figures 12.11, 12.12, and 12.13 show the output windows of the completed design.

These charts (e.g., Figure 12.12) provide a "critical pavement thickness" for use in areas where traffic is highly concentrated. In areas of dispersed traffic, thinner pavements may be used, as indicated in Figure 12.14.

As a general rule of thumb the designer should specify full pavement thickness T where departing aircraft will be using the pavement; pavement thickness of $0.9T$ will be specified where traffic will be arrivals such as high-speed turn-offs; and pavement thickness of $0.7T$ will be specified where pavement is required but traffic is unlikely, such as along the extreme outer edges of the runway (8).

California Bearing Ratio Method

An older method of designing flexible pavements is based on the California bearing ratio (CBR). This method of pavement design was developed in the late 1920s by the California Division of Highways. It was modified and adopted for airfield pavement

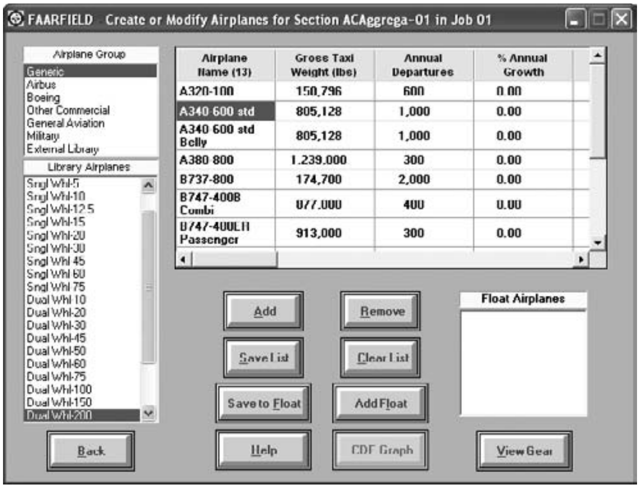


Figure 12.11 FAARFIELD airplane window: flexible-pavement example.

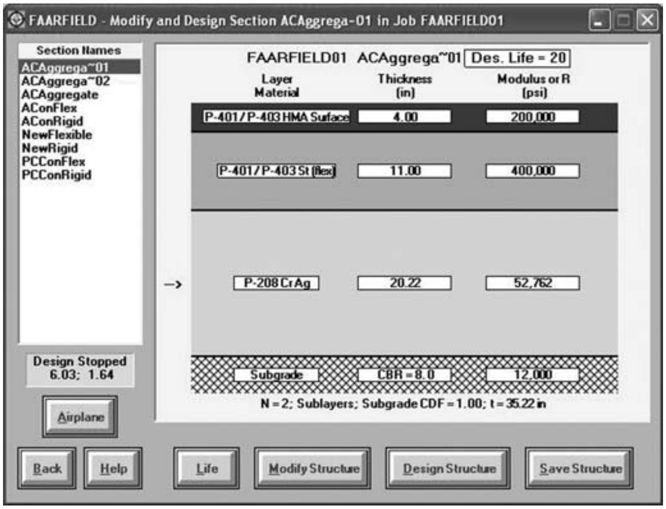


Figure 12.12 FAARFIELD structure Window: flexible-pavement example.

design by the Corps of Engineers at the beginning of World War II. Since its adoption, it has been further modified on the basis of empirical and theoretical studies to account for high-pressure tires and multiple-wheel landing gears.

The Departments of the Army and Air Force (12) recommended that the laboratory CBR test not be used in determining CBR values of base courses. Instead, selected CBR ratings have been assigned, as shown below:

Type	Design CBR
Graded crushed aggregate	100
Water-bound macadam	100
Dry-bound macadam	100
Bituminous intermediate and surface courses, central plant, hot mix	100
Limerock	80
Stabilized aggregate	80

The Corps of Engineers conducted extensive full-scale tests of airport pavements during the 1950s. Analysis of the results of those tests and studies of the performance of pavements in actual service indicated that the CBR design criteria for single-wheel loads could be expressed by two parameters: thickness/(contact area)$^{1/2}$ and CBR/tire pressure (14). These parameters were shown in the form of a single curve that separated service failures and nonfailures for capacity operations (5000 coverages of the pavement). The curve is expressed mathematically as follows:

$$t = \left[\frac{P}{8.1(\text{CBR})} - \frac{A}{\pi} \right]^{1/2} \tag{12.11}$$

where

t = design thickness (in.)
P = single-wheel load (lb)
A = measured tire contact area (in.^{2})

In 1959, the equation was modified to account for load repetitions and multiple-wheel configurations. The modified equation employed the concept of an equivalent single-wheel load (ESWL):

$$t = f\left[\frac{\text{ESWL}}{8.1(CBR) - A/\pi}\right]^{1/2} \tag{12.12}$$

Section ACAggrega~01 in Job FAARFIELDPCRIGID01
Working directory is C:\Program Files\FAA\FAARFIELD

The structure is New Flexible. Asphalt CDF was not computed.
Design Life = 20 Years
A design for this section was completed on 02/23/10 at 19:55:37.

Pavement Structure Information by Layer, Top First

No.	Type	Thickness, in.	Modulus, psi	Poisson's Ratio	Strength *R*,psi
1	P-401/P-403 HMA Surface	4.00	200,000	0.35	0
2	P-401/P-403 St (flex)	11.00	400,000	0.35	0
3	P-208 Cr Ag	19.88	57,845	0.35	0
4	Subgrade	0.00	12,000	0.35	0

Total thickness to the top of the subgrade = 35.88 in

Airplane Information

No.	Name	Gross Wt, lb	Annual Departures	% Annual Growth
1	A320-100	150,796	600	0.00
2	A340-600 std	805,128	1,000	0.00
3	A340-600 std Belly	805,128	1.000	0.00
4	A380-800	1,239,000	300	0.00
5	B737-800	174,700	2,000	0.00
6	B747-400B Combi	877,000	400	0.00
7	B747-400ER Passenger	913,000	300	0.00
8	B757-300	273,500	1,200	0.00
9	B767-400 ER	451,000	800	0.00
10	B777-300 ER	777,000	1,000	0.00
11	B787-8 (Preliminary)	486,000	600	0.00
12	A340-200 std	568,563	1,200	0.00
13	A340-200 std Belly	568,563	1,200	0.00

Additional Airplane Information

Subgrade CDF

No.	Name	CDF Contribution	CDF Max for Airplane	P/C Ratio
1	A320-100	0.00	0.00	1.21
2	A340-600 std	0.05	0.05	0.59
3	A340-600 std Belly	0.00	0.03	0.58
4	A380-800	0.01	0.01	0.42
5	B737-800	0.00	0.00	1.22
6	B747-400B Combi	0.01	0.01	0.57
7	B747-400ER Passenger	0.01	0.02	0.57
8	B757-300	0.00	0.00	0.73
9	B767-400 ER	0.03	0.05	0.60
10	B777-300 ER	0.85	0.85	0.40
11	B787-8 (Preliminary)	0.03	0.03	0.58
12	A340-200 std	0.00	0.00	0.59
13	A340-200 std Belly	0.00	0.00	1.17

Figure 12.13 FAARFIELD summary Window: flexible-pavement example.

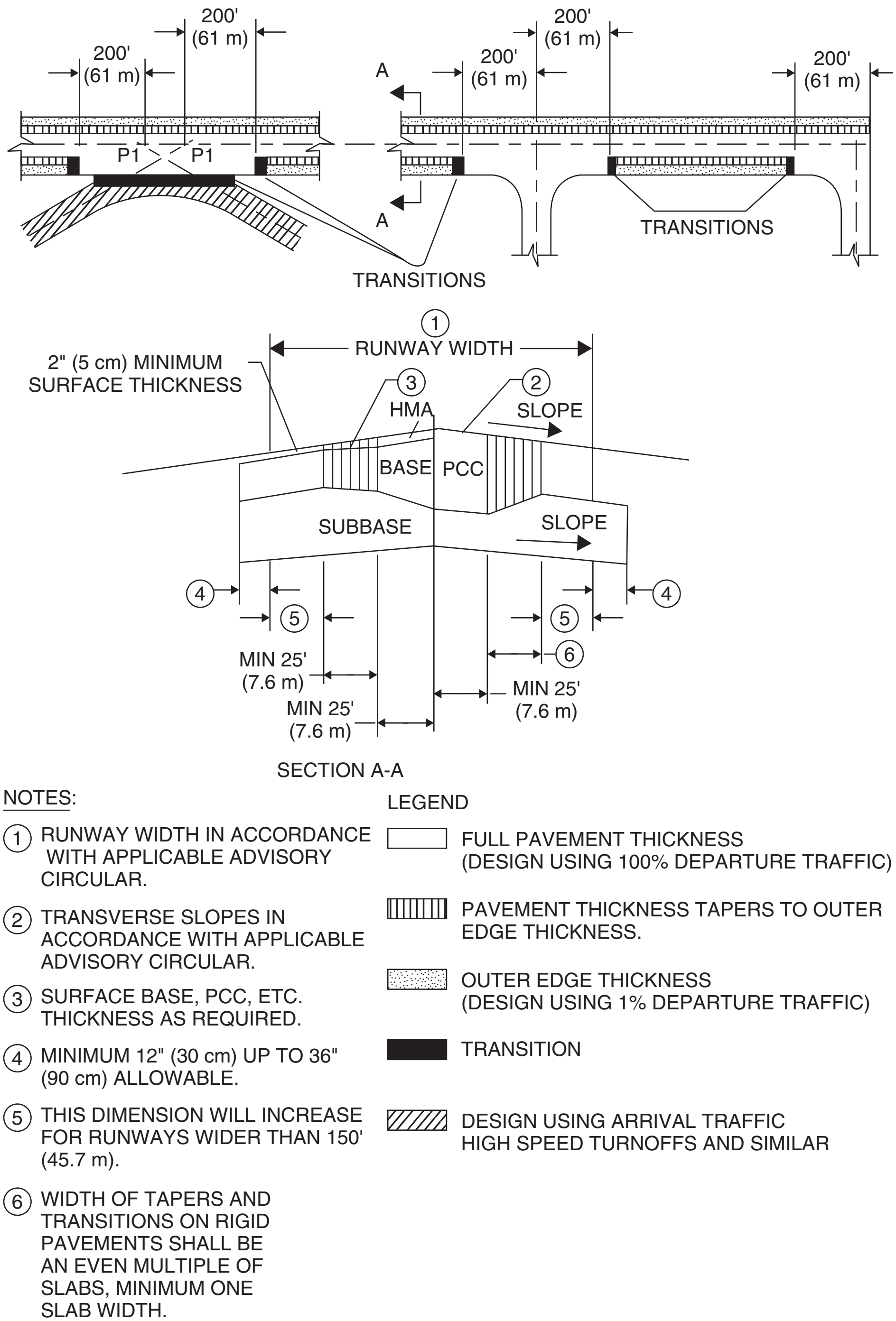


Figure 12.14 Typical plan and cross section for runway pavement showing critical and non-critical areas (flexible and rigid pavements).

where

f = percentage of design thickness (0.23 log c + 0.15)
ESWL = equivalent single-wheel load, defined as that "load on a single tire that produces the same vertical deflection on the supporting medium as that particular multiple-wheel assembly with the same single-wheel tire contact area" (14)
c = coverage, sufficient wheel passes to cover every point of a traffic land once

In the late 1960s, the Waterways Experiment Station studied pavement thickness requirements for aircraft with multiple-wheel heavy gear loads. Such aircraft were defined as those with gross loads exceeding 600 kips (e.g., the C-5A and the Boeing 747). That research indicated that equation 12.12 for low-intensity traffic is adequate for all wheel-gear configurations. However, with an increase in coverages, the equation yields thicknesses that are too great. The better pavement performance for multiwheel configurations was attributed in part to "interior soil confinement afforded by a larger number of perimeter wheels" (12). Therefore, the equation was further modified as follows:

$$t = a_i \left[\frac{\text{ESWL}}{8.1(\text{CBR})} - \frac{A}{\pi} \right]^{1/2} \qquad (12.13)$$

where

a = load repetition factor, which depends on the number of wheels in each main landing gear assembly used to compute the ESWL

The load repetition factor allows design for any desired number of aircraft passes (i.e., operations). Table 12.8 lists representative load repetition factors.

Equation 12.11 is recommended for CBR values of 15 or less. For CBR values greater than 15, a minimum pavement thickness based on durability may apply.

For a given aircraft load and wheel assembly configuration, it is possible to compute equivalent single-wheel loads for various depths based on the theory of elasticity. [Detailed procedures for making such calculations have been described by Ahlvin (13).] By solving equation 12.11 for CBR, one may then develop a CBR–design thickness curve for a particular aircraft.

A simple graphical procedure based on the CBR is recommended for the design of flexible pavements for military airfields. Fourteen CBR design curves (Table 12.9), exemplified by Figure 12.15, have been published (11) for various classes of military usage and gear configurations (see Table 12.10).

Table 12.8 Recommended Load Repetition Factors a_i for Use in Equation 12.11

	Number of tires used to compute ESWL				
Number of passes	1	2	4	12	24
1,000	0.72	0.70	0.68	0.65	0.64
5,000	0.83	0.77	0.73	0.69	0.67
10,000	0.88	0.81	0.76	0.70	0.68
100,000	1.03	0.88	0.79	0.72	0.69

Source: Hammitt II, G. M., et al., *Multiple-Wheel Heavy Gear Load Pavement Tests*, Vol. 4, Technical Report S-71-17, prepared for the U.S. Army Engineer Waterways Experiment Station, November 1971.

Table 12.9 CBR Flexible-Pavement Design Curves (11)

Army Class I airfield, type B and C traffic areas
Army Class II airfield, type B and C traffic areas
Army Class III airfield, type B and C traffic areas
Navy and Marine Corps single-wheel aircraft, 150 psi tire pressure, type B and C traffic areas
Navy and Marine Corps single-wheel aircraft, 400 psi tire pressure, type B and C traffic areas
Navy and Marine Corps dual-wheel aircraft, type B and C traffic areas
Navy and Marine Corps C–5A aircraft, type B and C traffic areas
Air Force light-load pavement, type B and C traffic areas and overruns
Air Force medium-load pavement, type A traffic areas
Air Force medium-load pavement, type B, C, and D traffic areas and overruns
Air Force heavy-load pavement, type A traffic areas
Air Force heavy-load pavement, type B, C, and D, traffic areas and overruns
Air Force shoulder pavement
Air Force short-field pavement, type A traffic areas, and overruns

Table 12.10 Landing Gear Conversion Factors

To convert from	To	Multiply departures by
Single wheel	Dual wheel	0.8
Single wheel	Dual tandem	0.5
Dual wheel	Dual tandem	0.6
Double dual tandem	Dual tandem	1.0
Dual tandem	Single wheel	2.0
Dual tandem	Dual wheel	1.7
Dual wheel	Single wheel	1.3
Double dual tandem	Dual wheel	1.7

Source: FAA.

The following procedure is recommended for use of the curves:

1. Determine design CBR of subgrade.
2. Enter the top of the graph with the design subgrade CBR and follow it downward to the intersection with the appropriate gross weight curve.
3. From the point of intersection, extend a horizontal line to appropriate aircraft passes curve, then downward to the required total pavement thickness above subgrade.

The thickness of the surface and base course can be determined by a similar procedure and by entering the graph with the design CBR of the subbase material. It may be necessary to increase the thickness of the surface and base indicated by the graph to a required minimum thickness. Each of the military services specifies a minimum combined thickness of base and surface, which depends on conditions of loading, traffic, and strength of the base. The thickness of the subbase can be determined by subtracting the thickness of the surface and base from the total thickness. A minimum thickness of 6 in. is usually recommended for the subbase.

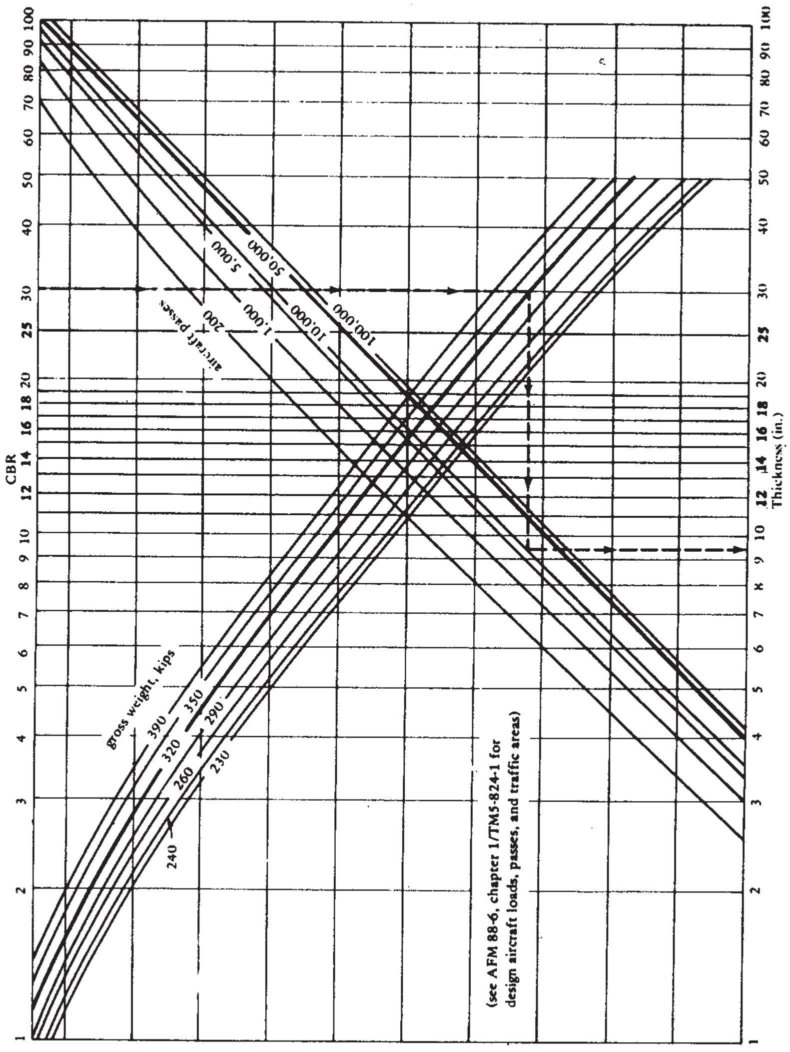


Figure 12.15 Example of CBR design curve (15).

The CBR method of design of flexible aircraft pavements is shown for reference purposes only. It has been superseded by the FAA method discussed in previous sections.

12.7 RIGID-PAVEMENT DESIGN METHODS (U.S. PRACTICE)

Ray, Cawley, and Packard (14) have outlined significant historical milestones that led to present-day rigid-pavement design procedures. They credit Dr. H. M. Westergaard with the first serious effort to develop a theoretical design procedure for airport pavements. Westergaard's research (15), which was performed for the Portland Cement Association and first published in 1939, resulted in design equations that were used during World War II for the design of many military airports.

In 1948, Westergaard published a new set of formulas for the calculation of stresses in concrete airfield pavements (16). Using Westergaard's formulas, Pickett and Ray developed influence charts for analyzing pavement stresses and published them in transactions of the ASCE in 1951 (17). Westergaard's equations and Pickett's and Ray's charts have been widely used since that time. Packard developed a computer program for the design of concrete pavements that was first published by the Portland Cement Association (PCA) in 1967 (18).

Concrete pavement design procedures in the United States have also been influenced by full-scale pavement research conducted by the Corps of Engineers and the Navy. These agencies, as well as the FAA (earlier known as the CAA) and the PCA, published design procedures reflecting pavement condition surveys that were made to evaluate pavement performance with respect to the thickness design procedures employed. The PCA conducted such a survey in the late 1940s in cooperation with the CAA. The PCA performed additional surveys at civilian airports in 1962 and 1963 (19) and at military airports in 1956, 1965, and 1966. During this period, the Corps of Engineers monitored pavement performance at Air Force bases, and the Navy performed pavement evaluation studies at Naval Air Stations in the United States and overseas.

Ray et al. (14) compared four methods for designing and determining the thickness of rigid airport pavements. The methods employed by the FAA, the PCA, the U.S. Navy, and the Corps of Engineers were examined. Differences were noted in assumed loading condition, the recommended safety factor, the curing period for determination of concrete strength, the level of traffic, and the use of a saturation correction for sensitive subgrade soils. Despite these differences, the writers reported (15):

> Differences in design assumptions balance one another so that approximately the same slab thicknesses are obtained by the four procedures. . . . This similarity of design results is not surprising because each procedure was developed from the Westergaard analysis and coupled with safety factors or other adjustment to reflect performance experience.

Since that work was published, advances in methods of analysis have allowed the FAA to develop a new procedure that permits the analysis of pavements to be carried out using three-dimensional finite-element analysis for the computation of stresses in concrete slabs. In the following description of this recommended FAA design method, we have drawn freely on reference 8.

FAA Method of Rigid-Pavement Design

General. Rigid pavements for airports are constructed from a thickness of PCC laid on a granular or treated subbase course supported by a compacted subgrade. With the publication of reference 8, the FAA set out a new recommended method of design of rigid pavements for airports using three-dimensional finite-element analysis for the computation of the stresses in concrete slabs. The method is able to compute the critical stresses in slabs which usually occur at slab edges and is applicable therefore to new rigid-pavement design and the design of rigid overlays.

Only one mode of failure for the rigid pavement is considered, the cracking of the concrete slab, which is controlled by limiting the horizontal stress at the bottom of the slab. The design procedure is carried out by the FAARFIELD program which is available from the FAA (10). The method used is to input the airplane loading plus the subbase and subgrade data and iterate on the concrete layer thickness until the CDF (cumulative damage factor) is 1.0. On reaching this value the program indicates the design conditions are satisfied and the pavement design solution is declared.

Pavement Considerations. **Concrete Pavement.** The pavement must provide a durable surface with good nonskid performance, must have a texture that prevents the infiltration of water into the subgrade, and must provide structural strength to support the applied loads from aircraft. The FAA sets out standards for the quality of the concrete, quality testing, methods of construction and handling, and quality of workmanship in reference 8.

Subbase. Although theoretically there is no need for a subbase below a PCC pavement slab, the FAA recommends a minimum 4-in. (102-mm) subbase course according to a recommended specification. A variety of subbase materials are authorized by reference 8. Stabilized materials are required for subbases under rigid pavements serving airplanes weighing 100,000 lb (45,359 kg) or more. These stabilized materials include the cement-treated base course, econocrete base course, and plant mix bituminous pavement course materials. More than one layer of subbase material may be used, but the layering process must not sandwich a granular layer between two stabilized layers.

Subgrade. The subgrade compaction requirements of rigid pavements are the same as those for flexible pavements and are shown in Table 12.6. Where softer subgrades are found, there is a danger that the cyclic loading of the pavement may cause an intermixing of the subbase and the subgrade, which can subsequently create voids that cause pavement foundation pumping. Geosynthetic membranes can be used to avoid this problem.

In addition to the soil survey and the classification of the soil foundation according to the USCS, the design of a rigid pavement requires the determination of the foundation modulus that can be assigned to the subgrade. This can be expressed as the modulus of subgrade reaction (k) or the elastic (Young's) modulus E. Either can be used as input to the design program as they are automatically linked in the calculations by the equivalency equation

$$E_{SG} = 26k^{1.284}$$

If they are accessible, the k modulus for existing pavements can be determined directly by plate-load testing. Inaccessible subgrades can be assessed by determining the elastic modulus E from nondestructive tests (NDTs) such as the falling-weight deflectometer; the procedures for plate bearing tests are given in reference 20. Where only CBR tests are practical, the modulus of the subgrade reaction can be computed by

$$k = (1500 \times \text{CBR}/26)^{0.7788}$$

Caution and engineering judgment are needed in the use of this conversion for the selection of a design value of k from the CBR because the values obtained are approximate.

Determination of Concrete Slab Thickness. FAARFIELD computes the concrete stresses on the assumption of edge loading of the slab. The airplane gear is assumed to be tangential (parallel) or perpendiculat to the slab edge. The larger of two stresses is selected but reduced by 25% to allow for load transfer through the slab joints. This reduced stress is taken as the design stress for slab thickness computation.

Design Inputs. **Concrete Strength**. The flexural strength of concrete is set to meet the specification of P-501, with a minimum flexural strength of 600–700 psi, when measured according to ASTM C78. The minimum thickness of concrete surfacing is 6 in. for pavements to serve aircraft with gross weights in excess of 30,000 lb (13,608 kg). A fixed modulus of 4,000,000 psi (27,580 MPa) has been set in the program for concrete in order that the results of the design would approximate those obtained in designs by the former FAA method using Westergaard design curves:

Subgrade Modulus. Subgrade modulus is input as either the E or k value.

Design Life in Years. For FAA purposes this is normally assumed to be 20 years. The program is able to accept other design life inputs.

Structural Layer Data.FAARFIELD can accept up to three subbase layers for a new rigid design. For standard base/subbase materials, the Poisson ratio and modulus are built in to the program. For variable stabilized and undefined layers, the user is able to set values for these. Materials for the subbase are identified by their corresponding FAA design specifications.

Airplane Mix. The user inputs specific information for the aircraft type (which automatically uploads the aircraft gross weight), the number of annual departures, and the percentage annual growth of traffic.

Outputs

Minimum Layer Thickness. The program calculates the thickness of the PCC slab only. However, it enforces minimum thickness standards to subbase layers as specified in the AC

Critical and Noncritical Areas. The program computes the depths of pavement in noncritical areas achieved by reducing the concrete slab thickness in locations where traffic is light or likely to be spread from a single track, as set out in Figure 12.14.

Example 12.5 Design of a Rigid Pavement (FAA)

Input Data

Design life: 20 years

Pavement Constituents

Surface and base course: PCC surface course over 6 in./P-306 econocrete

Subbase: P-209 crushed aggregate

Subgrade: CBR 8.0

Aircraft Mix

No.	Airplane name	Gross taxi weight (lb)	Annual departures	% Annual growth
1	B747-400B combi	877,000	800	0.00
2	B777-200ER	657,000	1,200	0.00
3	Adv.B727-200 option	210,000	1,200	0.00

Output

The program output is shown in Figures 12.16–12.18. The pavement should have a 16-in. PCC slab on a base of 6 in. of P-306 econocrete, with a subbase of 6 in. of P-209 crushed aggregate.

Reinforced-Concrete Pavement

Reinforced steel placed in concrete pavements helps to maintain structural integrity across cracks that develop in the slab. Reinforced pavements require fewer joints and less joint maintenance, and there are fewer problems associated with joints, such as pavement pumping. It is claimed that reinforced pavements last longer than plain concrete pavements.

There are two types of reinforced-concrete pavement:

1. Conventional or jointed pavements
2. Continuously reinforced pavements

Steel used in conventional reinforced pavements is normally in the form of welded wire fabric or bar mats distributed throughout the concrete. The quantity of steel used should be sufficient to maintain aggregate interlock along the faces of the cracked

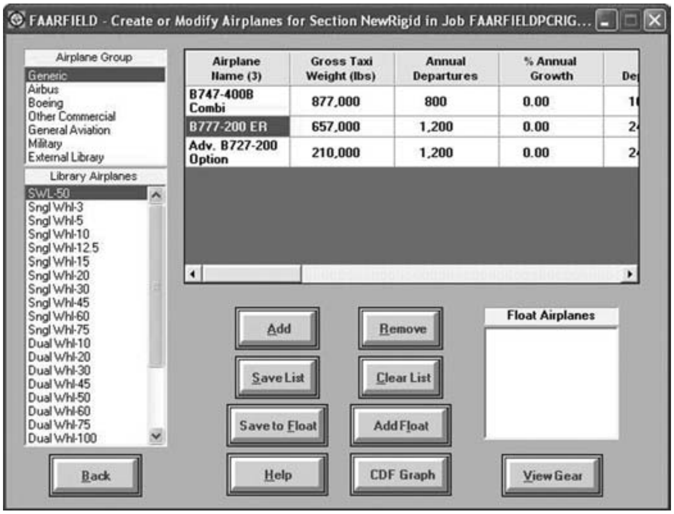


Figure 12.16 FAARFIELD rigid-pavement design: airplane loading window.

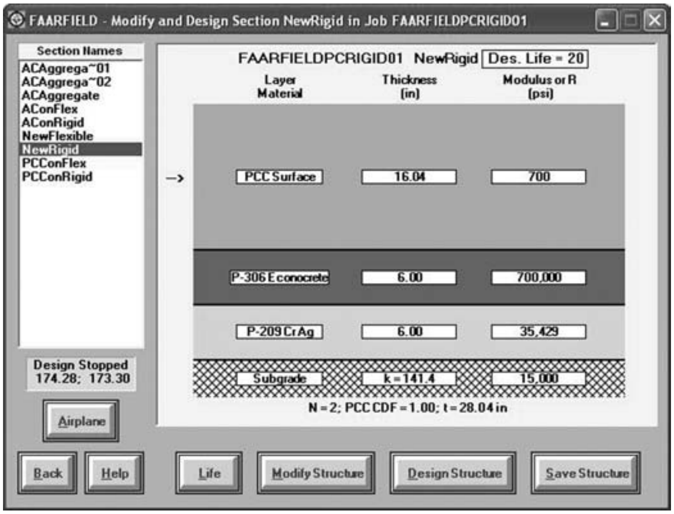


Figure 12.17 FAARFIELD rigid-pavement design: slab section design window.

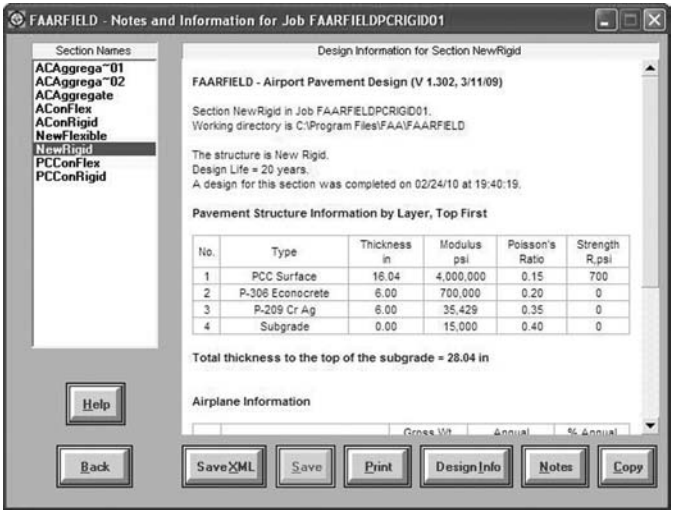


Figure 12.18 FAARFIELD rigid-pavement design: summary window.

slabs. The amount of steel in conventionally reinforced pavements depends on the joint spacing, slab thickness, and other factors; typically, 0.05–0.30% of the cross-sectional area of the pavement is steel (21).

A continuously reinforced concrete pavement has relatively heavy continuous steel reinforcement in the longitudinal direction and has no transverse joints except at intersections with existing pavements or structures. The amount of longitudinal steel in continuously reinforced pavements is typically 0.6% of the gross cross-sectional area of the pavement (21).

Reinforced-concrete pavements have not been extensively used in the United States. Most designers here prefer to avoid the added costs of steel reinforcement and to control slab cracking by judicious design and placement of joints. However, serious consideration should be given to the use of reinforcement in situations where special cracking problems are likely to occur. For example, the Corps of Engineers (20) requires reinforcement to control cracking (a) in odd-shaped slabs, (b) at mismatched joints in adjacent pavements, (c) in pavements incorporating heating pipes, (d) in pavements containing utility blockouts, such as storm drainage inlets, hydrant refueling outlets, and certain types of flush lighting fixtures, and (e) in overlay pavements where it is not feasible to match the joint pattern in the lower pavement.

More detailed information on the amount, size, spacing, and strength of reinforcing steel for concrete pavements is given in the literature (8, 20, and 21).

Jointing of Concrete Pavements

Variations in temperature and moisture content produce volume changes and warping of pavement slabs and cause significant stresses to occur. To reduce the effects of these stresses and to control pavement cracking, joints are installed. By this means, the pavement is divided into a series of slabs of predetermined dimensions. The slabs should be approximately square or as near as is possible.Various types of joints are shown in Figure 12.19; typical uses of these joints are described in Table 12.11.

Table 12.11 Pavement Joint Types

Type	Description	Longitudinal	Transverse
A	Thickened edge isolation joint	Use at intersections where dowels are not suitable and where pavements abut structures; consider at locations along a pavement edge where future expansion is possible	Use at pavement feature intersections when the respective longitudinal axis intersects at an angle; use at the free edge of pavements where future expansion, using the same pavement thickness, is expected
B	Hinged contraction joint	For all contraction joints in taxiway slabs < 9 in. (230 mm) thick; for all other contraction joints in slabs, 9 in. (230 mm) thick, where joint is placed 20 ft (6 m) or less from pavement edge	Not used
C	Doweled contraction joint	May be considered for general use; consider for use in contraction joints > 9 in. (230 mm) thick, where joint is placed 20 ft (6 m) or less from pavement edge	May be considered for general use; use on last three joints from a free edge and for three joints either side on an isolation joint
D	Dummy contraction joint	For all other contraction joints in pavement	For all other contraction joints in pavement
E	Doweled construction joint	All construction joints excluding isolation joints	Use for construction joints at all locations separating successive paving operations, “headers”

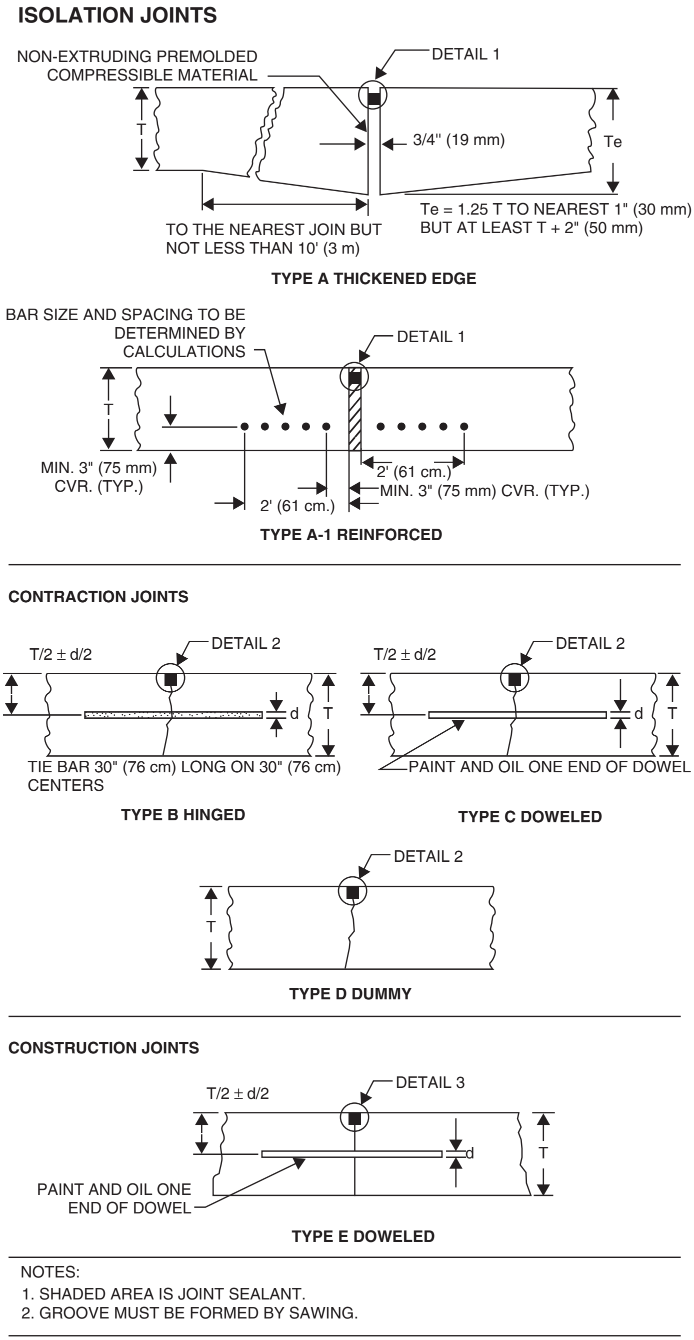
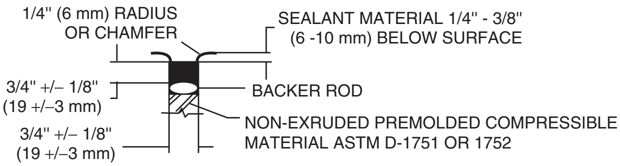
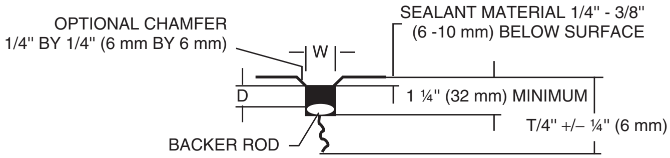


Figure 12.19 Details of joints in rigid pavement (8).

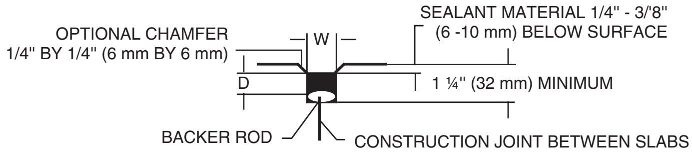
DETAIL 1
ISOLATION JOINT



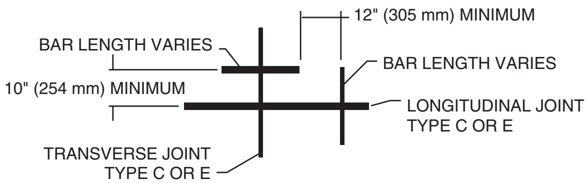
DETAIL 2
CONTRACTION JOINT



DETAIL 3
CONSTRUCTION JOINT



PLAN VIEW
POSITION OF DOWELS AT EDGE OF JOINT
TYPE C, E



NOTES:
1. SEALANT RESERVOIR SIZED TO PROVIDE SHAPE FACTOR, W/D. FIELD POURED AND PERFORMED SEALANTS REQUIRE DIFFERENT SHAPE FACTORS FOR OPTIMUM PERFORMANCE.
2. BACKER ROD MATERIAL MUST BE COMPATIBLE WITH THE TYPE OF SEALENT USED AND SIZED TO PROVIDE THE DESIRED SHAPE FACTOR.
3. RECESS SEALER 3/8–1/2 IN (10–12mm) JOINTS PERPENDICULAR TO RUNWAY GROOVES.
4. CHAMFERED EDGES ARE RECOMMENDED FOR DETAILS 2 AND 3 WHEN PAVEMENTS ARE SUBJECT TO SNOW REMOVAL EQUIPMENT OR HIGH TRAFFIC VOLUMES.

Figure 12.19 *(Continued)*

There are three functional classes of pavement joints: isolation, contraction, and construction joints:

1. *Isolation joints* provide space for the expansion of the pavement and are most commonly used between intersecting pavements and adjacent to structures. Two types of expansion joints are used: those with a thickened edge (type A, Figure 12.19), and those with a reinforced edge (type A-1).
2. *Contraction joints* provide controlled cracking of the pavement that occurs because of contraction, caused by a decrease in moisture content, a drop in temperature, or the shrinkage which accompanies the curing process. Contraction joints also reduce the stresses caused by slab warping. Details for contraction joints are shown as types B, C, and D in Figure 12.19.
3. *Construction joints* are required when two abutting slabs are constructed at different times, such as the end of a work day, or between paving lanes. Details for construction joints are shown as type E in Figure 12.19 (8).

Experience has shown that poor performance may result if keyed longitudinal construction joints are used in pavements accommodating wide-bodied jet aircraft when the subgrade modulus is less than 400 pci. Specific recommendations for such conditions are given in reference 8.

Table 12.12 summarizes the recommended spacing of joints for nonreinforced pavements.

12.8 PAVEMENTS FOR LIGHT AIRCRAFT

Some airports serving light aircraft may not require an all-weather pavement; an aggregate-turf surface may be adequate. However, it is seldom possible to provide and maintain a stable turf surface because of heavy traffic or adverse weather conditions. Some areas of airports serving light airplanes may not require bituminous or concrete paving. A turf or aggregate turf surface may be sufficient in these ares. Such surfaces are constructed by improving the stability of the natural soil with the addition of aggregate prior to turfing. Light flexible pavements are generally used for pavements serving lightweight aircraft, and a high type plant mix bituminous surface course is preferred.

Light Flexible Pavements

These consist of surfacing, base, subbase, and subgrade. Like pavements for heavier aircraft, these may be designed using the FAARFIELD design program. The FAA specifies the subgrade compaction requirements in reference 8 as well as minimum pavement thicknesses:

Hot-mix asphalt surfacing: 2 in. (50 mm) minimum

Base: 3 in. (75 mm) minimum

Additional layer thickness may be required to achieve construction requirements.

Table 12.12 Recommended Maximum Joint Spacings—Rigid Pavement with or without Stabilized Base

Part I, Without Stabilized Base			
Slab Thickness		Joint Spacing[a]	
in.	mm	ft	m
6	152	12	3.8
6.5–9	165–229	15	4.6
>9	>229	20	6.1

Part II, With Stabilized Base			
Slab Thickness		Joint Spacing[a]	
in.	mm	ft	m
8–10	203–254	12.5	3.8
10.5–13	267–330	15	4.6
13.5–16	343–406	17.5[b]	5.3[b]
>16	>406	20	6.1

[a]Transverse and longitudinal joint spacing.
[b]For typical runway and taxiway geometries, the corresponding longitudinal joint spacing is 18.75 ft (5.7 m).
Notes:
Joint spacings in this table are maximum values that may be acceptable under ideal conditions.
Smaller joint spacings may be used if indicated by past experience.
Pavements subject to extreme seasonal temperature differentials or extreme temperature differentials during placement may require shorter joint spacings.
Jointing for light load rigid pavements is covered in reference 8.

Light Rigid Pavements

These pavements consist of:

PCC base

Subbase: Rigid pavements designed to serve airplanes between 12,500 lb (5670 kg) and 30,000 lb (13,608 kg) require a minimum base of 4 in. (102 mm). No subbase is required for designs to serve aircraft of less than 12,500 lb except when poor soil conditions are encountered.

Subgrade: AC150/5320 – 6E specifies the degree of compaction required of the subgrade.

The use of FAARFIELD is not necessary for light-duty rigid pavement design. The following pavement thicknesses are recommended by the FAA:

Rigid pavements for aircraft 12,500 lb (5670 kg) or less: 5 in. (127 mm) or 6 in. (152 mm) if dowelled joints are used

Rigid pavements for aircraft between 12,501 lb (5670 kg) and 30,000 lb (13,608 kg): 6 in.

All pavement areas should have the same pavement thicknesses; there are no reductions in thickness in lightly traveled sections.

12.9 AIRCRAFT AND PAVEMENT CLASSIFICATION NUMBERS

In 1981, the ICAO (22) proposed the aircraft classification number/pavement classification number (ACN/PCN) method for classifying the load ratings of aircraft and bearing strengths of aircraft pavements. Because this method is not intended for pavement design, it is only briefly described here. It is described in more detail in references 22 and 23.

The ACN is a number expressing the relative loading severity of an aircraft on a pavement for a specifed standard subgrade strength. The PCN is a number expressing the bearing strength of a pavement for unrestricted operations (23). An aircraft with an ACN equal to or less than the PCN can operate without weight restriction on the pavement.

The procedure for determining ACNs is outlined below, first for flexible pavements and then for rigid pavements.

Determination of ACNs for Flexible Pavements

A graphical procedure, encompassing three steps, can be used to determine the ACN value for a flexible pavement.

Step 1. Using the pavement thickness requirement chart published by the manufacturer, determine the thickness of pavement that will allow 10,000 load repetitions by the main wheel gear for the specified aircraft mass and subgrade category. This thickness is known as the reference thickness, t_c. ACNs are normally computed at two different masses: maximum apron mass and a representative operating mass empty. Four subgrade categories are used for flexible pavement based on the CBR. (See Table 12.13.)

Step 2. Using the reference thickness obtained in step 1, obtain a derived single-wheel load for the selected subgrade category from Figure 12.20. The derived single-wheel load is that load which, when applied to a pavement of thickness t_c, will induce the same applied stress to the pavement. For this step, a standard single-wheel tire pressure of 1.25 MPa (181 psi) is assumed.

Step 3. The ACN is computed as twice the derived single-wheel load, expressed in thousands of kilograms. In this instance, the ACN can be read directly from Figure 12.21.

Table 12.13 Subgrade Categories for ACN–PCN Method

Subgrade category	Modulus of subgrade reaction, psi/in. (rigid pavements)	California bearing ratio (flexible pavements)
High	550	15
Medium	300	10
Low	150	6
Ultralow	75	3

Source: Aircraft Loading on Airport Pavements, ACN-PCN, Aerospace Industries Association of America, Washington, DC, March 1983.

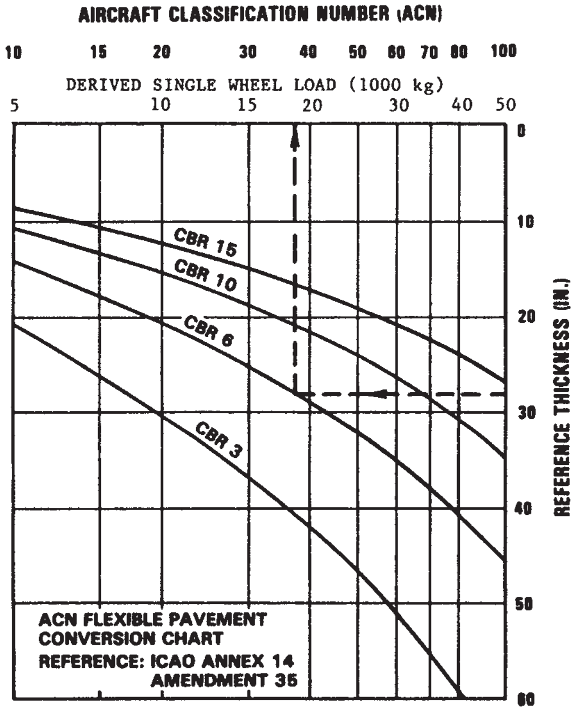


Figure 12.20 ACN flexible-pavement conversion chart.

Determination of ACNs for Rigid Pavements

This procedure differs only slightly from that described for flexible pavements, and it also involves three steps:

Step 1. Using the pavement thickness requirement chart published by the manufacturer and the specified aircraft mass, determine the thickness of the concrete slab which, when loaded at the center of one main wheel gear of the aircraft, gives a maximum flexural stress of 400 psi (2.75 N/mm) on a subgrade whose modulus of subgrade reaction is one of the standard values. (See Table 12.11.)

Step 2. Using the reference thickness obtained in step 1, obtain a derived single-wheel load for the selected subgrade category from Figure 12.21. Again, a standard single-wheel tire pressure of 1.25 MPa (181 psi) is assumed.

Step 3. The ACN is computed as twice the derived single-wheel load expressed in thousands of kilograms, or else it can be read directly from Figure 12.21.

Computer programs to determine ACN values have been developed by the U.S. Army Corps of Engineers Waterway Experiment Station and the PCA for flexible and rigid pavements, respectively (23). For many aircraft currently in use, ACN values have been published by the ICAO (24), eliminating the need to use the programs or the graphical procedures.

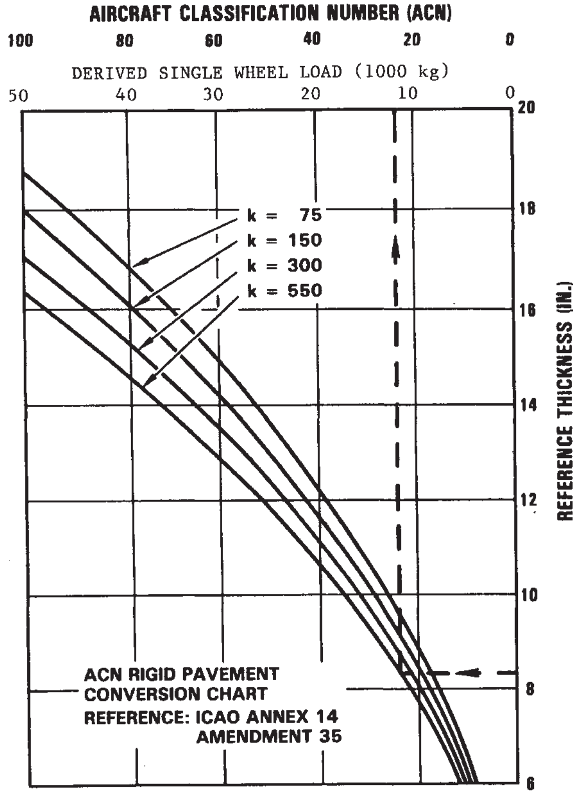


Figure 12.21 ACN rigid-pavement conversion chart.

Determination of PCNs

The airport authority is free to choose the method used to determine the PCN values of airport pavements. Two general approaches are commonly used: (a) make a technical evaluation and (b) base the load rating on aircraft experience.

If an airport pavement's basic or reference thickness and subgrade classification are known, a technical evaluation using Figures 12.16 and 12.17 can be used to determine the pavement classification number for the pavements. In the aircraft experience approach, the ACN of the most critical aircraft is determined using the steps previously described. This number is published as an equivalent PCN for the pavement.

The ICAO (24) recommends that, in addition to a PCN, airport authorities publish the following information about each pavement:

1. Pavement type rigid or flexible, indicated by R or F
2. Subgrade strength category (high, medium, low, ultralow—A, B, C, and D, respectively)
3. Maximum tire pressure allowable (high, medium, low, very low—W, X, Y, X)
4. Evaluation method used to establish the PCN. Technical or by experience: representing a knowledge of a specific type and mass of aircraft satisfactorily supported by the pavement under regular use—T and U, respectively

Typical pavement strength reporting using the ACN-PCN method would be

PCN60/F/B/W/T.

Any aircraft with an ACN of 60 or less could operate without any restrictions.

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13

Airport Access

13.1 ACCESS PROBLEM

In the early days of aviation, the access trip presented no substantial problem to the air traveler. The typical airport, or "aerodrome," of the 1920s and 1930s was sited on the periphery of the town it served. The relatively high cost of air travel meant that only a few individuals used the mode, in comparison with the large numbers using the railroad for intercity travel. These few travelers could reach the airport by car, driving over the relatively lightly traveled roads with low traffic volumes associated with urban fringe areas before World War II. By 1965, access to airports was very much affected by the separate impacts of rapid urbanization, the trend to almost universal car ownership, and the fall in real air travel costs which vastly increased the number of air trips made. Currently, a typical access journey for a traveler unable to use a direct special-purpose route involves travel by either auto or bus over congested suburban roads to an airport complex that has suffered continuous encroachment of suburban development. On arrival at the airport, the traveler is confronted with a high-volume interface bearing little resemblance to the informal air terminal of prewar days.

Figure 13.1 indicates the scale of changes in first-origin-to-final-destination times for a short-haul trip over the last 50 years. It indicates that potential time savings brought about by the introduction of jet aircraft have been partially or wholly negated by increases in surface access and terminal processing time, and this is the essence of the problem. Clearly, the impact of poor access has maximum implications for short-haul trips, where the proportion of access time to the overall trip time is high.

Definition of Access

There are no precise points marking where the access trip begins and where it ends. The designer cannot assume, therefore, that the access trip is over once the air passenger has arrived in the general vicinity of the air terminal.

Satisfactory design of the access system entails integrated care for the passenger's needs from the origin point of the trip until the beginning of terminal processing. Movement during terminal processing is normally regarded as a function of terminal design, but the better terminal designs have integrated consideration of access and terminal processing to ensure smooth interfacing of the submodes of the total air journey. In preparing the design of access systems, there are usually three major areas of consideration:

1. Collection and processing, if necessary, of passengers in the central area of the city and other centers of high demand

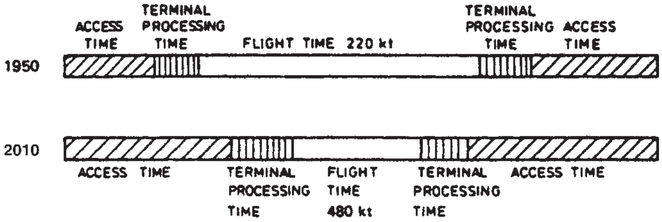

Figure 13.1 Comparison of short-haul city-center-to-city-center travel, 1950–2010.

2. Movement of passengers, cargo, and service traffic to the airport by surface or air vehicles
3. Distribution of access traffic and internal circulation traffic to terminals and gate positions

Access for Whom?

In planning an access system, the planner should discard the misconception that airport access is for air travelers only; in fact, at many airports, the travelers may be in the minority. The airport population is diverse, and any access mode must serve a number of disparate users:

Air travelers
Senders and greeters
Visitors
Employees
Air cargo access personnel
Persons who supply services to airport

The split of airport population between the various groups varies greatly between airports and depends on such factors as the airport size and function, the country of location, and such considerations as the number and size of based air carriers. Table 13.1 gives the estimated proportions of the various elements of the airport population for a number of facilities. It can be seen that there is a large variation in these figures. Each estimate itself hides large variations across time at the airport in question.

By the late 1980s, many of the world's largest airports had large numbers of employees working within the airport boundary. Very large airports such as London Heathrow, Frankfurt, Paris Charles de Gaulle, Atlanta, and Los Angeles have many thousands of employees. Surveys carried out by the Airport Council Interantional (ACI) and others (1, 2) indicate that some high-density airports have 900–1200 jobs per million annual WLU.* These figures result in a number of airports by 2010 having up to 100,000 workers on site, employed by all categories of companies. This equates to the entire population of a substantial town and generates the number of work trips equivalent to the central business district of a city of close to a million persons. The situation is aggravated by the tendency for development of non-aviation-related employment to occur off the actual airport site but in close proximity. Such is the case where either

*One work load unit (WLU) is equivalent to one passenger or 100 kg of freight.

Table 13.1 Proportion of Passengers, Workers, Visitors, and Senders/Greeters at Selected Airports

Airport	Passengers	Senders and greeters	Workers	Visitors
Frankfurt	0.60	0.06	0.29	0.05
Vienna	0.51	0.22	0.19	0.08
Paris–Orly	0.62	0.07	0.23	0.08
Amsterdam	0.41	0.23	0.28	0.08
Toronto	0.38	0.54	0.08	Not included
Atlanta	0.39	0.26	0.09	0.26
Los Angeles	0.42	0.46	0.12	Not included
New York–JFK	0.37	0.48	0.15	Not included
Bogota	0.21	0.42	0.36	Negligible
Mexico City	0.35	0.52	0.13	Negligible
Curaçao	0.25	0.64	0.08	0.03
Tokyo–Haneda	0.66	0.11	0.17	0.06
Singapore	0.23	0.61	0.16	Negligible
Melbourne	0.46	0.32	0.14	0.08
U.S. airports	0.33–0.56	—	0.11–0.16	0.31–0.42 (includes senders and greeters)

Source: Institut de Transport Aérien (ITA), Aix-en-Provence, France, and reference 1.

deliberately or not by design the area adjacent to the airport is developed into an *airport city*, which adds to the traffic within a corridor serving the airport. Clearly, the design of a movement system capable of serving adequately all movements to an airport and its vicinity is a major consideration in the selection of a suitable site and in the overall planning and design of any facility on the chosen location.

Access System

The potential complexity of the access system and the demand for facilities is sketched out in Figure 13.2. For the sake of simplicity, the system users considered are the "individuals" requiring access provision: passengers, visitors, and employees (air cargo is not shown). The requirements of in-town terminals, out-of-town or satellite terminals, and terminals at the airport are represented for a variety of modes. The infrastructure specified often depends greatly on whether a car is available to the individual. Road modes seldom cater to less than 70% of all access trips, but the airport designer should be aware that, even in the United States, with the world's highest car ownership, approximately one-quarter of the population has no available car. Implicitly, therefore, some public transport is necessary at all reasonably sized air carrier airports. The conventional solutions are limousine, special car, or bus service, which places minimal additional infrastructure demand on a system essentially designed for private automobile access. At large airports, with large numbers of terminating passengers, access by auto and limousine only is likely to be prohibitively expensive to the community from the viewpoint of providing adequate access routes outside the airport boundary. There are also substantial problems resulting from the requirements for internal circulation roads and parking requirements. At such large airports, mass transit facilities must

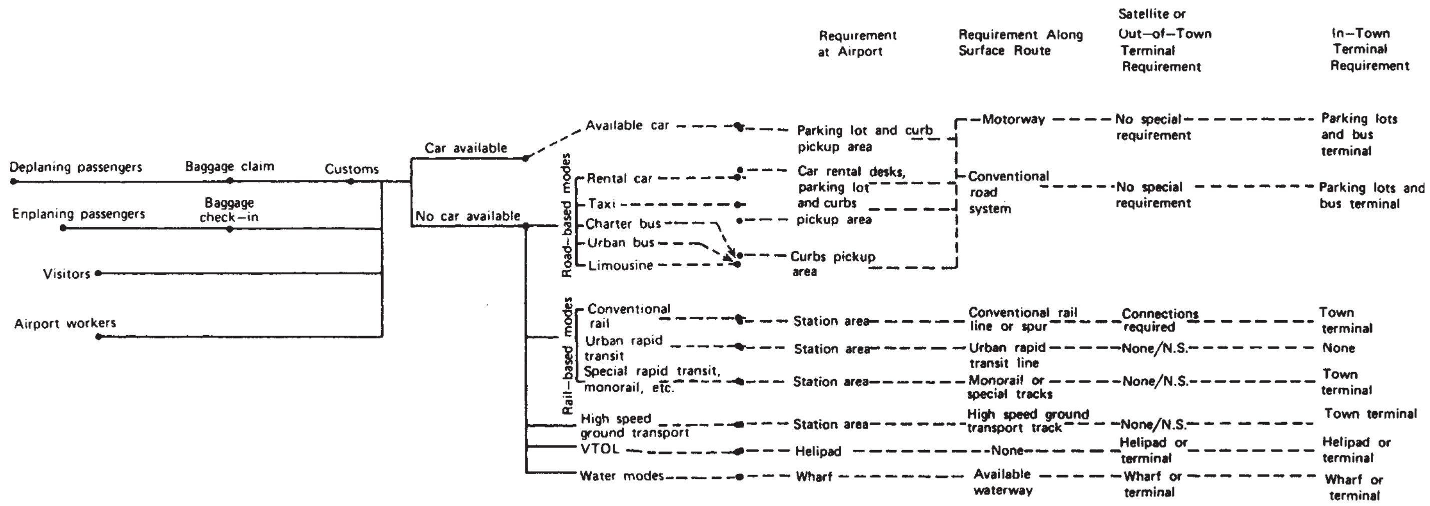

Figure 13.2 Access system.

be provided on and off the airport to permit higher density access movements, and Figure 13.2 shows that the infrastructure requirements for the higher density systems, such as conventional rail (e.g., London-Gatwick, Amsterdam), special rail (London Heathrow, Munich, Tokyo Narita), urban rapid transit (e.g. Atlanta, London-Heathrow), or TGV* (Paris CdeG), are substantial.

Careful site planning is required for the terminal facilities and rights-of-way on the airport. Additionally, airport planners find themselves closely involved in many aspects of the planning and design of these facilities outside the airport boundary, even though the airport may not be financially involved in these areas.

13.2 DETERMINING MIX OF ACCESS MODES

Figure 13.3 presents a simplified conceptual model of the process by which the mix of access modes is selected. Demand estimates over time for passengers, employees,

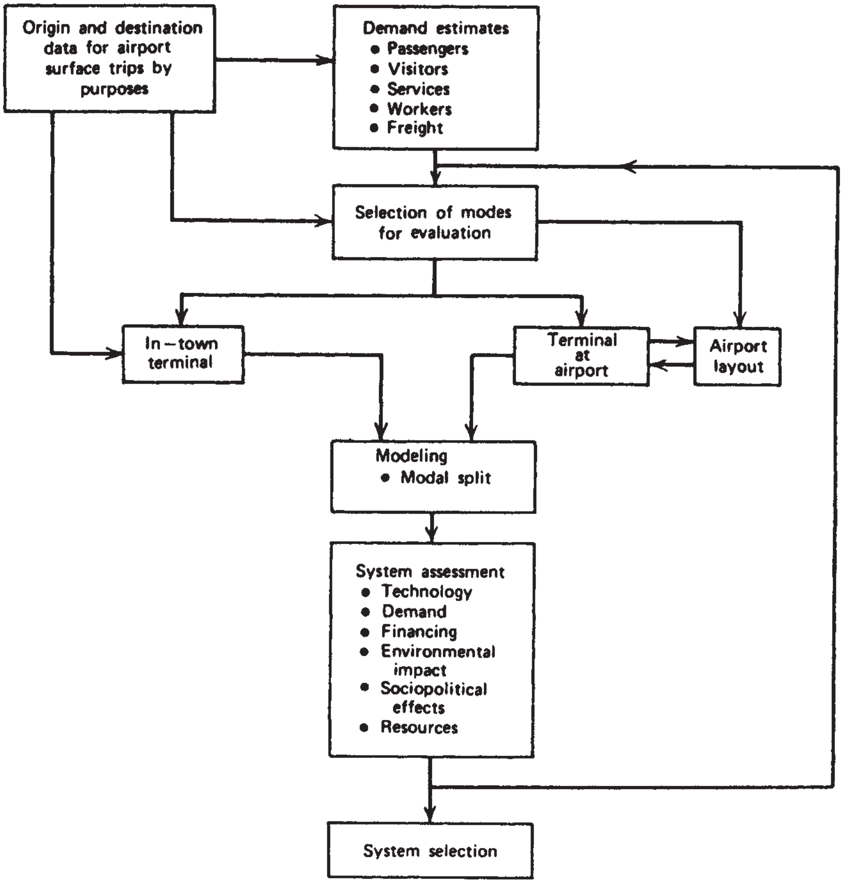

Figure 13.3 Access mode selection.

*Train à Grande Vitesse (high-speed train: 250 km/hr).

services, visitors, and freight are determined from available origin–destination data. Unless a special survey has been carried out at the airport, reliable data will be difficult to obtain. In such cases, and, of course, for "green field" sites, synthetic origin–destination patterns must often be constructed.

To determine the type of access network to be assessed, some assumptions must next be made on the nature, location, and scale of the terminal interchanges to be provided, both at the airport and at other points, such as satellite access terminals or in-town access terminals (e.g., 42nd Street Port Authority terminal, Penn and Grand Central Stations in New York, Etoile, Les Invalides and Gare Montparnasse for Orly-Paris and Victoria Coach Station, and services from Kings Cross and Euston rail stations). The next stage is to identify possible mode options, with sufficient definition to allow a reasonable estimate of modal characteristics with respect to cost and general levels of service. At this time, the possible harmful effects of access modes, usually in terms of socioeconomic impact, can be enumerated for the individual options. One of the principal arguments against the expansion of London-Heathrow airport by the provision of a fifth terminal was the difficulty of absorbing the additional number of airport access trips on the existing road network, which was considered by some to be incapable of further expansion.

On the basis of modal-split models, either calibrated on existing access data or synthesized from relevant experience elsewhere, competing mode options can be evaluated in terms of ridership and the socioeconomic implications. Normally, the most satisfactory mode option or a combination of modes is accepted for detailed planning and design. If no option or combination appears to be satisfactory, recycling (i.e., changing both the network assumed for terminal interchanges and subsequent mode characteristics) is necessary. Eventually, at least one solution is achieved, which meets all assessment criteria. Where several are achieved, the "best" solution is accepted, that is, that which best satisfies all criteria.

13.3 AVAILABLE ACCESS MODES

To suit the variety of needs of airport users and to match the various airport situations, a number of access modes are available or can be designed. Although the auto mode dominates in the United States and most other countries, no single mode of transport qualifies as the one most suitable access mode for the line haul air journey. It is worthwhile examining some of the advantages and disadvantages of various modes used in airport access plans.

Automobile

The most prevalent mode of airport access in the United States and in all other developed countries is the personal automobile. The attractiveness of the mode stems from its great flexibility, with the strong convenience factor of direct origin–destination movement, especially where the air traveler is encumbered by large amounts of baggage or is accompanying elderly or handicapped persons or young children. Overall access journey speeds are potentially high, especially where the nonairport end of the trip is not located in the central city area; when parking at the airport is required for relatively short periods, journeys can be made relatively inexpensively by auto. This is especially true where there is more than one air traveler in each car.

The principal disadvantage of this mode is the high degree of surface congestion caused by individual cars on access routes, the high interaction with nonairport traffic, and the associated high level of parking infrastructure required at the airport. The mode can also be unreliable when congestion builds up, causing jams or slow-moving traffic flows along access routes. Since airport access by auto shares the general surface transport infrastructure, this mode is vulnerable to delays caused by traffic that is not associated with the airport. Parking in the immediate vicinity of some major airports is often so expensive that most long-term parkers are forced to use cheaper remote parking outside the airport boundaries. Use of such parking can materially affect access times and may seriously lower the level of convenience afforded by the overall access mode. Parking costs can be so great at airports that for some air travelers the cost will affect the choice of access mode.

The vast majority of the airports that will be in use in developed countries over the next 50 years are now already in operation and are already closely linked with existing transportation infrastructure. In the United States, a very few new airports will possibly be required to serve some of those great metropolitan centers where population growth is substantial. Other cities will increase the capacity of existing facilities at their airports rather than attempt to locate new facilities in “green field” sites. This is also very much the case in Europe, where population densities are high and airport authorities face strong local opposition to the environmental intrusion caused by the construction of an airport. Therefore, many of the access problems facing the existing airports will continue well into the future.

Taxicab

Taxicabs are a frequently used mode of access to airports, especially where the airport attracts a high proportion of business traffic and the distance between the airport and central city is not high (e.g., Ronald Reagan Washington National Airport). Being direct from origin and destination, with easy baggage handling, the mode offers a high level of convenience. Under most conditions, the overall trip speed is high, and, if several people travel together, the cost per capita can be considerably lower than for single cab occupancy.

In general, however, the taxicab mode is relatively expensive for the single traveler. Moreover, since taxis must share the existing road transport infrastructure, they are also vulnerable to surface congestion from nonairport traffic, and the trip may be slow. Taxis themselves tend to cause access congestion, since the rate of passenger loading and unloading is often quite low in comparison with the road space required. At some large airports, areas have been set aside at some distance from the passenger terminal as taxi “pool” areas. Taxis are summoned to the terminal area, as required, by a taxi dispatcher. This avoids long lines of waiting taxis causing traffic congestion at the terminal landside area.

Charter Bus

Access to many European airports, at holiday destinations in the Mediterranean and in ski areas, is gained by specially chartered buses that serve the chartered air flights. This is also the case in most Caribbean resorts. These buses are nonstop from their origin, thus offering a reasonably high level of service. Since load factors are high, costs of access are low; these costs are usually hidden in the overall charter fare. Charter buses add little to surface congestion on the access routes. However, special provision must be made in the pickup and setdown areas. It is also necessary to provide bus parking areas where charter bus traffic is large, for example, Vienna and Punta Cana in the Dominican Republic.

The chief disadvantage to this mode is that charter buses must share road access routes with other airport and nonairport traffic. Consequently, they are vulnerable to congestion and can be delayed considerably. Also, this specialized mode serves only a portion of the total access demand and is not available to the general public.

Urban Bus

In some cities, the airport can be accessed by conventional urban bus services, which form part of the overall congestion on access routes. In being integrated with the urban network, urban bus service can provide a high level of convenience for airport staff. However, if the urban bus service is to be used for staff, it must be remembered that many airport staff do not work at the passenger terminal. Arrangements must be made to distribute staff to their workplaces, which can be well separated, even by miles at large airports, from the areas served by regular buses.

From the viewpoint of the air traveler, the mode is less convenient. Routing can be difficult, especially in a strange city, and maneuvering luggage in the presence of peak loads of nonairport passengers is demanding at best. Urban buses are recognizably delayed by urban congestion; frequently, the scheduling and routing of the bus system are not particularly responsive to the needs of air travelers. Overall travel speeds are usually low because of frequent stops, and in general the service is bad. As already stated, however, buses can be useful in catering to the needs of airport-based staff. Very significant savings in staff car parking facilities can be achieved by providing adequate bus facilities.

Limousine and Special Bus

One of the most common forms of access mode is the limousine or special bus, which connects a limited number of pickup areas, usually in the central city area, with the airport. This mode has two principal advantages: it is reasonably cheap for the single passenger, although not necessarily for a large party traveling together, and it offers a high level of convenience for travelers originating in or near the central area.

The disadvantages of the mode are obvious. Limousines and special buses can serve only a few central city locations with nonstop service. However, having no segregated right-of-way, the mode is highly sensitive to surface congestion and can be unreliable. The service frequency in all but high-volume airports tends to be poor, consequently increasing overall access time. A significant disadvantage occurs if the user is required to enter the central area (e.g., a railroad station) without regard to first origin or last destination, needlessly attracting additional traffic into already heavily trafficked areas. In some cities, limousine service is extended to demand destinations outside the central area, but the cost of extended service is normally significantly higher.

Limousine service, which was common before the 1960s, has been reintroduced recently at some airports as a premium service operated either by a ground transport concessionaire or by an airline.

Conventional Railway

A limited number of airports are served by conventional railway lines (e.g., Frankfurt, Amsterdam, Zurich, and London-Gatwick). Railway access links often consist of special-purpose short spur lines constructed to connect with the existing rail network. Under such conditions, conventional rail access can be quite inexpensive. Since it is not subject to congestion from surface road traffic, the mode is usually reliable and free of delays. Conventional rail service, often direct, offers good rapid connection with the city center as well as overall speeds higher than those provided by urban rapid-transit systems having numerous and unavoidable station stops en route. An added benefit is the availability of a service that does not entail additional obtrusive track infrastructure.

Conventional rail systems often give relatively poor overall access time in spite of good line speeds because of the infrequency of scheduled departures. In addition, use of the service usually requires departure from the central city; therefore, only the central area is well served by this mode. Table 13.2 indicates that for most cities the central business district (CBD) generates a significant but minor portion of air passenger traffic (3). Furthermore, baggage-laden air passengers encounter some difficulty at central railway stations when mixed with other passenger traffic, including commuters at peak-hour periods. Finally, the rail mode satisfies the access need only partially, since another trip, by taxi or other means, is frequently required to get the traveler to and from the rail station. Conventional rail systems have proven to be most satisfactory where the in-town terminus provides easy access to an extensive urban distribution system: taxi, bus, or urban rapid transit.

Conventional Urban Rapid Transit

At some airports, there is direct access at the air terminal into the metropolitan urban rapid-transit system (e.g., Atlanta, London Heathrow, Singapore, Paris Charles de Gaulle, and Washington, D.C.). This form of access mode has several significant advantages. Usually, the rapid-transit system is a coordinated part of the overall city transit system, giving the air passenger reasonable access to a large portion or the urban

Table 13.2 Share of Airline Passengers with Trip Ends in CBD, United States

Airport	Percentage to CBD/Downtown
New York La Guardia	46%
New York John F. Kennedy International	32% (to Manhattan)
Reagan Washington National	33% (to central Washington, D.C.)
Chicago Midway	20%
Baltimore/Washington International	14% (to central Baltimore)
Newark International	14% (to Manhattan)
Chicago O'Hare International	14%
Philadelphia International	14%
Washington Dulles International	12% (to central Washington, D.C.)
Hartsfield Atlanta International	7%
Denver international	20% (of nonresident business passengers)

Source: Improved Public Transportation Access to Large Airports, Leigh Fisher Associates, Matthew Coogan, Federal Transit Administration, Transit Research Cooperative Program Report 62, Transportation Research Board, Washington, DC, 2000.

area. Because the mode does not suffer from delays due to the surface road transport system, the traveler has a reliable service that does not itself add to road traffic congestion. In the situations where airport rapid-transit links have been built, they have usually consisted of spurs to existing systems. Consequently, an inexpensive service can be provided without constructing obtrusive transport infrastructure. The percentage of travelers carried by this mode may be small but can be as high as 25% (Heathrow, 1990). Urban rapid transit is observed to be very useful for the carriage of airport workers and some categories of visitors. In the case of Heathrow, this convenience was a significant factor in the decision to build the underground extension.

Because most rapid-transit systems are on a radial plan, airport links of this nature tend to serve central areas best, although not exclusively, because a whole network is available. As with urban buses, urban subway trains must make frequent stops en route, leading in many cases to high overall trip times and low overall speeds. And again, perhaps the biggest objection to this mode comes from the necessary mixing of urban commuter passengers with baggage-carrying airport parties. This gives air travelers severe difficulties at crowded central rapid-transit stations where station design has not considered their needs and no porters are available.

A number of urban rapid-transit lines have been connected to airports yet have failed to attract a large ridership. This has been due often to design faults that involve the baggage-laden traveler with an interchange which may be inconvenient, slow, or even physically exhausting. The three chief faults appear to be the following:

1. The distance from parts of the air terminal to the rail terminal is too far to walk with baggage.
2. The rail terminal, which is remotefrom the airport terminal, is served by a shuttle bus, constituting a slow and inconvenient interchange.
3. The interchange requires moving baggage up and down flights of stairs, which may present large perceived or actual difficulties to the traveler.

Specialized Rail Systems and High-Speed Ground Transport

Despite differences in performance characteristics and in kind, specialized rail systems and high-speed ground transport systems can be discussed simultaneously in terms of advantages and disadvantages. Inherently, their functional characteristics are similar as far as the airport link is concerned. For the purpose of this discussion, high-speed ground transport can be regarded like any mode with overall travel speeds in excess of conventional rail speeds averaging over 80–100 mph, operating on separate track from conventional rail. The attraction of specialized rail systems is simply stated. Their attraction lies in their ability to provide rapid, nonstop, reliable service between the central city and the airport terminal at a level of comfort and convenience matching the air trip itself.

During the 1980s planners were mainly interested in investigating dedicated high-speed grade-separated systems with top speeds up to 200 mph, preferably entirely independent of existing rail infrastructure. On careful examination, however, the difficulties associated with this form of high-speed dedicated system become manifest:

Such systems are likely to be very expensive, either overtly in the form of high fares or covertly in the form of heavy subsidies to real total costs.

Furthermore, systems as proposed or designed serve only the central city reasonably well and only a minority of passengers wish to access the city center.

Airport-to-city-center systems attract passenger traffic by other modes into the already congested city center.

Transfers between other feeder and distribution systems at the central city terminal face the baggage-impeded traveler with transfer problems with other modes.

Passengers brought in to the central city require an adequate and convenient accessible public transport system to distribute them to their final destination.

Possibly the overriding difficulty associated with high-speed dedicated systems is the need for segregated rights-of-way through urban areas. This may involve either prohibitively expensive tunneling or the construction of less expensive but environmentally obtrusive grade separated structures, for which there is little community support.

The need for segregated right-of-way increases with the size of the urban area and the density of central development, but the cost of this segregation also increases significantly with greater urban density.

Examination of Figure 13.4 reveals why high-speed rail systems are feasible only for relatively long distances. The time savings for short access distances are so small that passengers are unlikely to be attracted away from the auto mode. However, large access distances are necessary only for airports serving very large urban areas, such as New York, London, and Tokyo. Indeed, this scale of urban area is necessary to generate a CBD-to-airport corridor of demand, where the level of ridership requires a dedicated right-of-way. Cities with urban populations of 2 million or less are likely to have relatively low numbers of passengers whose prime origin or destination is the CBD itself.

Various estimates have indicated that an annual ridership of 3–5 million is necessary to make special access mode fares reasonably competitive with other forms of public transport or the automobile. However, the cost of providing dedicated rights-of-way from the periphery of a large metropolitan area to the CBD can be very large, and the level of urban disruption during the construction period severe.

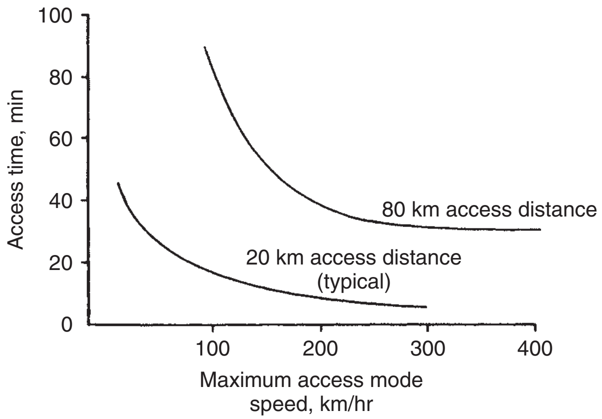

Figure 13.4 Comparative access times for different maximum access mode speeds (4).

In the 1990s, a number of new airports and a few existing facilities decided to provide dedicated nonstop or limited-stop rail access from city centers. A number of these rail services are discussed in the following section.

Current Planning of Rail Access

In the 1970s there were few airports served by rail access and these were mainly in Europe. Some were nonstop services but sharing the rail network track (London Gatwick); others were services integrated into and part of the national or metropolitan rail network (e.g., Schiphol Amsterdam, Zurich, Geneva). Where early dedicated facilities had been provided, their performance often had been less than satisfactory (e.g., the monorail connecting central Tokyo with Haneda Airport). As a general rule, the percentage of access trips made by way of these systems was only a small fraction of all access trips. Research had shown that even where special rail facilities existed, less than 30% of access trips had been carried, leaving 70% to be carried by road-based modes (1). London Gatwick Airport had been an important exception to this rule; once, the Gatwick rail link carried more than half the airport's passengers. However, as the profile of the passenger moved away from that of the leisure traveler and the road network around southern London improved, the rail's modal share dropped to less than 31%.

Studies of rail access feasibility were made in the United States and Europe (4, 5). Although the urban structure and the socioeconomic and demographic makeup of Europe and North America were quite different, remarkable similarities were found in the conditions of airport access.

The attractiveness of the CBD was found to be relatively low and the origins and destinations of access trips are found to be widely spread across the urban region, indicating that the special airport–CBD link could serve only a limited proportion of all trips. This was still the case when research was carried out in the early 2000s; see Table 13.2 (3). Moreover, where any form of public transport was provided for airport access in the United States, its usage by passengers was relatively low, leaving a large proportion of trips to be made by auto and taxi. Most airports were found already to have freeway or high-design arterial access routes linking into either the interstate or motorway systems. However, as the large airports continued to grow in passenger volumes, rail access had to be reevaluated. Some of the world's major airports were handling four times the level of passenger traffic they had in the early 1970s when many of the rail access evaluations had been carried out.

By the late 1980s, the need to supply rail access at large non-U.S. airports became apparent with the planning of major expansions of some of the largest existing European airports (London Heathrow, Paris Charles de Gaulle) and new airports such as Munich Franz Joseph and Oslo Gardemoen. Major new large airports were also in the planning stage in Asia, particularly in South Korea, China, Hong Kong, Thailand, and Malaysia. By 2010, conventional rail service, either as part of the national rail system or as part of the metropolitan rapid-transit system, was available to many large airports in Europe and Asia. Figure 13.5 shows the market share rail and bus provide to a number of these international airports (3). These can be compared with figures that can be obtained from Figure 13.6 which show comparable statistics for U.S. airports with rail service (3). This would suggest that in the United States the use of rail as an access mode is subject to considerable resistance which is not apparent elsewhere.

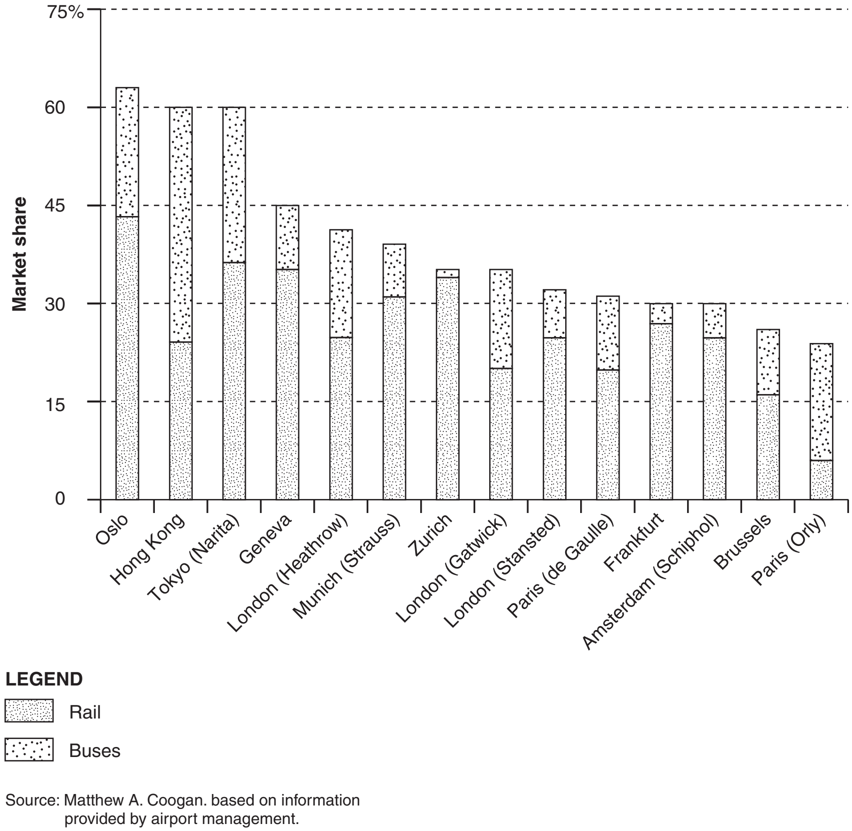

Figure 13.5 Market shares of rail and bus at international airports. *Source*: Improved Public Transportation Access to Large Airports, Leigh Fisher Associates, Matthew Coogan, Federal Transit Administration, Transit Research Cooperative Program Report 62, Transportation Research Board, Washington DC 2000.

Successful new rail systems have been completed at a number of the new large Asian airports. Beijing, which is 32 km from the city, has two rail services, the Airport Express line which connects in the downtown area to the Beijing Subway and the Airport Light Rail line which stops at the airport terminals and two intermediate stops to the CBD. At Kuala Lumpur International Airport, the CBD is served by an Airport Express rail line with a top speed of 100 mph and the KL Rapid Transit service with a station at KLIA. In South Korea, the new Incheon Airport is connected to the old airport at Kimpo (22 mi) and to Seoul Central Station (a further 12 mi). Important rail connections are also provided to Hong Kong airport and to Tokyo Narita.

The Asian and European systems described here involved nogenuine high-speed technology. The maximum operating speeds of these systems are in the range of 80–120 mph and they operate on conventional track. Some services, such as Heathrow Express, are partially integrated into conventional mainline services. Generally, the provision of rail access has been achieved without major disruption to the inner urban areas during the construction period and without the use of unsightly right-of-way structures.

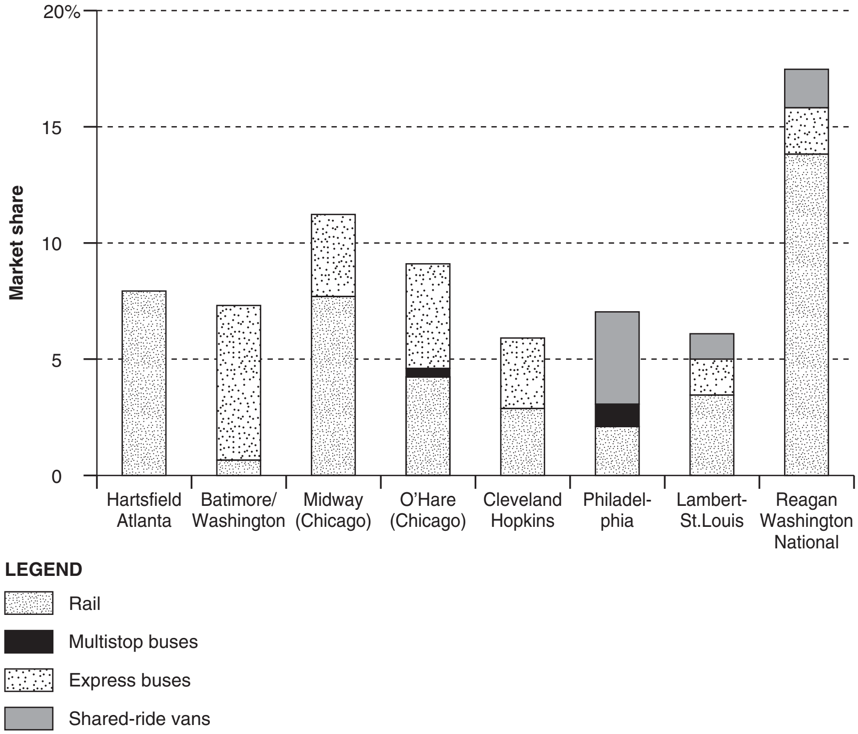

Figure 13.6 Market share of rail and bus transportation at U.S. airports with direct rail connection. *Source*: Improved Public Transportation Access to Large Airports, Leigh Fisher Associates, Matthew Coogan, Federal Transit Administration, Transit Research Cooperative Program Report 62, Transportation Research Board, Washington DC 2000.

VTOL Links

The most rapid and congestion-free method of linking major air passenger generators with the airport is the use of vertical takeoff and landing (VTOL) aircraft. After the late 1940s, a federal subsidy encouraged helicopter operations in New York, Chicago, and Los Angeles. Later, in 1964, operations were begun at San Francisco. All of these enterprises had an operational history that was less than satisfactoy, being plagued with accidents, financial troubles, and inadequate demand (6). The NASA–Houston link in Texas and the Heathrow–Gatwick link between the two main London airports were more successful for a short time. (The latter operation had to be abandoned due to environmental complaints concerning helicopter noise, complaints which were accepted by the British government.) Experience with helicopter airport access services indicates that two conditions help to contribute to their success: first, a significant physical barrier (such as the bodies of water around San Francisco or New York) and second a poor road and rail linkage (such as existed between Heathrow and Gatwick airports at the time of the helicopter service). Helicopter access services are still provided at a few airports around the world such as in the New York area to the three major airports and Teterboro, at Tokyo Narita Airport, and at Dubai International.

Integrated VTOL systems have the advantage in that air passengers have a minimum of inconvenience from baggage transfer at the airport, and, if the nonairport end of the link is close to the final destination, the overall access time can be very low. Because of high individual passenger cost, VTOL links have drawn their customer support principally from business travelers.

Although service levels of VTOL links can be excellent, the chief drawback of this mode of access still remains its expense; fare levels are up to 10 times those of other modes, such as bus and limousine. Furthermore, the nature of the service is such that only a very few nonairport locations can be served, severely limiting the area coverage available. Obviously, the noise of helicopters in congested downtown areas makes this mode extremely intrusive environmentally. In the past, the demand for such an expensive premium service was low. Indeed, services have tended to be introduced and fairly rapidly abandoned because of inadequate demand. Only when demand is fairly high will environmental intrusion normally become a major factor, although recent experience in Western Europe has indicated that vehement opposition can be expected for antinoise groups at any frequency of service.

Waterborne Modes

Where airports have direct access to a waterfront, waterborne modes have been used to transport people to the terminal. The intrinsic attraction of the waterborne modes is the lack of competition with road-based modes, and in a few cases waterborne modes have a special scenic attraction for passengers, as, for example, at Venice Airport, where the approach by water gives the visitor the traditional view of the city rather than a more commonplace approach to the landside by car or bus. San Francisco experimented with the use of hovercraft across the waters of San Francisco Bay, but the reliability of the service was found to be unacceptable. Other airports have initiated experimental use of the water taxis, but the mode has made little permanent impact on airport access provision.

13.4 ACCESS MODAL CHOICE MODELS

Some studies have been carried out to determine how modal choice operates in the selection of airport access mode:

Zonal Models

One model which has been used was calibrated in conjunction with the assessment of the feasibility of a rail link with Heathrow Airport and was of the form (6)

$$Y_1 = 98 - 40X_1 + 0.17X_2 \tag{13.1}$$

where

Y_1 = percentage of zonal trips made by public transport
X_1 = ratio of generalized cost (G.C.) by public transport to generalized cost by automobile in the zone*

*The generalized cost of the mode in this case constituted the marginal travel costs plus travel time costs, which were computed as varying from 0.25 × hourly wage for leisure purposes to 2 × hourly wage for business trips.

X_2 = percentage of zonal access origins and destinations made by nonresidents of the zone

The form of the equation indicates that modal choice can be modeled by an equation that accounts for travel cost and travel time and by a variable that serves as a surrogate for car availability. A satisfactory model of submodal choice was obtained in the form

$$Y_2 = 90 - 40X_3 \tag{13.2}$$

where

Y_2 = percentage of public transports trip by road-based mode
X_3 = ratio of generalized cost by road-based public modes to generalized cost by rail

It can be seen that, where the generalized costs for alternate public modes are similar, they are equally attractive.

Disaggregate Models

A more generalized modal choice model is of the form

$$P_k = \frac{e^{\mathrm{L_k}(X_1 \cdots X_n)}}{\sum_{\mathrm{all}\ j} e^{\mathrm{L}_j(X_1 \cdots X_n)}} \tag{13.3}$$

where

P_k = percentage of trips by mode k
L_k = some generalized cost function in terms of variables, $X_i = X_1, \ldots, X_n$
X_i = variable to which a cost function can be ascribed, e.g., travel time, fares, out-of-pocket costs, parking, fuel, taxes, maintenance, and running costs

A two-mode model has successfully been calibrated in the form:

$$L_k = 0.701 + 0.031\Delta C + 0.0216\Delta T \tag{13.4}$$

where

ΔC = travel cost difference
ΔT = travel time difference

Figure 13.7 shows the general form of the linear modal choice model of equation (13.2) (4). The graph indicates the effect, for typical journey costs, of positive and negative time savings for a 10-mi access trip (a typical figure for existing metropolitan airports). We find that the access trip is not particularly sensitive to savings in access time but is highly sensitive to overall changes in cost. Clearly, public transport is viable only when out-of-pocket costs are perceived to be considerably lower than costs for private transport, since most public transport modes have a built-in element of increased time costs due to greater access and waiting times.

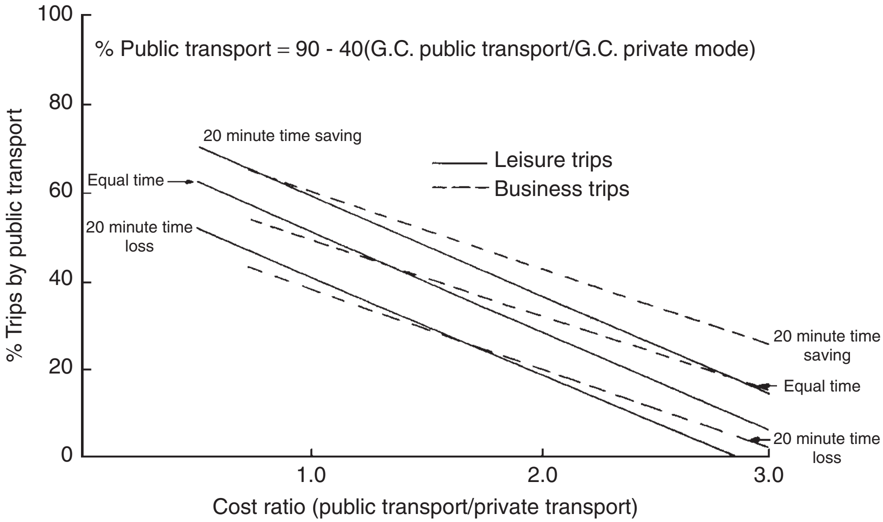

Figure 13.7 Modal-split relationship for business and leisure trips: London Heathrow Airport (4).

13.5 PARKING SPACE AT AIRPORTS (7)

The determination of the location and number of parking spaces at an airport requires detailed consideration. Parking demand is a complex function of the number of persons accessing the airport, the available access modes, the type of air traveler, the parking cost, and the duration of the parking period, which is determined by the type of person making the trip (i.e., traveler, worker, service personnel, or visitor). Demand from the travelers must be further categorized into business, leisure, long term, short term, and so on. It was noted earlier that air travelers may represent a minority of those entering the airport; the majority of this portion of the airport population may be visitors and workers.

Another complication in the estimation of demand arises because airports differ significantly with respect to the proportion of passengers coming into the transfer and transit category. Airports such as Atlanta, Schiphol Amsterdam, and Changi Singapore have a high number of annual enplanements, but a large percentage of the passengers are transfers from other flights, requiring no landside access. On the other hand, cities such as Kansas City, Sacramento, Rochester, and Manchester behave much more as terminal destinations. Enplanements alone, therefore, cannot be used as a guide to parking requirements. Any attempt to quantify the relationship between availability of parking space and total air passenger activity would indicate that there is a large variation about any normative line that could be derived for the relationship. Therefore relationships have been developed for originating passengers only. For planning purposes for hub airports, the FAA recommends use of the graph shown in Figure 13.8, which shows a nonlinear relationship between originating passengers and public parking places (7). The recommended graph for nonhub airports is shown in Figure 13.9 (8). Whitlock and Cleary have produced a design graph that relates short-term parking requirements

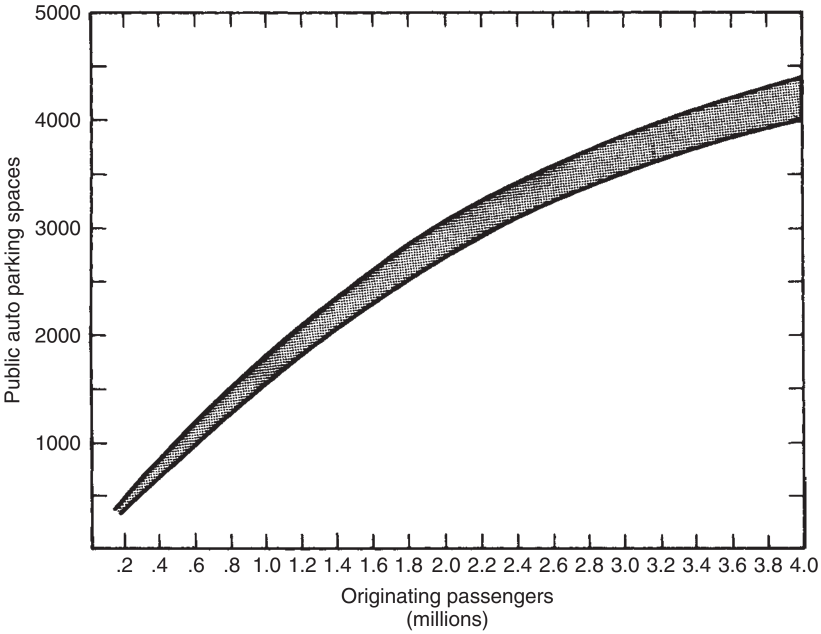

Figure 13.8 Relationship between annual originating passengers and public parking spaces (hub airports) (7).

to peak-hour originating passengers (9) (see Figure 13.10). These may be compared with the following overall or rule-of-thumb estimates:

Roads and Transport Association of Canada (smaller airports) (10)	1.5 spaces per peak-hour passenger (short term) 900–1200 spaces/million enplaned passenger (long term)

It is normal to price long-term and short-term parking fees differently in order to encourage high turnover in the short-term area, which is usually close to the passenger terminal. The amounts of short-term and long-term parking provided will also depend on the geometry of the airport and the availability of land in the terminal area. Clearly, parking location will interact with the design of the internal circulation roads.

There is no single answer to the actual demand for parking facilities at an airport. Pricing policy will be a strong determinant of demand; some airports on restricted sites purposefully set charges at levels that deter parking and encourage the use of public transportation, including taxis (11).

A common scenario for an airport with expanding traffic is for the initial provision of parking such that close-in spaces are given over to the short term and the long-term parking is more distant from the passenger terminal. As the airport grows, the short-term parking stays close to the terminal and grows at the expense of long-term spaces. The remaining long-term parking becomes medium-term or "business" parking and long-term parking is forced out to a remote site or even outside the airport boundaries to adjacent land. Both medium- and long-term lots are served by frequent shuttle service.

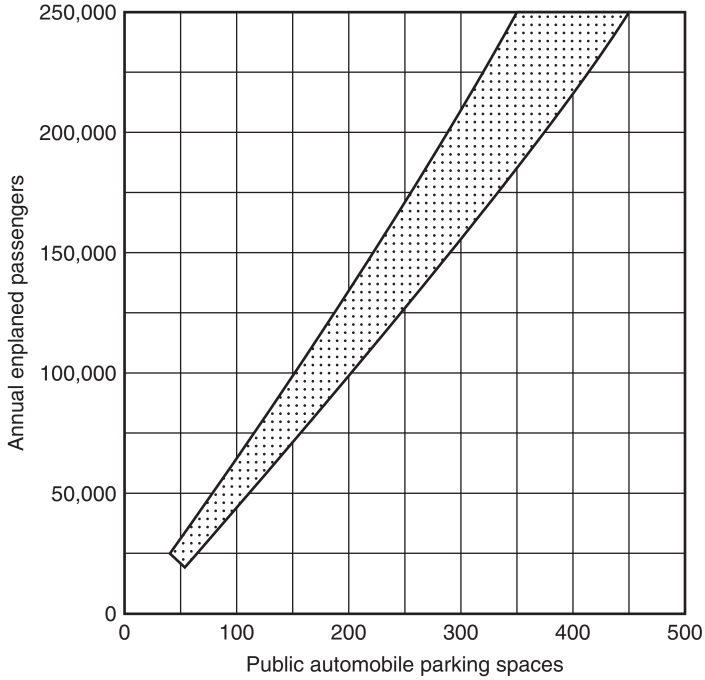

Figure 13.9 Relationship between annual originating enplaned passengers and public automobile parking spaces (nonhub airports) (8).

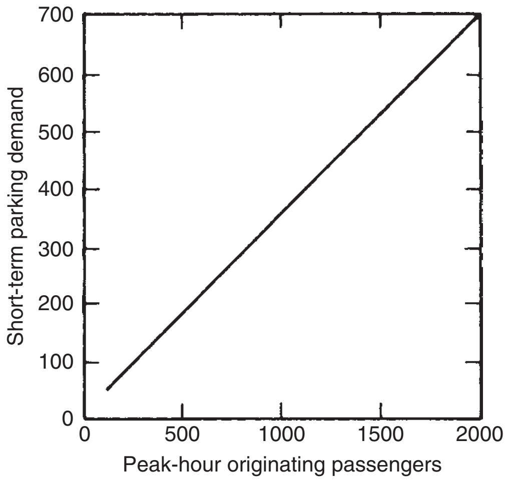

Figure 13.10 Relationship between short-term parking requirements and peak-hour originating passengers (transits and transfers excluded) (9).

A pricing structure is used among the various parking lots to balance the demand for the various facilities.

To ensure the adequacy of parking provision, a special study of airport access traffic should be made so that the various sectors of access traffic can be projected. Only then can a detailed plan be prepared to provide an acceptable level of parking availability at a price acceptable to the passenger.

The parking behavior of passengers is likely to be specific to an airport, depending on the type of passenger, type of trip (business or leisure), number in party, cost and ease of use of public modes, geography of the catchment area, and price of parking. Two airports serving the same catchment can see very different parking demands from the passengers, for example, London Stansted [high number of low-cost carriers (LCCs), charters, and leisure trips, few conventional carriers, no transfer traffic] and London Heathrow (no LCCs, no charters, all conventional carriers, high proportion of business trips, high transfer traffic).

In any management scheme for the provision and use of parking facilities, charges form a large part of the rationale of passengers' choice as do ease of use, comfort, and reliability of shuttle service to the terminal.

13.6 CURBFRONT DESIGN

For space estimates in the master planning process, the length of dropoff/pickup at curbfront can be estimated at 120 ft (35 m) per million originating or destined passengers; for purposes of curbfront planning, transit and transfer passengers can be ignored (12, 13). More accurate design figures can be obtained by estimating the total demand for curbfront from a detailed breakdown of traffic type and subsequent requirements in space minutes (14). This approach can be illustrated by the following example:

Example 13.1

Vehicle type	Peak enplaning volume	Peak deplaning volume
Private auto	300	350
Taxi	50	70
Limousine	20	20
Courtesy vehicle	10	10
Bus	10	10
Other	20	30

Using the figures in Table 13.3, which show the total number of foot minutes required for each vehicle type, the following can be computed:

Vehicle type	Peak enplaning (ft min)	Peak deplaning (ft min)
Private auto	16,500	24,500
Taxi	1,500	3,850
Limousine	2,100	4,600
Courtesy vehicle	450	1,050
Bus	1,800	2,650
Other	4,200	3,300
	26,550	39,950

Table 13.3 Curbfront Requirements at Fort Lauderdale–Hollywood Airport

		Average dwell time		Curbfront require	
Vehicle type	Vehicle length (ft)	Enplaning (min:sec)	Deplaning (min:sec)	Enplaning (ft min)	Deplaning (ft min)
Private auto	25	2:10	2:50	55	70
Taxi	25	1:15	2:10	30	55
Limousine	35	3:00	6:40	105	230
Courtesy vehicle	40	1:20	3:00	45	105
Bus	40	4:30	6:40	180	265
Other	35	6:00	3:10	210	110

Source: Reference 13; estimates from other airports can be obtained from references 9 and 15.

In theory, 1 lineal ft of curb space can provide 60 ft min of capacity in 1 hr. Cherwony and Zabawski (14) suggest that the practical capacity of a facility is only 70% of this figure, or 42 ft min.

$$\text{Hence, the enplaning frontage required} = \frac{26{,}550}{42} = 632\,\text{ft}$$

$$\text{and deplaning frontage required} = \frac{39{,}950}{42} = 951\,\text{ft}$$

Since the enplaning and deplaning peaks are unlikely to occur in the same operational hour, where there is one level of curbfront for both pickup and dropoff, the total required would be less than 1583 lineal ft (632 + 951). For unilevel operation, the flows in both directions should be calculated for the peak enplaning hour and the peak deplaning hour. Using the same procedure as outlined above, the maximum lineal curbfront obtained from the two calculations should be used for design purposes. It must be emphasized that, in order to use this approach, the figures contained in Table 13.3 must be in general agreement with conditions found to operate at the airport under consideration or the designer must generate his or her own values from observations on vehicle length and dwell time. Estimates from other airports can be found in references 15 and 16.

Curbfront design can also be carried out using the ACRP passenger terminal planning and design spreadsheets, which were previously discussed in Chapter 10 (17). This design method brings in the concept of level of service (LOS) in which the space available to maneuver and park temporarily at the curbside is considered in the design.

Inputs to the ACRP curbside model are design hour volumes by vehicle type, dwell time by vehicle type, and vehicle length by type.

Outputs are LOS in terms of curbfront supplied and curbfront range required for LOS C and fraction of available capacity used by the curbfront design. Figure 13.11 shows the screen for the ACRP curbfront design model for either a dropdown or pickup area. Figures 13.12(a)–(e) illustrate the degree of crowding at the various LOS and Figure 13.13 is a sketch of an eight-lane curbfront that could be expected at a major terminal.

Single-Curb Model								
Vehicle Type	Design Hour Demand in Vehicles	Peak 15 min as % of Demand 30%	Vehicle Dwell Time (min)	Multiple Stop Factor	Peak 15 min Demand in Minutes	Vehicle Length (ft)	Peak 15 min Demand (ft* min)	Peak 15 min Demand (ft)
Private Auto	500	**150**	3.0	1.0	**450**	22	**9,900**	**660**
Rental Car Shuttle*	50	**15**	2.0	1.0	**30**	50	**1,500**	**100**
Taxis	200	**60**	1.5	1.0	**90**	22	**1,980**	**132**
Limousines	100	**30**	2.0	1.0	**60**	50	**3,000**	**200**
Hotel Shuttles*	30	**9**	2.0	1.0	**18**	50	**900**	**60**
Airport Shuttles*	30	**9**	2.0	1.0	**18**	40	**720**	**48**
Buses*	30	**9**	2.0	1.0	**18**	50	**900**	**60**
Other	30	**9**	2.0	1.0	**18**	30	**540**	**36**
Total	**970**	**291**					Total	**1,296**

Existing Curbfront Length	1,200	ft
Effective Double Parking Capacity**	**2,400**	ft

Existing Capacity Ratio	**0.54**	
Existing Level of Service (LOS)	**B**	
Required LOS 'C' Curbfront Range = from	**997**	ft
to	**1178**	ft

* Consult the schedules to determine the maximum frequency of each vehicle
** Assumes a 4-lane curbside roadway where double parking is allowed

Travel Classification	Dwell Time (min)
Private Auto	2 - 4
Taxis	1 - 3
Limousines	1 - 3
Rental Car Shuttles	2 - 5
Hotel Shuttles	2 - 4
Other	varies

Travel Classification	Length (ft)
Private Auto	22
Taxis	22
Limousines	50
Rental Car Shuttles	50
Hotel Shuttles	40
Other	varies

Figure 13.11 Output screen terminal curb requirements. (Courtesy of Transportation Research Board.)

13.7 CAPACITY OF ACCESS ROUTES

Although the airport planner normally has no control over access facilities outside the limits of the airport, in many instances, the planner has influence on their planning and design because of the high volumes of traffic which can be generated by a high activity center such as an airport. Access routes must provide capacity for peak flows from the airport, which include workers, passengers, and visitors. Unfortunately, much of these flows tend to occur at the beginning and end of the working day and therefore coincide with peak urban traffic from nonairport sources. In estimating the capacities of access facilities both within and outside the airport boundaries, the values in Table 13.4 may be used. To convert the vehicular volumes to passenger volumes, Table 13.5, which gives average vehicle occupancy rates, can be used for U.S. airports. It is suggested that the figures in this table be checked against current usage patterns for the facility concerned or at similar facilities, because large variations from U.S. average values can be expected in other countries.

13.8 LAYOUT OF ACCESS

It is essential that, during the layout phase of master planning, very careful thought be given to the configuration of the access components of the plan (18). Often those aspects are compromised by site constraints, as are those of the airside. However, access should not be subordinated to the needs of airside and terminal layout; rather

(a)

(b)

(c)

Figure 13.12 Landside pick-up/dropdown: (a-c) LOS A to C; (d-e) LOS D to F. (Courtesy of Transportation Research Board.)

(d)

(e)

Figure 13.12 (*continued*)

it should receive equal consideration with respect to long-term requirements. This is particularly true where there is the possibility of extensive terminal expansion to cope with expected long-term growth of passenger demand. In such designs, it is essential that the initial design fit with or is easily modified to long-term needs.

For example, two-level access to the different arrival and departure levels will very likely be required in a centralized design by the time that originating and destined terminal traffic reaches 10 mppa. It will certainly be required when this figure reaches 15–20 mppa. To have to engage in double decking the access roads is an extraordinarily disruptive exercise, both to the access routes themselves and to the terminals.

It is recommended that the area immediately in front of the terminal across from the curbside be regarded as operational land required for parking. There is a temptation to use this land for commerical purposes: hotels, conference centers, and so forth. Perhaps this is a matter of opinion, but the authors strongly recommend against this type of

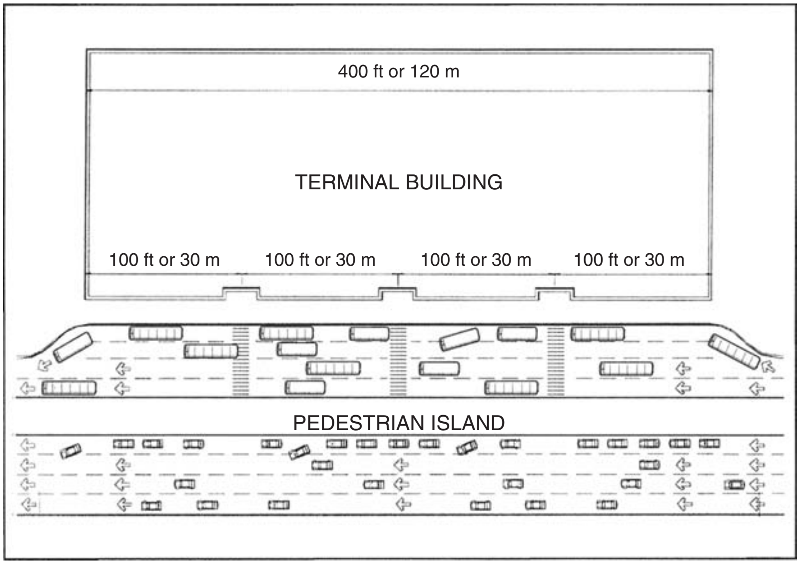

Figure 13.13 Sketch of typical curbside layout at a major terminal. (Courtesy of Transportation Research Board.)

Table 13.4 Achievable Capacities of Airport Access Route Facilities (15, 17)

Facility	Average hourly volume
Highways	
Main-access and feeder freeways (controlled access, no signalization)	1000–1600 vehicles/hr/lane[a]
Ramp to and from main-access freeways, single lane	900–1200 vehicles/hr/lane[a]
Principal arterial (some cross streets, two-way traffic)	900–1600 vehicles/hr/lane[a]
Main-access road (signalized intersections)	700–1000 vehicles/hr/lane[a]
Service road	600–1200 vehicles/hr/lane[a]
Public Transportation[b]	
Busways, individual vehicles	6000 passengers/hr/lane
Rapid transit	30,000 passengers/hr approx.
Conventional rail	5 trains/hr or 2500 passengers/hr/track

[a]Passenger car equivalents at LOS C and D.
[b]Allowance is made in public transportation estimates for difficulties in loading baggage and for the space required for baggage on specially designed vehicles.

Table 13.5 Typical Average Vehicle Occupancy Rates for Airport Ground Access (18)

Type of vehicle[a]	No. of passengers per vehicle
Private auto	1.9
Rental car	1.2
Taxi	2.5
Limousine	5.6
Other	4.2

[a]Buses not included.

land use so close to the terminal. Kennedy, O'Hare, and Newark airports are just three U.S. examples of major terminal modifications which in the long term had to take place within such areas previously used for parking. Had this space been preempted by other long-term leased uses, such necessary expansion would have been impossible.

Keeping the areas adjacent to the terminal free for parking leads to the simple geometry of internal circulation roads shown in Figure 13.14(a) at Schiphol Airport Amsterdam and in Figure 13.14(b) at La Guardia, New York. Figure 13.14(c) shows

Figure 13.14(a) Landside access layout. (Courtesy of Schiphol Amsterdam Airport, copyright Aerophoto-Schiphol B.V.)

Figure 13.14(b) Landside access layout—LaGuardia Airport, New York. (Courtesy of The Port Authority of New York and New Jersey.)

Figure 13.14(c) Landside access layout—Paris Orly Airport. (Courtesy of Aeroports de Paris.)

Figure 13.15(a) Landside access layout showing Fernbahn Station—Frankfurt Airport. (Courtesy of FRAPORT, Flughafen Frankfurt/Main AG.)

the unnecessarily complicated network of internal circulation roads at Orly, which has "sterilized" close-in land for other uses. The passenger terminals of both Schiphol and Frankfurt airports have maximum opportunity for lateral expansion along the axes of their access roads.

Where rail service is to be provided, the location of the station also requires careful consideration. In a centralized terminal, such as Amsterdam or Brussels, the selection of the station site is fairly obvious, either under or immediately adjacent to the passenger terminal itself. In Frankfurt [Figure 13.15(a)], the original site of the rail station was under the passenger terminal, but when the Fernbahn high-speed rail connection was made, a second new station was built, adjacent to the curbside facilities. Similarly, a centralized position was chosen for the rail station at the new Munich Airport [Figure 13.15(b)]. Here, however, the great length of the terminal has resulted in less than optimal walking distances for passengers.

Paris Charles de Gaulle [Figure 13.15(c)], is a highly decentralized design. The distances between terminals are so large that the two rail stations connected to the Paris Regional Network and the high-speed TGV are accessed by landside bus shuttles. Although shuttles are not popular with passengers and others, offering as they do inconvenience and physical difficulties to the encumbered and disabled, they are increasingly being used as airport passenger terminals grow larger to accommodate

Figure 13.15(b) Landside spinal access layout showing highway link on left and rail link on the right. (Courtesy of Munich Airport.)

Figure 13.15(c) Landside access layout—Paris Charles de Gaulle Airport. (Courtesy of Aeroports de Paris.)

increasing passenger traffic. The alternative is multiple station stops at the airport; these slow the performance of the rail link with respect to connection times to the central city.

13.9 SUMMARY

In the medium term (5–10 years), airport planners realize that the principal access mode will continue to be the private auto on roads serving the general urban area. The inconvenience caused by shared right-of-way is not usually sufficient to merit the construction of dedicated access modes. However, since the writing of the first edition of this book, in 1979, there has been a remarkable growth in the number of large airports choosing to provide access by high-capacity rail. Dedicated rail lines have been provided at new airports such as Oslo, Munich, Hong Kong, Beijing, and Seoul Inchon. New spur lines have been built connecting existing large airports to existing networks at London Heathrow, New York JFK, and Paris Charles de Gaulle. With growing volumes of access traffic over the years, it may be possible to improve access service by the use of buses operating on reserved bus lanes, at least in peak hours. Some traffic not destined for the central business district can be served by satellite suburban terminals at convenient points on the metropolitan highway system; rather than operation by the airport authority or the airlines, these would be operated by ground transport bus concessionaires giving common facilitation for all airlines. To prevent severe congestion of surface roads, it is better to limit the capacity of available parking rather than attempt to restrict demand by means of high parking charges. The pricing mechanism may fail in periods of sharp peaking. Both European and North American experiences indicate that, for business travelers, there is little elasticity of parking demand with respect to price. High elasticity is observed only for travelers requiring long-term parking, for example, vacation traffic.

Where airports can be connected to existing urban rapid-transit networks, such links should be provided. Connecting the airport to a network, rather than providing a point-to-point airport to CBD link, for example, offers the unencumbered traveler a reasonable alternative to the car. Equally, the airport worker in the long term is more likely to locate at a point that can be served by public transport.

Finally, it must be acknowledged that access potentially constitutes a most severe capacity limitation to airport operation. Some observers, for example, have indicated that such is the case for Los Angeles International, Heathrow, and Charles de Gaulle airports (19, 20). Therefore, care is essential in siting new airports and continually planning the access of existing airports to ensure that the necessary access capacity can be provided throughout the life of the airport in accordance with the demands of the airport master plan, even up to the level of ultimate development.

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14

Heliports, STOLports, and Vertiports

14.1 INTRODUCTION

Since the 1960s air transport professionals have recognized that helicopters, or vertical takeoff and landing (VTOL) aircraft, are important components of the air transportation system. Conventional helicopters serve a variety of specialized functions but are relatively insignificant as passenger common carriers except in the provision of services to offshore oil and gas production platforms and to island communities. There has also been interest in short takeoff and landing (STOL) operations and in aircraft that require either a very short runway or no runway at all. Vertical takeoff and landings are provided for by heliports, STOL operations have STOLports, and near vertical operations of vertical or short takeoff and landing (V/STOL) aircraft are designed to be handled at vertiports. At V/STOL facilities, the aircraft can either take off vertically or with a very short ground run. Such aircraft include convertible rotorcraft and convertible airplanes with tilt-rotor or tilt-wing capability. Often grouped together in the literature under the generic term V/STOL, the aircraft included in the above titles range from helicopters, to tilt-rotor, tilt-wing, and tilt-jet aircraft, to STOL aircraft that serve short- to medium-range routes and are barely indistinguishable from conventional aircraft. This chapter describes existing design standards and recommendations for helicopter operations and discusses the provision of facilities at STOLports and vertiports.

14.2 HELICOPTER CHARACTERISTICS AND TRENDS

Helicopters

Although Leonardo da Vinci produced a conceptual design for a helicopter as early as about 1500, the first successful helicopters were not produced until 1923—by Pateras Pescara and Etienne Oemichen of France. In 1924, Oemichen's machine traveled 1 km with a payload of 200 kg. The first significant practical application of helicopters for military purposes occurred during the early 1940s, and civilian development followed World War II. Since that time, this versatile aircraft has been used for a wide range of activities, including police and traffic patrols, fire fighting, crop seeding and fertilizing, search and rescue operations, and public transportation service.

The helicopter is a rotary wing aircraft that depends principally for its support and movement on the lift generated by one or more power-driven airfoils rotating on vertical axes. Its main value lies in its ability to hover and to fly sideways as well as forward. Because of its maneuverability and its ability to take off and land vertically, it can operate safely from clear areas that are little larger than the craft itself. Compared to conventional takeoff and landing (CTOL) and STOL aircraft, helicopters and other VTOL aircraft are costlier and noisier and require more power for comparable payloads (see Figure 14.1).

Helicopters range in overall length from about 28 to 99 ft and in height from about 9 to 25 ft. The smallest helicopters have a capacity of two people and a maximum takeoff weight of about 1370 lb. The largest helicopters are capable of transporting 40 or more passengers, plus a crew of 3, and have a maximum payload of over 40,000 lb (1). According to the FAA, two- to five-place helicopters make up the majority of the civil helicopter fleet.

Helicopters are relatively slow; normal speeds range from 0 to 100 mph for small models to 0 to 185 mph for larger aircraft. Typical cruising altitude for helicopters is 1000–1500 ft, although many can fly at altitudes up to 10,000 ft above sea level. Helicopters are best suited for short-haul transportation, typically serving trips up to about 75 mi. However, certain large models, such as the now-retired Sikorsky MH-53M, were capable of transporting full passenger loads of 55 persons up to 600 nm (1100 km).

Table 14.1 gives dimensions of typical small, medium, and large helicopters; Figure 14.2 illustrates popular helicopter configurations.

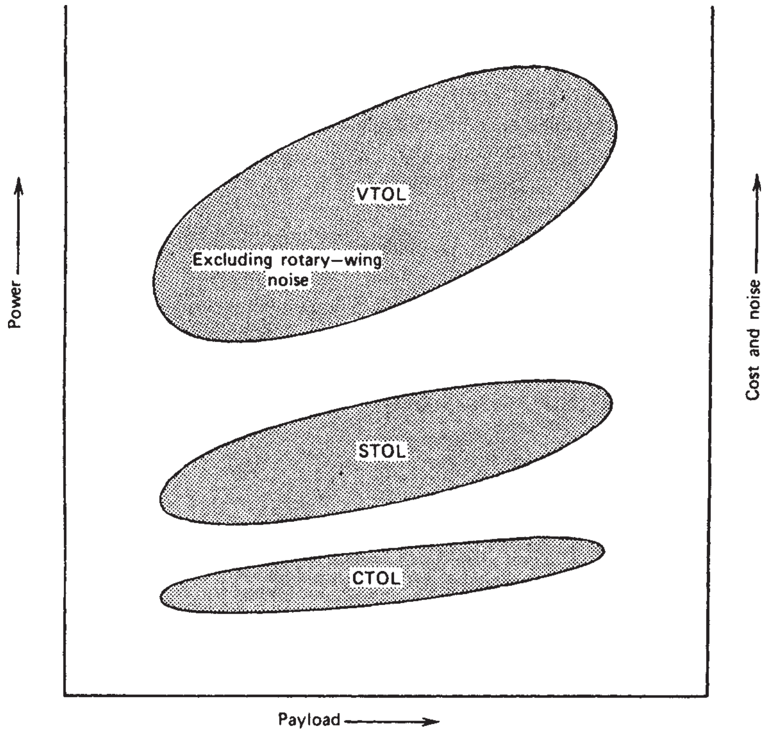
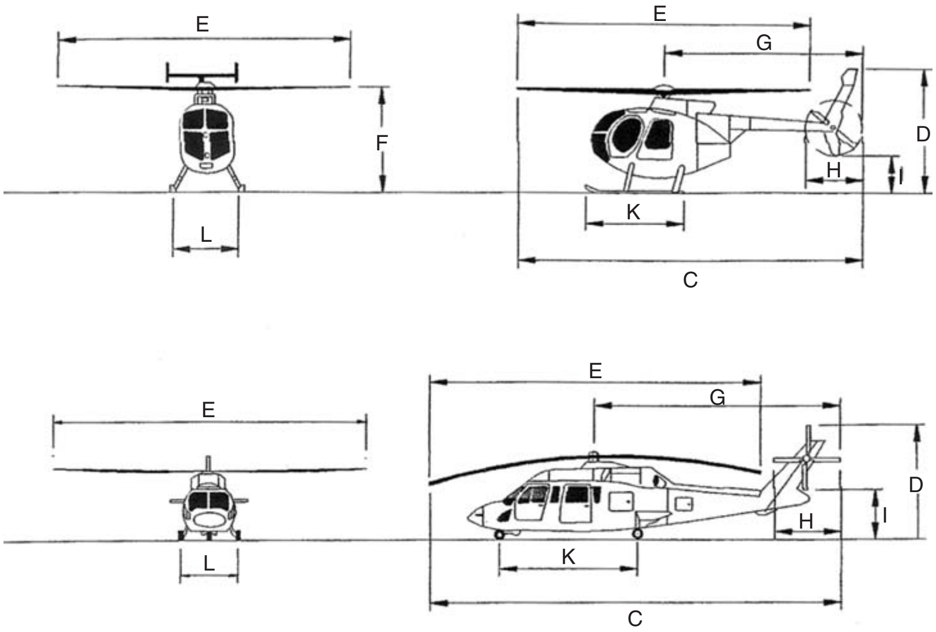


Figure 14.1 Basic technical and economic comparisons of various aircraft groups. (*Source: A Brief Review of V/STOL Aircraft*, Douglas Aircraft Company, Report MDC-JO690/01, March 1970.)

Table 14.1 Dimensions of Typical Helicopters

A[a]	B	C	D	E	F	G	H	I	J	K	L	M	N
Manufacturer model	Maximum takeoff weight	Overall length	Overall height	Diameter/ number of blades	Main rotor ground clearance	Hub to Aft end	Tail diameter/ number of blades	Rotor ground clearance	Undercarriage Type	Undercarriage Length	Undercarriage Width	Number of engines type	Crew & passengers
Agusta													
A 109	5,977	43	11	37/4	10	25	6.7/2	2.3	wheel	11.6	7.5	2-T	1 & 7
Bell													
206-B3	3,200	39.1	10.4	33.3/2	6	22.5	5.4/2	2.1	skid	8.3	6.8	1-T	1 & 4
212	11,200	57.2	12.6	48/2	7.5	33.2	8.5/2	6.1	skid	12.1	8.8	2-T	1 & 14
Boeing													
107	20,000	84	17	50/3	15	59	50/3	16.9	wheel	24.9	12.9	2-T	3 & 25
Eurocopter													
316 Alouette III	4,630	33.37	9.74	36.08/3	9.8	27.72	6.27/3	2.8	wheel	11.5	8.5	1-T	1 & 4
EC-130	5,291	41.47	11.84	35.07/3	10.96	23.7	Fenestron	5.3	skid	10.5	7.87	1-T	1 & 7
MDHelicopters													
MDX Explorer	6,500	39	12	34/5		23	NOTAR	3.3	skid	7.3	7.3	2-T	1 & 7
Sikorsky													
S-58	13,000	65.8	16	56/4	11.4	38	9.5/4	6.4	wheel	28.3	14	2-T	2 & 16
CH-53E	69,750	99.5	28.3	79/7	17	59.6	20.0/4	9.5	wheel	27	13	3-T	3 & 55

[a]Letters in column headings refer to Column 1 in list at bottom of Figure 14.2



A Manufacturer name and helicopter model

B Maximum takeoff weight in pounds

C Overall length in feet (rotors at their maximum extension)

D Overall height in feet (usually at tail rotor)

E Rotor diameter in feet

F Rotor plane clearance in feet

G Distance from rotor hub to tip of tail rotor in feet

H Tail rotor diameter (in feet)

I Tail rotor ground clearance in feet

J Type of undercarriage

K Undercarriage length in feet

L Undercarriage width in feet (The distance between the outside edges of the tires or the skids)

M Number and type of engines

N Number of crew and passengers

Figure 14.2 Typical helicopter dimensions (1).

14.3 PLANNING AND DESIGN OF HELIPORTS

A *heliport* is the area of land, structure, or water that is used or intended to be used for landing and takeoff of helicopters, together with appurtenant buildings and facilities (1). It may be either at ground or water level or elevated on a structure. A minimum-facility heliport that does not have auxiliary facilities, such as a waiting room, hangar, parking, fueling, and maintenance, is referred to as a *helistop.* Cleared areas normally used for other purposes can also accommodate occasional helicopter operations. Sites such as these are called “off-heliport landing areas,” not heliports.

Heliports are classified by the FAA (1) into the following groups of usage and size:

General aviation (public and private)
Transport
Hospital
Helicopter facilities on airports
Federal
Military

The general aviation designation is an indication of use rather than ownership. A heliport that is used for public transportation is classed as a public-use heliport, regardless of ownership. At private-use heliports (PPR—prior permission required), usage is restricted to the owner or to persons authorized by the owner. PPR heliports are owned by individuals, companies, or corporations and are used exclusively by the owner.

Transport heliports are intended to accommodate air carrier operators providing scheduled or unscheduled service with large helicopters.

Special-use heliports that do not accommodate public transportation helicopters (e.g., police heliports) are considered private-use heliports even though they are publicly owned. Federal heliports are those facilities operated by a nonmilitary agency or department of the U.S. government, while military heliports are operated by one of the uniformed services.

Selection of Heliport Sites

The versatility and maneuverability of the helicopter make it possible to operate such aircraft in congested and highly developed areas of a community. However, the potential of the helicopter’s unique operating characteristics cannot be fully realized until an adequate system of heliports is provided. One of the most important aspects of planning and design of a system of heliports is the selection of appropriate sites. Site selection studies should be undertaken with the goal of maximizing user convenience, aircraft safety, and community acceptance. The first step should consist of the identification and analysis of available sources of information. Such a desk study should include the following components:

1. A review of available relevant studies (e.g., metropolitan airport system plan, comprehensive land use plan, and areawide transportation plan). Such studies may contain forecasts of land uses, trip origins and destinations, travel time data for surface transport, and other useful information.

2. An analysis of available wind data to determine desirable orientations for heliport approaches.
3. A study of National Geodetic Survey quadrangle sheets, road maps, and aeronautical charts, from which feasible sites are selected for further evaluation.
4. A study of land costs in the areas of interest. An aerial inspection of each site by helicopter can be especially helpful in evaluating possible obstacles to flight, available emergency landing locations along the approaches, wind turbulence, and other features relating to aerial navigation.

Finally, a detailed on-site inspection of each site under study should be made before a final comparison is made of alternative sites.

At least eight factors should be considered when potential sites for heliports are analyzed. These are discussed in turn:

1. Class and layout of heliport
2. Convenience for users
3. Airspace obstructions
4. Coordination with other aircraft movements
5. Direction of prevailing winds
6. Social and environmental factors
7. Turbulence
8. Visibility

Class and Layout of Heliport. The size or class of the heliport and the size of the largest helicopter to be served will determine the dimensions of the landing and takeoff area, as described in the next section. The amount of space needed will be a determinant of the number of potentially suitable sites.

Convenience for Users. Because helicopters provide a short-haul transportation service, landing areas must be as close as possible to the actual origins and destinations of persons using the helicopters. Inordinate delays and inconvenience in accessing the helicopter service will negate the inherent time-saving and convenience benefits of the helicopter. Special studies of traffic are recommended to identify areas of highest demand. Comparisons of total travel time with that of other modes will be helpful in making forecasts of helicopter usage.

Airspace Obstructions. Physical objects such as buildings, poles, towers, and the like may be hazardous to helicopter flights. Thus, a study must be made to identify potential hazards. Imaginary obstruction clearance planes have been published by the FAA, and their use is described in this chapter.

Coordination with Other Aircraft Movements. In the interests of safety, FAA studies must be made to ensure that use of the proposed heliport sites would not interfere with landing and takeoff operations at any nearby airport. This factor is especially important when the proposed site is at or near an existing airport, since the FAA must approve the use of airspace.

Direction of Prevailing Winds. Landing and takeoff operations by helicopters preferably should be made in the opposite direction of prevailing winds. To the extent that other factors permit, approach–departure surfaces should be oriented to aim landing and takeoff operations into the wind.

Social and Environmental Factors. Many people consider the noise of helicopters to be objectionable. The need to locate heliports in close proximity to large concentrations of population makes the problem of helicopter noise especially difficult. In selecting a helicopter site, the planner should endeavor to minimize the effects of helicopter noise, especially in the area immediately surrounding the heliport.

Airport planners should also take into account water and air quality, land usage, and other social and environmental factors. In the United States, planners must perform an environmental assessment and provide an opportunity for a public hearing for all federally funded development projects. The FAA provides guidance material indicating the steps to be taken for the consideration of environmental impact (2, 3).

Generally, community zoning regulations permit the use of heliports in industrial, commercial, manufacturing, agricultural, and unzoned areas. However, it may be necessary to seek revision of the existing zoning regulations to permit the development of needed heliports. Restrictions on the heights of buildings in helicopter approach–departure paths should also be included in the zoning ordinance.

Turbulence. In the case of elevated heliports, nearby buildings or rooftop structures may cause troublesome wind turbulence, possibly necessitating flight tests to determine the nature and extent of the problem. It may be found that a certain potential site is acceptable most of the time, despite adverse turbulence in high winds. In such a case, the FAA suggests that the heliport be approved for use up to a predetermined wind velocity limit.

Visibility. The use of elevated heliports may be restricted because of low clouds, especially on buildings of 100 ft or higher. Fog, smoke, glare, and other restrictions to visibility may rule out the use of some potential heliport sites.

Layout and Design of Heliports

The size and shape of a heliport and the type of service facilities offered depend primarily on three factors:

1. Nature of available site
2. Size and performance characteristics of the helicopters to be served
3. Number, size, and location of buildings and other objects in the vicinity of the heliport

A purpose built facility with the main operational areas, taxiways, parking apron and terminal is shown in Figure 14.3. This sketch shows the principal operational components of a heliport: the final approach and takeoff area (FATO), the touchdown and landing area (TLOF), and the safety area.

The FATO is "a defined area over which the final phase of the approach maneuver to hover or to land is completed, and from which the takeoff maneuver is commenced"

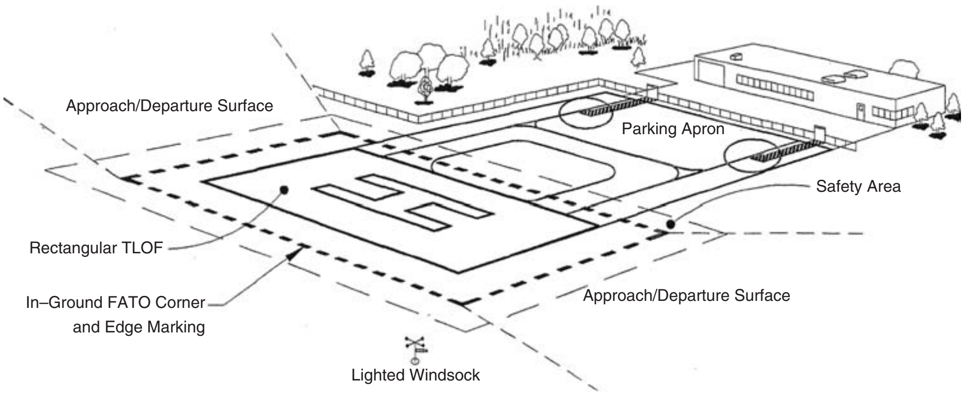


Figure 14.3 Typical TRANSPORT heliport (1).

(1). The FATO may be a rectangle for transport heliports or either rectangle or circle for general aviation (GA) heliports and is normally centered on the takeoff and landing area, its length and width or diameter being defined by the FAA requirements shown in Table 14.2.

The FATO dimensions are shown in Table 14.2, but these may be increased for elevated heliports where the FATO outside the TLOF is non−load bearing. No more than one TLOF can be contained in a FATO which should be capable of sustaining at least the static loads of the design helicopter.

The TLOF which is entirely contained within the FATO may be at ground level, on an elevated structure, or rooftop. The TLOF can be elongated to increase the safety margin of operations but the FATO will also be required to be elongated.

In certain circumstances, parking spaces for helicopters may be required at general aviation heliports if more than one helicopter at a time is expected to use the facility. At transport heliports, the size of the apron depends on the number and size of the helicopters to be accommodated. Parking positions must be designed to accommodate the full range of size and weight of anticipated traffic. A special study of helicopter traffic may be necessary to determine the number of parking spaces required. Parked helicopters should have a clearance of at least one-third the rotor diameter or 10 ft (3.05 m) from a takeoff and landing area or fixed or movable object. In certain circumstances, a helicopter may be allowed to park in the FATO or takeoff or landing area. However, such a practice is undesirable in that it prevents the area from being used by other helicopters for takeoffs and landings.

At transport and general aviation heliports, the level of helicopter traffic and the volume of passengers, mail, and cargo may justify the construction of one or more buildings to facilitate passenger and cargo movements and the service and storage of the aircraft.

Tables 14.2, 14.3a, and 14.3b summarize design criteria for general aviation and transport heliports, including taxiway widths, slopes, and clearances to buildings and obstacles, as recommended by the FAA. Reference 1 gives guidance on the planning and design of hospital heliports and helicopter facilities at airports.

Table 14.2 Heliport Dimensions[a,b]

Dimension	General aviation heliports ft (m)	Transport heliports ft (m)
TLOF width	1 × RD	1 × RD but not less than 50 ft (15.2 m)
TLOF length	1 × RD	1 × RD but not less than 50 ft (15.2 m)
FATO width	1.5 × OL	2 × RD but not less than 100 ft (30.5 m)
FATO length	1.5 × OL	2 × RD but not less than 200 ft (61 m) *Minimum distance between FATO and TLOF × perimeters should be not less than* [0.5 × (1.5 × OL − 1× RD)]
Minimum safety area width:		
TLOF and FATO perimeter marked, std. H marking	GA: 1/3 RD but not less than 20 ft (6 m) PPR heliports: 1/3 RD but not less than 10 ft (3 m)	Safety area should extend outward on all sides of the FATO for a distance of not less than 30 ft (9 m)
TLOF and FATO perimeter marked	GA: 1/3 RD but not less than 30 ft (9 m) PPR heliports: 1/3 RD but not less than 20 ft (6 m)	
FATO perimeter marked, std. H marking	GA: ½ OL but not less than 20 ft (6 m) PPR: ½ OL but not less than 20 ft (6 m)	
FATO perimeter marked	GA: ½ OL but not less than 30 ft (9 m) PPR: ½ OL but not less than 30 ft (9 m)	
Minimum width of VFR approach/departure path at TLOF	Width of FATO	Width of FATO
Minimum width of VFR approach/departure path at highest point	500 ft (152 m)	500 ft (152 m)
VFR approach path length	4000 ft (1219 m)	4000 ft (1219 m)
Slope of VFR approach path	8:1	8:1
Slope of VFR transitional surface	2:1	2:1
Hover taxi parking position: minimum recommended clearance between arcs generated by tail rotor, objects, and buildings	1/3 RD but not less than 10 ft (3.05 m)	1/3 RD but not less than 10 ft (3.05 m)
Ground taxi parking position: minimum recommended clearance between arcs generated by tail rotor, objects, and buildings	10 ft (3.05 m)	10 ft (3.05 m)

[a]RD: Rotor Diameter of design helicopter.
[b]OL: Overall length of design helicopter.
Source: FAA.

Table 14.3a Taxiway and Taxi Route Dimensions: General Aviation Heliports

Taxiway type (TW)	Centerline marking type	TW edge marking type	Minimum width of paved area	Lateral separation between TW edge markings	Tip clearance on each side	Total Taxi route width
Ground taxiway	Painted	Painted	2 × UC	2 × UC	10 ft (3 m)	1 × RD plus 20 ft (6 m)
Ground taxiway	Painted	Elevated	2 × UC	1 × RD but not greater than 35 ft (10.7 m)	15 ft (4.6 m)	1 × RD plus 30 ft (9 m)
Ground taxiway	Flush	Flush	Unpaved but stabilized for ground taxi	2 × UC	10 ft (3 m)	1 × RD plus 20 ft (6 m)
Ground taxiway	Flush	Elevated	Unpaved but stabilized for ground taxi	1 × RD but not greater than 35 ft (10.7 m)	15 ft (4.6 m)	1 × RD plus 30 ft (9 m)
Ground Taxiway	None	Elevated	2 × UC (paved or unpaved but stabilized for ground taxi)	1 × RD but not greater than 35 ft (10.7 m)	1/3 RD plus 10 ft (3 m)	RD < 35 (10.7 m): 5/3 RD + 20 ft (6 m) RD = 35 ft (10.7 m): 78.3 ft (23.9) RD > 35 ft (10.7 m): 2/3 RD + 55 ft (17 m)
Hover Taxiway	Painted	Painted or lush	2 × UC	2 × UC	1/3 RD plus 10 ft (3 m)	RD < 35 (10.7 m): 5/3 RD + 20 ft (6 m) RD = 35 ft (10.7 m): 78.3 ft (23.9 m) RD > 35 ft (10.7 m): 2/3 RD + 55 ft (17 m)
Hover taxiway	Flush	Elevated	Unpaved	1 × RD but not greater than 35 ft (10.7 m)	1/3 RD plus 10 ft (3 m)	RD < 35 (10.7 m): 5/3 RD + 20 ft (6 m) RD = 35 ft (10.7 m): 78.3 ft (23.9 m) RD > 35 ft (10.7 m): 2/3 RD + 55 ft (17 m)
Hover taxiway	None	Elevated	Unpaved	1 × RD but not greater than 35 ft (10.7 m)	1/3 RD plus 20 ft (6 m)	RD < 35 (10.7 m): 5/3 RD + 40 ft (12 m) RD = 35 ft (10.7 m): 98.4 ft (30 m) RD > 35 ft (10.7 m): 2/3 RD + 75 ft (23 m)

These criteria do not apply to offshore helicopter facilities. A heliport located on an offshore structure such as an exploration or production platform for oil or gas is referred to as a *helideck* in ICAO publications. Recommendations for the design of such facilities are given in reference 4.

Table 14.4 shows the recommendations of the ICAO for the geometric design of heliports according to international standards. There are significant differences from the previously cited FAA standards.

Where helicopter operations are to be provided at airports with the provision of a separate helipad, it is necessary to separate the heliport operations from the runway operations of conventional aircraft. The recommended separations using FAA standards are shown in Table 14.5 and those for ICAO in Table 14.6.

Table 14.3b Taxiway and Taxi Route Dimensions: Transport Heliports[a]

Taxiway type (TW)	Centerline marking type	TW edge marking type	Minimum width of paved area	Lateral separation between TW edge markings	Tip clearance on each side	Total Taxi route width
Ground taxiway	Painted	Painted	2 × UC	2 × UC	10 ft (3 m)	1 RD plus 20 ft (6 m)
Hover taxiway	Painted	Painted	2 × UC	2 × UC	1/3 RD plus 10 ft (3 m)	RD < 35 ft (11 m): 5/3 RD plus 20 ft (6 m) RD = 35 ft (11 m): 78.3 ft (24 m) RD > 35 ft (11 m): 2/3 RD + 55 ft (17 m)

[a]RD: rotor diameter of design helicopter.
TW: taxiway.
UC: undercarriage length or width (whichever is larger) of the design helicopter.

Table 14.4 ICAO Geometric Design Recommendations for Heliports at Surface Level (5)

	Helicopter classification		
	Class 1	Class 2	Class 3
TLOF: minimum dimension	0.83*D*	0.83*D*	0.83*D*
FATO: minimum mimension	*D*	*D* (>3175 kg) 0.83*D* (3175 kg or less)	*D* (>3175 kg) 0.83*D* (3175 kg or less)
Safety area: additional radial or peripheral distance outside FATO	Greater of 3 m or 0.25*D* and min. external side dimension shall be 2*D* or min. outer diameter shall be 2*D*	Greater of 3 m or 0.25*D* and min. external side dimension shall be 2*D* or min. outer diameter shall be 2*D*	Greater of 3 m or 0.25*D* and min. external side dimension shall be 2*D* or min. outer diameter shall be 2*D*
Width of ground taxiway	1.5 UCW	1.5 UCW	1.5 UCW
Width of ground taxi route	1.5 LOW	1.5 LOW	1.5 LOW
Air taxiway	2 UCW	2 UCW	2 UCW
Air taxi route	2 LOW	2 LOW	2 LOW
Helicopter stand	1.2*D*	1.2*D*	1.2*D*
Helicopter stand protection zone	0.4*D* beyond stand	0.4*D* beyond stand	0.4*D* beyond stand
Helicopter stands designed for hover turns with air taxi routes or taxiways:			
Simultaneous operations	2*D*	2*D*	2*D*
Nonsimultaneous operations	2 LOW	2 LOW	2 LOW

Definitions:
D = Helicopter greatest dimension.
UCW = Largest width of undercarriage.
LOW = Largest overall width.

Table 14.5 Recommended Distance between FATO Center to Runway Centerline for VFR Operations: FAA

	Small helicopter: 6000 lb or less	Medium helicopter: 6001–12,000 lb	Heavy helicopter: >12,000 lb
Small airplane: 12,500 lb or less	300 ft (91 m)	500 ft (152 m)	700 ft (213 m)
Large airplane: 12,000–300,000 lb	500 ft (152 m)	500 ft (152 m)	700 ft (213 m)
Heavy airplane: >300,000 lb	700 ft (213 m)	700 ft (213 m)	700 ft (213 m)

Table 14.6 FATO Minimum Separation Distances: ICAO

For Aeroplane mass and/or helicopter mass of	Distance between FATO edge and runway edge or taxiway edge is
Up to but not including 3175 kg	60 m
3175 kg up to but not including 5760 kg	120 m
5760 kg up to but not including 100,000 kg	180 m
100,000 kg and over	250 m

Approach–Departure Paths

The imaginary approach–departure surfaces shown in Figure 14.4 make it possible to identify objects that may constitute a hazard to helicopter operations. The surfaces shown are applicable to general aviation and transport heliports serving helicopters using VFR nonprecision approach procedures. Reference 1 specifies the approach–departure surfaces for heliports with precision instrument procedures.

As shown in Figure 14.5, curved VFR approach–departure paths are permitted. As of 2011, the detailed dimensions of the curved airspace requirements have not been published by the FAA.

It is suggested that at least two object-free approach–departure paths be provided, separated by arcs of at least 135°. In configuring the routes, the heliport planner should take into account prevailing winds, noise-sensitive areas, visual aids, and hazards to air navigation.

Figure 14.6 and Table 14.7 illustrate the schematic layout of the takeoff climb/approach surfaces defined by the ICAO which serve either rectangular or circular FATOs (4).

Marking of Heliports

Several marking configurations have been used to identify heliport facilities. The FAA recommended marking of the takeoff and landing area, illustrated in Figure 14.7, consists of a letter "H," at least 10 ft (3 m) in height for a PPR general aviation heliport, up to 60 ft (18.3 m) for other general aviation facilities, and up to 75 ft (22.9 m) for a transport heliport. The marking is centered on the takeoff and landing area or on the FATO if it is marked. Surfaces which have limited weight-carrying ability are identified with a number which appears, from the direction of approach, in a rectangular box below and to the right of the heliport symbol. The number shows the maximum allowable

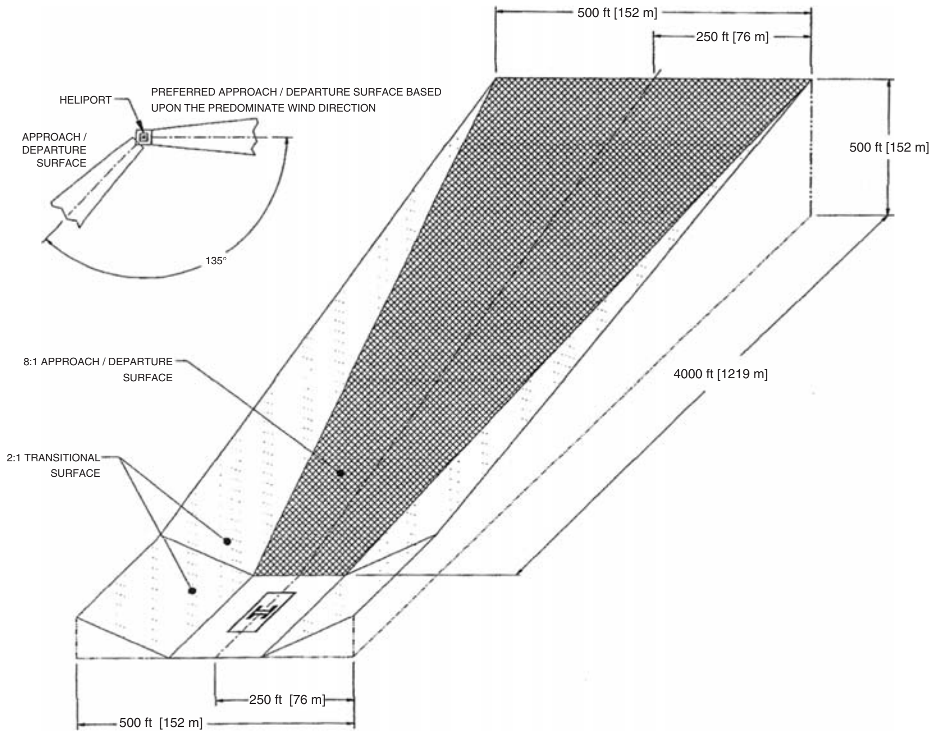


Figure 14.4 VFR TRANSPORT heliport approach/departure and transitional surfaces (1). Not drawn to scale.

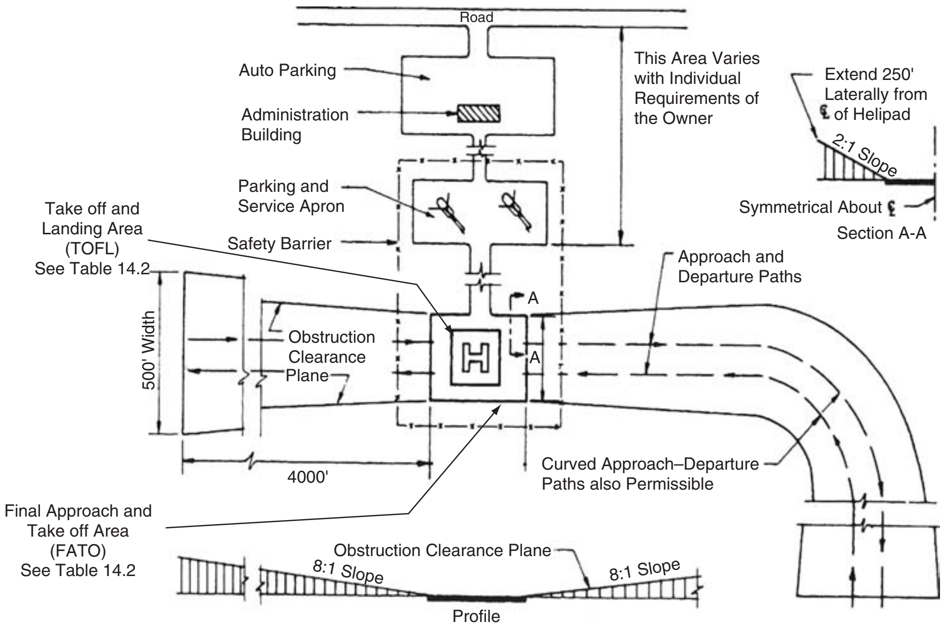
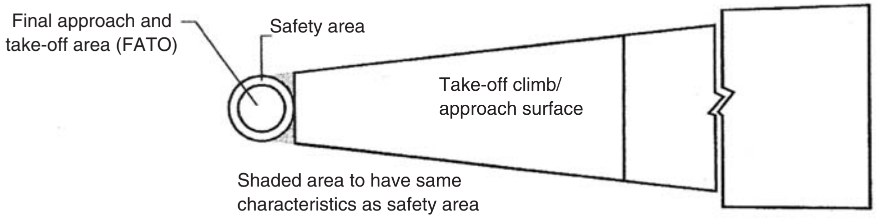
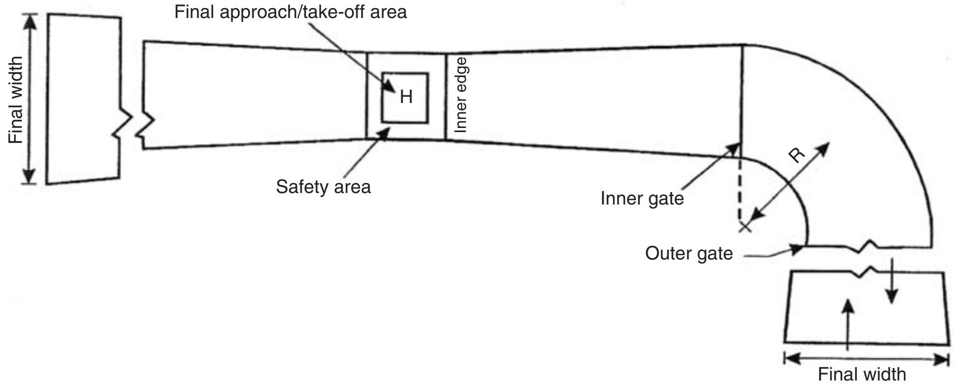


Figure 14.5 Principal components of a heliport with visual approach procedures (1).



(a) Circular final apporoach and take-off area (straight approach–departure)

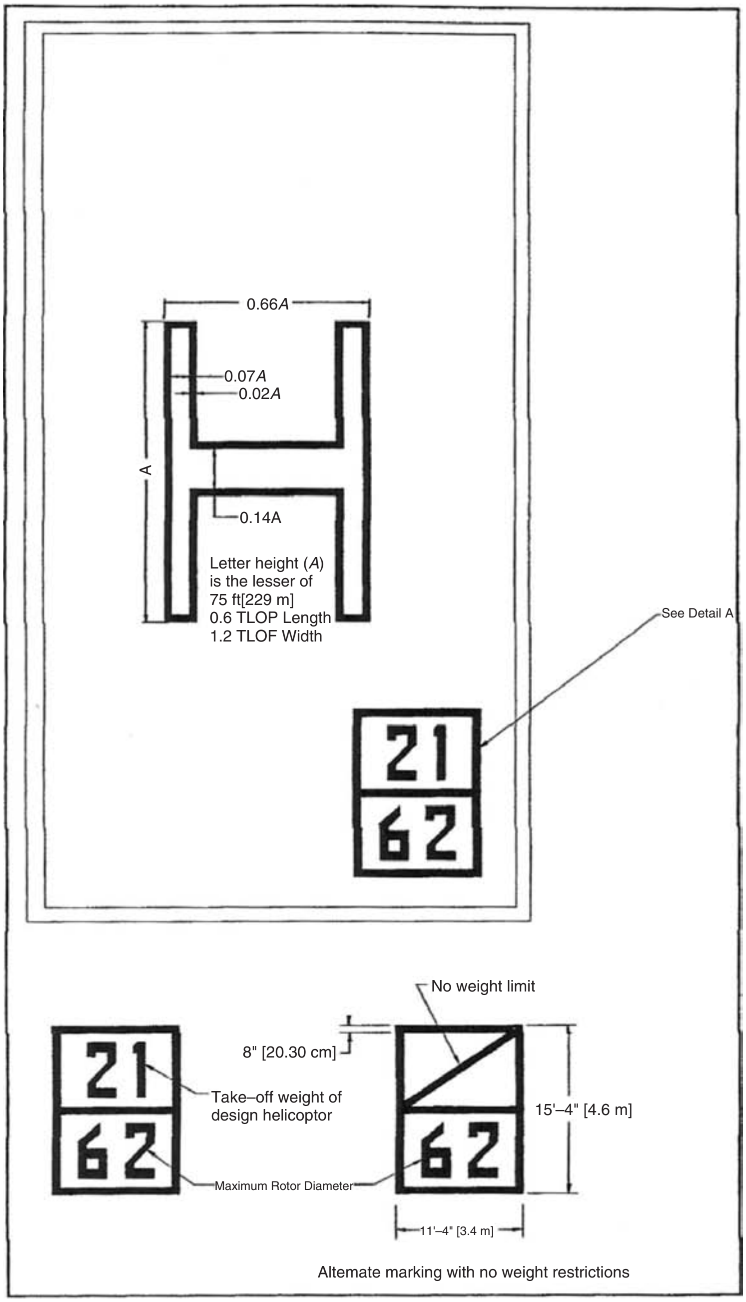


(b) Squared final approach and take-off area (curved approach–departure)

Figure 14.6 Plan views of VFR approach/departure obstruction protection surfaces (4).

Table 14.7 Obstacle Limitation Surfaces VFR: ICAO

Approach surface			
Inner edge			
Location	Outer edge of safety area		
Length	Equal to width of FATO plus safety area		
Side edges	Diverting uniformly from the vertical plane		
	Class 1	**Class 2**	**Class 3**
First-section divergence			
Day	10%	10%	10%
Night	15%	15%	15%
Second-section divergence			
Day	10%	10%	10%
Night	15%	15%	15%
Slope (maximum)			
First section	8%	8%	8%
Second section	12.5%	12.5%	12.5%
Third section	15%	15%	15%



NOTES:

The **H** should be oriented on the axis of the preferred approach/ departure path.
21 indicates the TLOF has limited weigth-carrying capability in thousands of pounds
62 indicates the rotor diameter of the largest helicopter for which the TLOF is designed.

Figure 14.7 Standard FAA transport heliport markings (1).

weight in thousands of pounds. Also shown in this box is the maximum permissible rotor diameter in feet. Figure 14.7 shows the markings for a transport heliport.

Standard heliport markings are white, but when placed on a light-colored surface, they should be outlined in black to make them more conspicuous. The perimeter of the TLOF is marked by a solid white line, that of the FATO by a dashed line.

Hospital heliports should be identified by a white cross with a red H superimposed on its center. To increase its conspicuity, the cross may be painted on a red background and enclosed with the standard edge marking.

The FAA recommends that a windsock of minimum 8 ft (2.5 m) be located in a prominent but unobstructing location adjacent to the landing area. It should be clearly visible to the pilot on approach at a distance of 500 ft (152 m). The color of the windsock, recommended to be white, yellow, or orange, should contrast with its background and should be lighted if night operations are expected.

Taxiway centerline markings and apron parking position markings may also be necessary at busy heliports. These centerline markings are typically a continuous 6-in. (15-cm) yellow line. Edge markings of the paved portion of a taxiway should be two continuous 6-in.- (15-cm-) wide yellow lines. Figure 14.8 shows the schematic layout of a three-position transport heliport parking apron served by a single taxi route from the TLOF with taxiway and taxi route markings. Details of the pavement markings for the individual parking positions are shown in Figure 14.9, which also shows the location of the position identifier and the display of the largest rotor diameter to be accommodated.

Lighting of Heliports

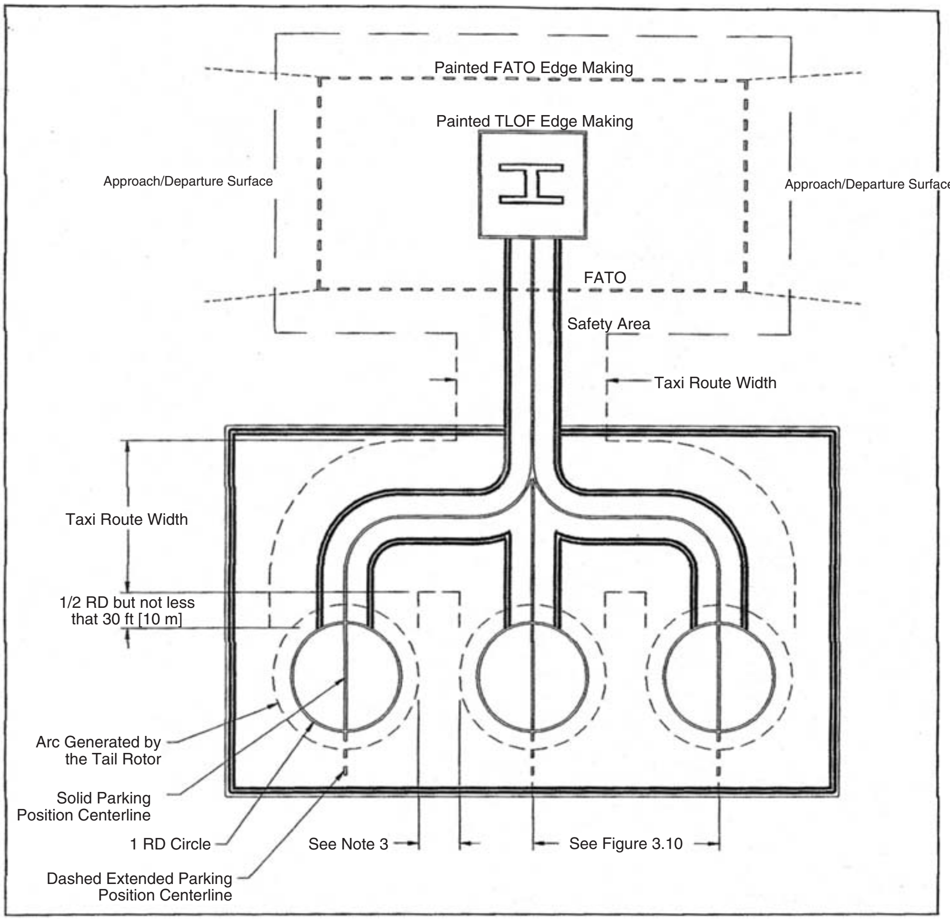
The lighting that is necessary at a given heliport depends on the size of the facility and the amount and nature of helicopter traffic that occurs at night. Six types of heliport lighting are described in the following paragraphs:

1. Identification beacon
2. Obstruction lighting
3. Perimeter lighting
4. Landing direction lights
5. Floodlighting
6. Taxiway lights

This listing is not intended to be exhaustive, but it includes the principal types of heliport lighting employed to facilitate helicopter operations during periods of darkness or poor visibility.

An identification beacon is recommended for heliports that are to be used at night, unless the heliport is a part of an airport. The FAA specifies that a heliport beacon have flashing lights coded white–green–yellow and flashing 30–45 times a minute. It should be visible at night at a distance of 3 mi. The beacon should be located within 0.25 mi of a ground-level heliport. In the case of elevated heliports, special efforts may be necessary in locating the beacon to avoid problems with glare.

All objects that penetrate the obstruction clearance surfaces described previously constitute a potential hazard to navigation. When it is not feasible to remove such obstructions, they should be marked and lighted in accordance with the publication



NOTES:

1. For simplicity, some markings have not been shown on this figure (such as parking position identifier, passenger walkway, and rotor diameter of the largest helicopter that the FATO/TLOF or the parking position is designed to accommodate).
2. The design of these parking positions is based on the presumption that the helicopter may pivot about the mast prior to exiting the parking position.
3. The minimum recommended clearance between the arcs generated by the tail rotor.
   Hover taxi operations: 1/3 RD
   Ground taxi operations: 10 ft (3 m)
4. Rotor diameter and weight limitation markings are not shown for simplicity.

Figure 14.8 Helicopter parking area design: turnaround parking positions, FAA TRANSPORT heliport (1).

Obstruction Marking and Lighting (5) provided an FAA aeronautical study has determined that the object would not be a hazard to air navigation if so marked and lighted. If nighttime operations are anticipated, standard aviation red warning lights and beacons should be placed on towers, flagpoles, smokestacks, and other objects that penetrate the imaginary surfaces. Specifications on the number, type, and placement of obstruction lights are given in reference 5.

As Figure 14.10 illustrates, the FAA specifies that four or more green lights be equally spaced along each side of the TLOF. Green lights should also define the limits

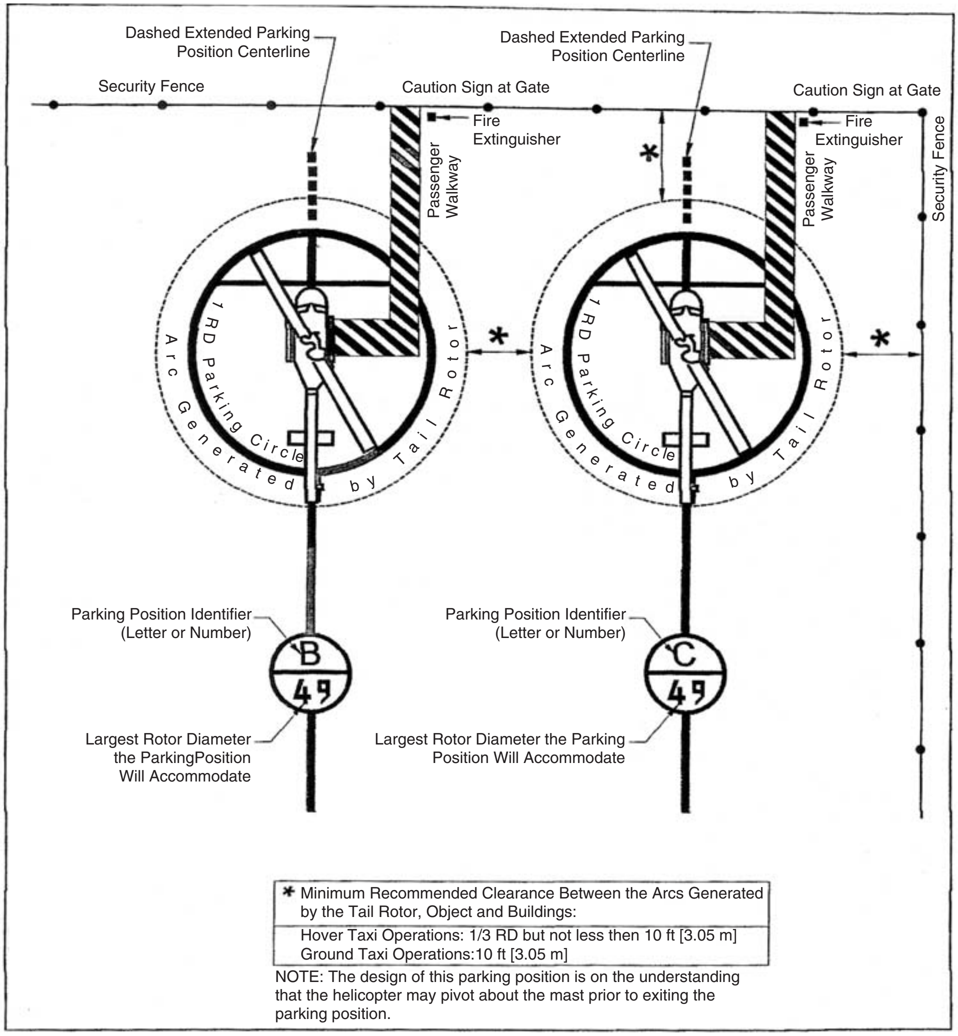
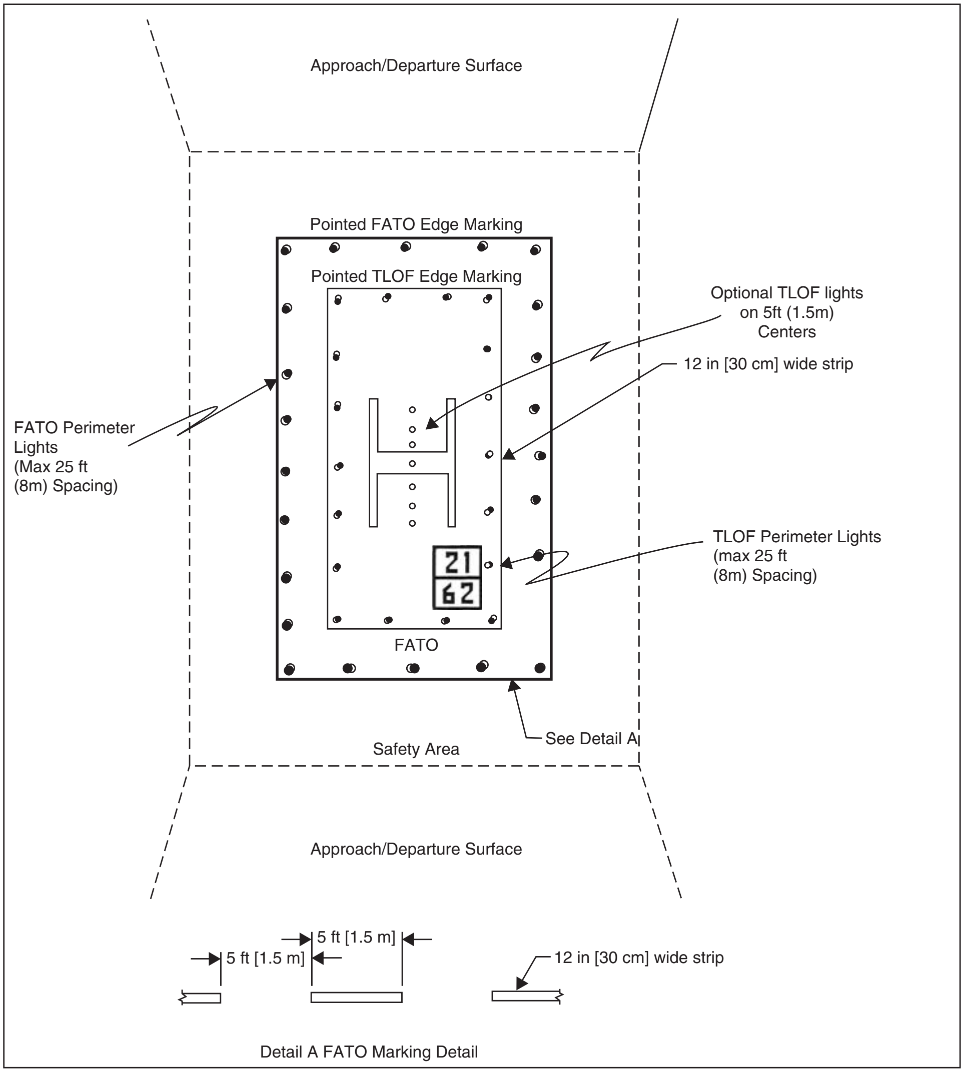


Figure 14.9 Recommended TRANSPORT heliport parking position marking (1).

of the FATO. These should be at each corner and should be on each side spaced not more than 25ft (8 m) apart. The purpose of perimeter lighting is to identify the takeoff and landing area positively during darkness and times of poor visibility. These lights, which are considered necessary for nighttime helicopter operation, should be of low silhouette and should have a hemispherical light distribution.

Lines of five yellow landing direction lights may be employed, with spacing of not more than 15 ft. Selective illumination of these lines of lights communicates to the pilot the desired direction for landing and takeoffs.

Taxiway centerline lights are flush green lights, bidirectional for straight sections. Taxiway edge lights consist of omnidirectional blue lights that outline the usable limits of the taxiway route. These lights are usually located 10 ft beyond the edge of the taxiway.



NOTES:
1. The **H** should be oriented on the axis of the preferred approach/departure path.
2. The perimeter of the TLOF and/or the FATO should be marked.
3. The perimeter of a paved or hard surfaced TLOF should be defined with a continuous, white line.
4. The perimeter of a paved FATO should be defined with a 12-inch-wide (30 cm) dashed white line. (See detail A)

Figure 14.10 Paved TLOF and FATO—marking and lighting. (*Source:* Adapted from ref. 1.)

Floodlighting may be used to improve the overall visibility of the heliport landing surface and to illuminate ramps, aprons, and taxiways. Care must be taken to ensure that floodlights do not dazzle or hinder pilots rather than aid them when they are taxiing or making a landing approach. Floodlights may be installed on adjacent buildings to avoid obstructions of lighting poles.

Elevated Heliports

Heliports may suitably be located on rooftops of large buildings and on piers and other waterfront structures. Elevated heliport sites are especially desirable in heavily developed business districts, where open land is scarce and expensive and where buildings would interfere with operations at ground-level sites. Elevated sites do not require the acquisition of additional land and may provide better accessibility for the helicopter traffic. On the other hand, suitable elevated sites may be difficult to locate and more costly to prepare than ground-level sites and may be less accessible to the helicopter users.

Landing pads for elevated airports come in two basic types:

1. Roof-level helipads, which rest directly on the roof.
2. Helipads on decks which are supported by columns or pedestals and framing that transmit the loads to existing building columns. (In some reference literature, these are referred to as helidecks, although the FAA no longer uses this term.)

In either case, it is recommended that the height of the touchdown area be at least equal to that of the surrounding parapet wall to provide adequate clearance to helicopters during landings and takeoffs. A safety net or fence at least 5 ft (1.5 m) long should be installed around the helipad. It is recommended that the net begin below the surface of the touchdown area and not rise above it.

The obstruction clearance requirements described previously are applicable to elevated heliports. The designer should take special care to ensure that elevator shafts, air conditioner towers, and other rooftop structures do not interfere with safe helicopter operations.

The recommended dimensions of rooftop landing and takeoff areas are the same as for ground heliports. When an elevated helipad is used, however, its dimensions should not be less than 1.5 times the rotor downwash ground effect.

Many commercial buildings can support small helicopters without major structural modifications. A simple wood or metal pad to spread the concentrated loads over the existing structural members may be all that is required.

The roof landing surface should be designed so that it will not fail under impact loads of helicopters making a hard landing. To allow for the effects of impact, the FAA recommends designing the landing surface to support a concentrated load equal to 75% of the gross weight at each main landing gear (i.e., for dual-wheel configurations, 37.5% at each wheel of the gear). The loads should be applied over the footprint area of the tire or landing skid. For operational areas outside the touchdown area, the maximum static loads may be used in the design of the pad and structural framing.

The surface of the helicopter load distribution pad or other platform should be solid so that the motor downwash will produce the maximum "ground cushion."

Elevated heliport landing facilities should be constructed of weather-resistant and fire-retardant materials. Arrangements should be made for the safe confinement and disposition of any flammable liquid spillage. The designer should, of course, comply with local building codes and fire regulations.

Heliport Pavement Design

Procedures for the design of heliport pavements differ only slightly from those used to design pavements for light to moderate sized CTOL aircraft. Although a paved surface for the landing and takeoff area is desirable, turf may be used for heliports that serve low volumes of small helicopters. It has been found that, if the supporting soil is mechanically stabilized by the addition of granular materials, a turf or aggregate turf surface may be suitable for helicopters with gross weights up to 10,000 lb. The FAA states that a 6-in.-thick Portland cement concrete (PCC) surface in most instances is capable of sustaining helicopter loads of up to 20,000 lb (9070 kg). Above this loading, thicker pavements are required. PCC pavement surfaces are recommended for all heliports, not asphalt.

The decision to pave the operational areas normally depends on the gross weight of the largest helicopter served, the number of helicopter operations, the local climatic conditions, and the size of wheel loads of the ground service equipment. The thickness of heliport pavements is determined primarily by the characteristics of the supporting soil and the gross aircraft weight. The procedures for the design of airport pavements described in Chapter 12 are generally applicable to the design of heliport pavements.

The downwash from helicopter rotors manifests itself in the form of undesirable erosive velocities. The magnitude of the downwash velocities and the extent of turbulence in the landing area are largely functions of the gross weight of the helicopter. Where large helicopters are to be served, areas in the immediate vicinity of the touchdown area and other areas where helicopters hover must be properly stabilized to control erosion of the surface. At public heliports, the FAA recommends that the entire landing and takeoff area be stabilized. If hover taxiing is to occur, it is suggested that a width equal to approximately twice the rotor diameter be stabilized along the proposed taxiway.

Nonprecision Instrument Operations at Heliports. Helicopter operations can continue during periods of low visibility where nonprecision approach/departure missed-approach procedures are permitted. The design of nonprecision approaches is a complex matter which cannot be covered even summarily in this book. The reader is referred to references 6 and 7 for detailed information. Only the more important aspects with respect to heliport design can be touched upon here. An improved lighting system is recommended for the FATO, as shown in Figure 14.11.

An additional light is inserted between each perimeter light in the front and rear rows, displaying alternate white and green lights on either side of the FATO to a landing helicopter on final approach.

Heliport Instrument Lighting System. In addition to the enhanced perimeter lights of the FATO, the HILS is laid out as in Figure 14.11, consisting of 24 unidirectional white lights. These are in the form of extending edge bars to the right and left of the approach and wing bars which extend the rear- and front-edge lights of the FATO perimeter lights. Edge bar lights are spaced at 50-ft (15.2-m) intervals measured from the front and rear row of the FATO perimeter lights; the wing bar lights are set at 15-ft (4.57-m) spacing from the line of the FATO perimeter side lights.

Additional TLOF lights are optional. If provided, these are a line of seven flush white lights installed at 5-ft (1.7-m) spacing along the centerline of the TLOF pavement. Aligned to the approach course, these lights provide final directional guidance and better definition of the TLOF surface.

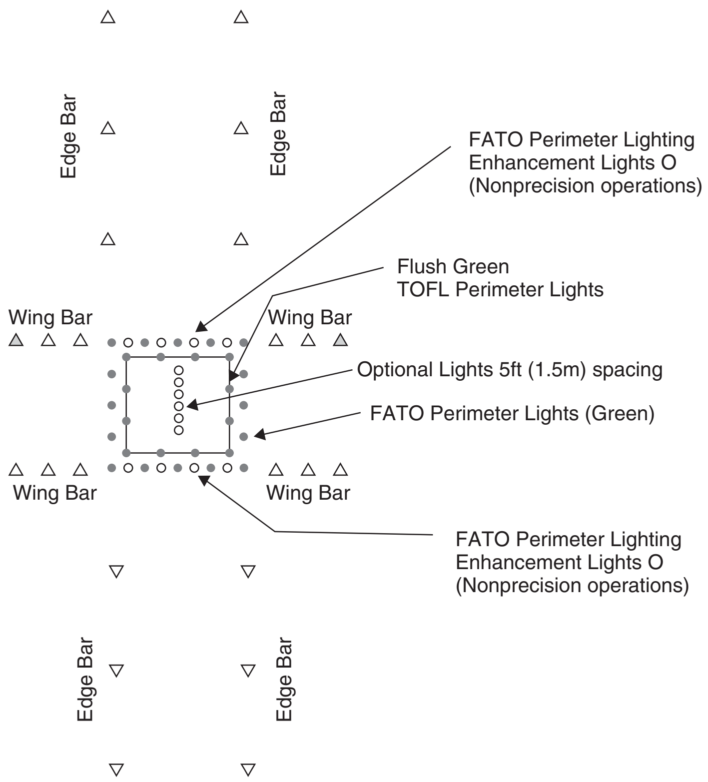


Figure 14.11 Heliport instrument lighting system (HILS): nonprecision. (*Source*: Adapted from ref. 1.)

The obstacle evaluation surfaces defined as VFR approach/departure apply also at an airport with a nonprecision approach. There are additional restrictions on the final-approach segment surfaces, the visual segment of the nonprecision approach, and the missed-approach surfaces. The reader is referred to references 1, 5, 6, and 7, which cover matters too complex and extensive for coverage here.

Precision Approach Heliports. In areas with poor meteorological conditions, the all-weather reliability necessary for a helicopter air carrier operator to be successful may require the provision of precision instrument approach/departure/missed approach procedures. These may also be necessary to provide the operational standards requisite of business, executive, and corporate heliport users not using air carrier service. Precision approach operations must be established in accordance with FAA Order 8260.3 (6). In its technical literature, the FAA is careful to indicate that heliport owners wanting to develop instrument procedures should contact the FAA flight procedures office early in the development process because the design of airspace for precision instrument operations at a heliport is a complex process (1). The main differences from VFR and nonprecision instrument requirements are:

1. Final-approach reference area (FARA) and FATO
2. Lighting requirements
3. Obstacle evaluation surfaces

As of 2011, no precision approach operations have been approved at any heliport in the United States. It is likely that any future approaches will rely heavily on the availability of more advanced GPS technology than was available when the FAA requirements set out in reference 1 were prepared. Given the status of heliport precision approaches at the time of writing, it seems inappropriate to devote more space to the topic here.

14.4 PLANNING AND DESIGN OF STOLPORTS

STOL Operations and STOL Aircraft

In the 1960s, aviation planners began to propose establishing city-center-to-city-center air services using aircraft that required only short runways and quiet aircraft, so-called STOL operations. Some STOL aircraft exist in concept only; others have been extensively researched and flight tested. Some have even been placed in commercial service largely to purpose-built STOLports.

One approach to STOL service is to employ existing low-wing-loading turbo propeller aircraft. A prominent example of this type of aircraft is the de Havilland DHC-6 “Twin Otter,” a twin-engine turboprop aircraft having a capacity of 20 passengers and a cruising speed of 200 mph. Although used extensively for “bush flights” into short primitive airstrips, the Twin Otter has also been used in STOL operations into city centers.

The de Havilland Aircraft Company has also manufactured a larger STOL aircraft, the DHC-7. This four-engine turboprop aircraft has a capacity of 50 passengers and a cruising speed of 266 mph. Low noise levels are assured by its large, slow-turning propellers and moderate power requirements. The faster de Havilland DHC-8, a twin-engine turboprop aircraft with a capacity of 36 passengers and a cruising speed of 310 mph, was placed in service in 1984.

One of the shortcomings of existing STOL turboprop aircraft with low wing loadings ($\sim$80 lb/ft^2) is a low ride quality. To improve this, the use of deflected slipstream turboprop technology has been tried in aircraft such as the McDonnell-Douglas 188. High-lift short-field capacity is attained on this aircraft from large, full-span, triple-slotted trailing edge flaps which are completely immersed in the downward slipstream from the propellers (8).

Designers studied the feasibility of developing a larger capacity swept-wing fanjet STOL aircraft to achieve higher cruising speed. Such aircraft would attain higher wing loadings (and slower landing and takeoff speeds) by means of action of gas exhaust from the engines along the wing trailing edge. This concept, known as the jet flap, produces supercirculation about the wing, resulting in augmented lift that is added to the vertical component of the thrust vector of the high-momentum gas and the basic conventional wing lift (8).

Two basic variations of this concept have been proposed:

Externally Blown Flap. The engine exhaust gas is maintained outside the wing.

Internally Blown Flap. The exhaust gas is directed “through a ducting network in the wing to a narrow slot at the wing trailing edge, then downward through a flap system” (8).

Table 14.8 Physical Characteristics of Selected STOL Aircraft

	Aircraft manufacturer and model		
Data item	DeHavilland DHC-6	DeHavilland DHC-7	Dornier 228-202
Overall length (ft)	51.8	80.6	54.3
Wingspan (ft)	65.0	93.0	55.7
Overall height (ft)	18.6	26.2	15.9
Type of gear	Single wheel	Dual wheel	Single wheel
Wheelbase (ft)	14.8	27.5	20.7
Tread (ft)	12.5	23.5	10.8
Maximum ramp weight (lb)	12,500	44,000	13,735
Turning radius (ft)	41.0	64.0	48.5
Number of engines	2	4	2
Powerplant (type and hp)	Pratt & Whitney PT6A-27, 620 shp	Pratt & Whitney PT6A-50, 1035 shp	Garrett TPE331-5-252D 715 shp
Number of seats	20 passengers	48 passengers	19 passengers
Fuel capacity (lb)	3,049	10,000	4,155
Clearance ground to propeller (ft)	—	5.2	3.5
Clearance ground to wing tip (ft)	9.4	13.2	6.2

Because aircraft noise is a primary factor in siting an urban STOL port, aircraft designers have attempted to develop quieter STOL aircraft. Some progress was made by NASA and Boeing within the Quiet Short-Haul Research Aircraft Flight Program, but this was abandoned in the early 1980s as interest in STOL declined. Physical characteristics of selected STOL aircraft are listed in Table 14.8.

14.5 PLANNING AND DESIGN OF STOL FACILITIES

One approach to relieve congestion at conventional airports was to provide STOL facilities to accommodate short-haul demand at congested CTOL airports or at separate, more convenient locations closer to the central city. However, few airports have been developed solely for STOL operations. Problems of noise, poor ground access, and obstacles to air navigation have been a major hindrance to the development of separate close-in STOLports. Because of the limited interest in the development of STOLports, the subject is only briefly treated here.

Almost all the factors that should be considered in selecting a CTOL airport site are applicable in choosing a STOLport location. Some of the factors of special concern include the following:

1. *Air Safety Factors.* Air traffic separation; changes to existing VFR and IFR traffic procedures; FAA review of airspace utilization; safety with respect to obstructions.
2. *Land and Land Use Factors.* Availability and cost of land; adjacent uses.
3. *Atmospheric Factors.* Direction and magnitude of winds, turbulence and cross-winds, temperatures, precipitation, and visibility.

4. *Engineering Factors.* Costs of construction; ruggedness of the terrain; quality of the foundation soil; availability of construction materials; surface drainage.
5. *Social and Environmental Factors.* Compatibility with neighboring uses; noise.

Although STOL operations are aeronautically feasible and seem, in certain applications, to possibly offer economic viability, experience with STOL facilities has been universally disappointing. London City Airport, a privately owned purpose-built STOLport located approximately 6 mi from the financial center of London opened in October 1987 with a runway of 3543 ft (1080 m) serving DH-7 and Dornier 228 aircraft. The STOLport rapidly converted its operations to take steeper than normal approaches with quiet conventional aircraft such as the BAe 146 and eventually larger aircraft. This was achieved by lengthening its runway to 4948 ft (1508 m) in March 1992. Using conventional aircraft as large as the Airbus 318 equipped with "steep-approach" technology, the airport is thriving. The Victoria Montreal downtown STOLport briefly provided services in the mid-1970s to Ottawa but closed soon after opening and the much publicized Disney World Airport in Florida in 1971 also ceased operations by the late 1970s, being turned into a car park. Other services were started and abandoned in New York La Guardia and Boston Logan.

STOL aircraft also made it possible to provide air service to remote mountainous areas that are inaccessible by conventional aircraft. For example, in 1985, the Himalayan kingdom of Bhutan acquired two Dornier 228 STOL turboprop aircraft to provide regular air service between Calcutta and Paro in Bhutan. Paro had a 1350-m runway at an elevation of 7300 ft above sea level surrounded by towering 10,000-ft mountains (9). By 1998, the runway had been lengthened and the STOL service replaced first by the BAe 146 and later by the A319.

Those wishing to design STOLports should refer to the current standards of the FAA and ICAO for guidance relative to separations and runway and taxiway dimensions and should work closely with the FAA or other traffic control authorities on matters relating to visual aids and obstructions to air navigation. The FAA has long since withdrawn its Advisory Circular AC 150/5300-8, Planning and Design Criteria for Metropolitan STOL Ports. With the cancellation of the FAA's QSATS Program, the thrust toward STOL transport was downgraded. An example of an operational STOL aircraft is shown in Figure 14.12.

Innovative VTOL Concepts

A number of innovative concepts have been considered for VTOL design to overcome the limitations of conventional helicopters which are short range and have low capacities and speeds, high noise levels, and high operational costs.

For example, a wing could be added to provide lift at cruise speeds, resulting in an unloaded main rotor. This design is known as a *compound helicopter.* Such a design would offer improvements in both speed and range, but the added wing would increase the empty weight, and, because of downwash on the wing, more rotor thrust would be required for VTOL.

A second proposed VTOL design, the *composite aircraft*, would rely for liftoff and descent on a rotor that would be stowed along the top of the fuselage at cruise speeds. Forward thrust for the stowed rotor aircraft could be provided by either propeller or turbofan.

Figure 14.12 Operational STOL passenger aircraft. (Courtesy of Bombardier Aerospace Commercial Aircraft.)

Another design consisted of an experimental aircraft with two counterrotating rigid rotors mounted one above the other on a common shaft. This system permitted the advancing side of both rotor discs to generate lift, offering high speeds without the need for a wing to off-load the rotor. Two outboard engines provided auxiliary thrust giving a cruise speed of 125 mph (185 kmph) and a maximum speed of 322 mph (518 kmph). This design has been tested at speeds of 240 knots in level flight.

Still another innovative concept for VTOL aircraft omits the rotor completely. Lift is provided by thrust vectored from the cruise engines. This concept has been utilized successfully in the Harrier aircraft which has seen service in the U.S. Marine Corps and the Royal Air Force. The U.S. version is manufactured by the McDonnell-Douglas Aircraft Company. The vectored thrust aircraft so far has been limited to military uses, and civilian applications are not expected in the foreseeable future.

Tilt-Rotor Aircraft. Tilt-rotor aircraft have a history dating back to the Bell XV-3 which first flew in 1955. In 1977, Bell Helicopter flew the XV-17 tilt-rotor aircraft using large helicopter rotors for vertical lift in the helicopter mode and for forward thrust in the airplane mode. When the rotors are tilted forward, a wing provides the lift. The tilt rotor combines the hover efficiency and maneuverability of a helicopter with cruise efficiency and good range and speed. This experimental aircraft led to the development of the V-22 Osprey in 1989, which was brought into military use in the 1990s. The Osprey has a troop capacity of 24–32 troops.

By 2012, the only tilt-rotor aircraft in real consideration for civilian use was the Bell/Agusta BA609, with a capacity of six to nine passengers and maximum weight of 16,800 lb (7600 kg); see Figure 14.13. Its certification for passenger service is scheduled for 2011. Tilt rotors may develop into a more significant fraction of the civil aviation fleet as technology advances. However, studies have indicated that, as of 2010, the tilt rotor, as exemplified by the Osprey, has neither the heavy-lift ability of the larger helicopters nor the range of conventional aircraft and as such has much to prove if it is to capture the short-haul city-center-to-city-center market as Figure 14.14 suggests

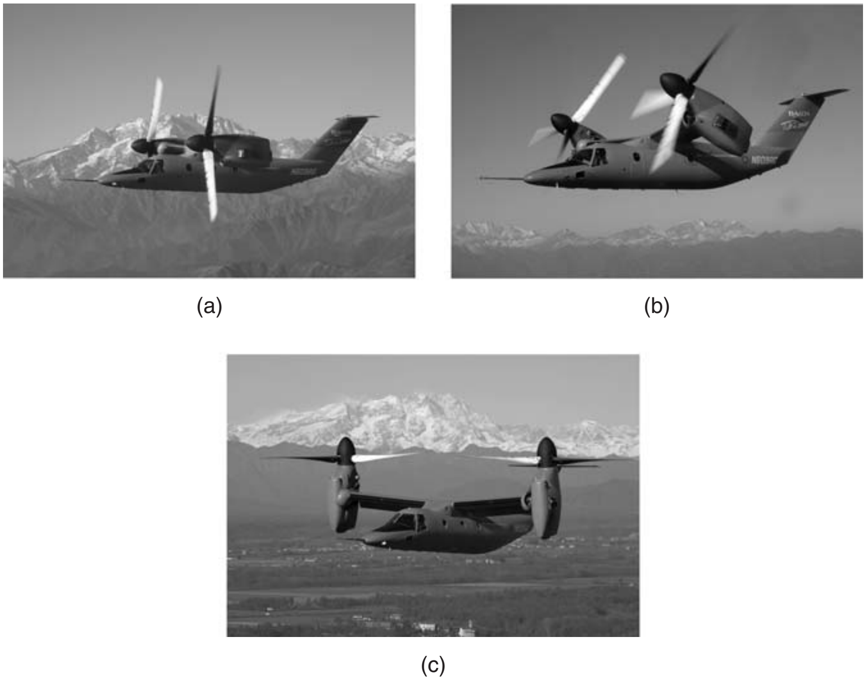


Figure 14.13 Tilt-rotor aircraft: (a) BA609 in horizontal flight en route, (b) BA609 in transitional flight, (c) BA609 in vertical flight for landing or takeoff. (Courtesy of Agusta Westland.)

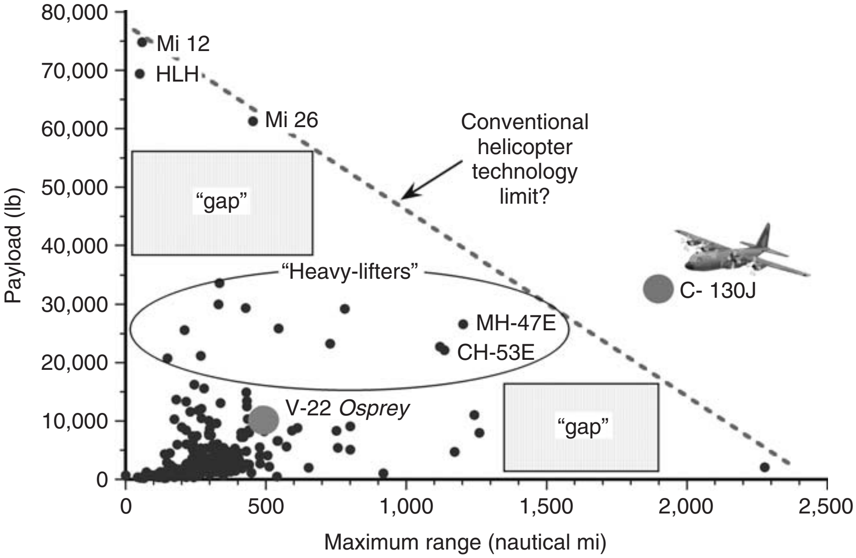


Figure 14.14 Tilt-rotor payload versus range. (Courtesy of J. G. Leishman.)

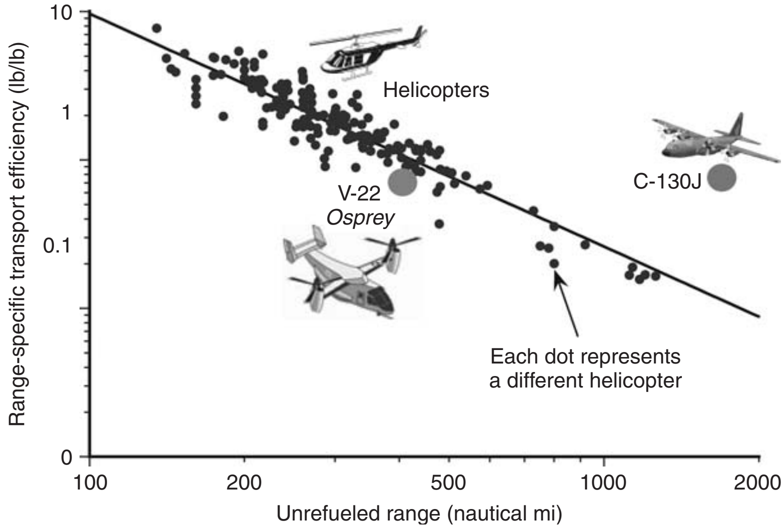


Figure 14.15 Range-specific transport efficiency versus unrefuelled range. (Courtesy of J. G. Leishman.)

(10). When the payload–range relationship is examined, the Osprey does not stand out from helicopters in performance. Although faster than helicopters, there is a significant penalty of payload against range, caused by the high fuel burn of the tilt rotor. Because tilt rotors are relatively heavy in comparison with helicopters and conventional aircraft, the *range-specific transport efficiency* of the V22 has been shown to be not much different from helicopters, as shown in Figure 14.15.* The tilt rotor would appear to have applications where the cruise speed of the aircraft gives a competitive edge in the proposed air transport market.

14.6 PLANNING AND DESIGN OF VERTIPORTS

In the 1980s and 1990s, many aviation pundits predicted that in addition to the rapid expansion of helicopter usage, significant city-center-to-city-center air traffic would be diverted to facilities using aircraft with tilt-rotor technology. These facilities, providing full support for the takeoff and landing of tilt-rotor aircraft, came to be known as vertiports. Such facilities would normally be capable of accommodating also the operation of helicopters. Limited-service vertiports intended to be used solely for tilt-rotor aircraft and rotorcraft engaged in picking up passengers or cargo were designated as vertistops.

The FAA has produced an advisory circular on vertiport design but issued it with the unusual caveat that an aircraft would have to designed to conform to the standards that the circular set out. Given the tenuous situation of the development of civil tilt-rotor aircraft, the FAA-published standards for planning and design of vertiports are not covered in this chapter. The reader is referred to reference 11.

*Range-specific transport efficiency is defined as the ratio of the payload weight transported to the fuel weight consumed for a specific transport range.

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15

Airport Modeling and Simulation

15.1 INTRODUCTION

Not long ago airport simulation was a novice concept for airport planning and capacity studies. It was not very well understood by airport planners, engineers, and other practitioners, and at times it was even looked at with doubt and mistrust. This changed during and after the 1990s as air transport researchers experimented with modeling and simulation techniques, considering them to have better understanding of the complex and intricate relationships governing airport operations. This came at a time when giant leaps in computer technology, hardware, and software made it possible to venture into approaches to adopt that were not possible to undertake a few years earlier. Transportation researchers and airport engineers joined hands to explore practical aspects of airport simulation and their utilization to enhance airport planning (both airside and landside) and their implementation for complex airport and airspace capacity studies. The primary objective here was to solve the lingering capacity shortages plaguing busy airports, the NAS airspace, and the airport system at large. Eventually, these new approaches were adopted to improve airport planning and design practices as well as capacity evaluation. During 1997–2002 forums and activities that fostered this effort were held by the American Society of Civil Engineers (ASCE) in simulation-focused conferences to discuss all aspects of applying simulation to airports (1) and the Transportation Research Board (TRB) in a series of workshops on airport–airspace simulations and other specialized meetings.* During this period, the FAA provided support and funded several airport simulation programs, including SIMMOD and ALSIM, which provided encouragement and support to the airport simulation community to achieve progress.

Today, no major airport development is conducted without the use at some level of airport modeling and simulation and GIS techniques, particularly in airport master plans, airport–airspace capacity studies, and assessment of airport impacts on the environment. After 2001, airport terminal simulation became essential and critical to comply with the more stringent security measures at airports.

The airport modeling and simulation framework is comprised of several interconnecting and interrelated models and simulation applications that are integrated and synchronized. Moreover, it is important for the airport planner and designer to understand the unique and specific technical characteristics of how and when to utilize one versus all others.

*Refer to the TRB website for TRB simulation workshop e-circulars and TRB records: http://www.trb.org/Main/Home.aspx.

Models are used extensively in the different components of the master plan process that this section covers. The most important and central to the entire airport development process is aviation demand forecast models. A section is dedicated to present the various levels, types, and formulations of forecasts models (discussed earlier in Chapter 2) and how they should be applied. The focus is more on the technical applications of the models and less on context.

Also described are all the airport airside simulations and their genesis and evolution from a first-generation SIMMOD to the second-generation TAAM for the airport to the most recent development in this field. The same is described for airspace simulations. Also, the modeling and simulation of the entire U.S. airspace system are discussed, as airports actually form the nodes of this system.

On the landside, the terminal and airport access simulation is discussed, covering their genesis and evolution leading to the models in use today. Beyond the description of the simulation models, the specific use of landside simulation models and the use of their output as direct input to facility design are also discussed with examples of airports that are currently in operation.

Airports increasingly require the GIS for their planning, management, and development. Section 15.7 provides a high-level introduction to GIS to provide the airport planner with the basics of this important and indispensable resource for airport planning and design.

15.2 DEFINITIONS AND CONCEPTS

The terms *model*, *simulation*, and *animation* are sometimes used interchangeably but they are not synonymous. It is very important to fully understand the meaning, function, and use of each and how each would be applied in the realm of air transport planning. Simulation is a relatively modern computerized feature used in this field that benefited from monumental advancement in computer technology during the 1980s. It progressively demonstrated its potential with "organic proliferation" across all aspects of our daily lives. Only two decades ago simulation was just another novice tool with unique fascination but not any real promise. It is prudent therefore to accurately define each term and its precise use in airport studies prior to describing the various simulation models covered.

A *model* is an abstract and idealized representation of reality put in a variety of forms: a graphic, an equation, or even a statement (2). Since models are abstractions of an assumed real-world system that can identify pertinent relationships, models are used rather than the real system primarily because manipulating the real-world system would be prohibitively costly or even impossible (3).

Since models are abstractions of the real system used to simplify and/or approximate certain features of the system, they are generally categorized into descriptive and prescriptive–normative models.

Descriptive models basically provide a description of the system behavior, particularly with respect to representation of embedded processes. These are used primarily to conduct analysis on the system processes.

Performance models are subset of descriptive models that focus on relating measures of system performance [e.g., levels of service (LOS), delay] to the system's physical and operational characteristics, primarily the demand–supply relationship.

Prescriptive–normative models aim to determine (prescribe) the system features that would achieve certain preset objectives (e.g., optimization, maximization, and harmonization) of the system components. They typically require articulation of the objective function of the descriptive model within the analytical framework. These are used primarily as design tools.

Analytical models provide real system representation through sets of equations and mathematical formulations and are typically used to solve "closed-form" problems. They are normally inexpensive, simple to use, and transparent to check and verify. But they often are too complex to apply, hence limiting applicability and detail of system representation, which requires simplifying assumptions to make them practicable.

Numerical models are used to avoid this problem by adopting numerical solutions or through approximation procedures to compute results for complex mathematical relationships that do not have ready analytic solution.

Simulations are models intended to replicate system processes as a function of time using a computerized representation of the real-world system utilizing mathematical, logical, or numerical models to predict system behavior by estimating the change of the system state over time. Simulation provides a process for computer representation of real-world systems through conducting experiments to understand behavioral aspects of the system or evaluate strategies to operate it (4). The primary advantage of simulation is the opportunity to provide considerable representation detail of complex system interactions that precludes analytic solutions in order to study real-world system behavior and monitor the operational performance of the systems without physically creating them.

Modeling tools may come in varying forms and levels of complexity and sophistication. Models could be *manual* (e.g., as simple as using pencil and paper), *physical* [e.g., solid two- and three-dimensional (2D, 3D) models], *graphical* (e.g., maps and drawings, and the more modern CADD and GIS), or *computer based* to process and manipulate data (including spreadsheets (e.g., Excel), programming languages (e.g., FORTRAN, BASIC, C++, JAVA), and special-purpose languages (e.g., GPSS, GASP, SLAM). Functional types of simulation models are:

- *Analytical Queuing*. Probabilistic models that use complex mathematical expressions derived from queuing theory.
- *Accounting*. Time-based deterministic models that use predefined rules to describe the state of the system.
- *Time Dependent.* Event-based stochastic models that use dynamic equations with mathematical-logical representation of Monte Carlo methods for fast-time reproduction of the state of the system.

The building blocks of the discrete-event simulation of a basic "service" process, shown graphically in Figure 15.1, include:

- *Entity* is the most basic unit of time-based discrete-event simulation, and it has unique sets of *attributes* that are common to group of entities.
- *Event* is a point in time on the simulation clock at which changes in the characteristics of the system take place.
- *Activity is* a transaction entities engage in throughout the simulation life that would define the system.

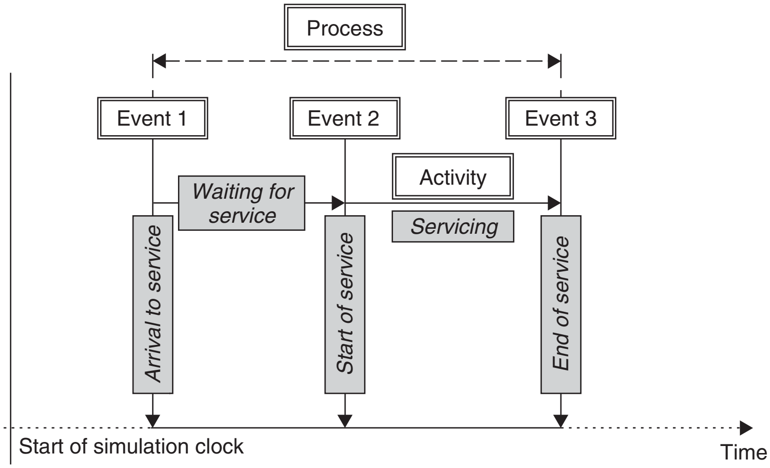

Figure 15.1 Conceptual graphic of service process (3).

- *Process* is a time-oriented sequence of events that encompass several activities that engage many entities.

The simulation model basic generic construct is represented by:

- *Input and Its Format*. In terms of numbers, graphics, sound, and other multimedia.
- *System Representation.* As defined by formulas of relationships between system variables and components.
- *Platform*. Mechanistic framework, or hardware, with input–output peripheral devices and tools, that is, the computer.
- *Output.* Compilation of simulation results represented as numbers in flat files, graphics in different formats, and animation. Animation is therefore only one form of the simulation output.

A simulation model's view of the real-world system could be either discrete or continuous. *Discrete-event simulation* describes system state changes discretely at isolated times called events. *Continuous simulation* represents system state changes dynamically in relation to the state variables. Simulation was first used among operations research (OR) analysts as a validation tool. Experienced modelers would like to think that a good simulation is part art and part science (4)!

Types of discrete-event simulations and examples of programming languages that were used for airport and airspace simulations include:

- *Event Oriented.* Uses event-based simulation languages, for example, SIMSCRIPT.
- *Activity Oriented.* Uses activity-based simulation languages, for example, ECSL.
- *Process Oriented.* Uses process-based simulation languages, for example, GPSS.

Object-oriented simulation is based on the object-oriented programming (OOP) construct. Mostly programmed in C++-OOP, this simulation framework is predicated upon *objects* with *attributes* that have *values* that communicate with other objects via '*messages*'. The OOP framework was a sensational success across disciplines, where it was successful and efficient in simulating distributed systems, virtual reality animations, and computer-controlled electromechanical systems (robotics). Consequently, a wide range of integrated simulations were adapted to advanced technologies that in aviation include advanced flight and air traffic control (ATC) animation-based simulators.

Specifically for airport–airspace, object-oriented airport simulations were met with praise as researchers proved how practical and efficient they were in representing the airport–airspace system and how successfully they solved problems related to capacity assessment, facility design, airspace ATC/air traffic movement (ATM) procedures, and environmental planning.

Basic prerequisites to ensure success of using simulations/models in representing systems for the purpose of planning, managing operations, and solving problems include understanding the meanings of resemblance, simplification, and idealization.

These would require the capability to:

- Understand the structure and function of relationships between system components and the environment and the simulation context
- Maintain clarity on simulation objectives and definition of system input and output
- Interpret all changes in system state and related operational characteristics
- Evaluate system behavior and its performance
- Translate the model description into a practical program format readily accessible for computer processing that is compatible with various computer formats
- Adequately monitor system attribute accuracy

Basic necessary requirements to conduct computer simulation require technologically current components that include:

- Efficient computer platform
- Effective operating system
- Computer simulation software, with suitable animation and graphics capabilities
- Input data peripheral devices for formats needed, for example, numeric, graphic, and multimedia
- Adequate data management, archiving, and retrieval for data and simulation output
- Output peripheral devices for formats required for output files reporting, simulation log, animation data dumps, and so on
- Postprocessing capability for reporting and animation replay

General types of models for the purposes of simulating system operation include:

1. *Analytic Models*. Exact representations of the system (closed-form solution) in the form of relationships between the dependent variable and the independent variables.
2. *Monte Carlo Simulation*. Description of a system with random variables derived from a stochastic distribution without consideration of the passage of time.

3. *Continuous Simulation*. Modeling of a system through differential equations describing mathematically the change of state variables over time represented in numerical solutions of these equations.
4. *Discrete-Event Simulation*. Description of a system using logical relationships describing the change in state variables over time (discrete changes). These models mimic the behavior of entities in complex systems by using the discrete-event simulation approach to follow system resources and activities performed. It is this kind that is most widely used to simulate airport operations.

Principles of Discrete-Event Simulation. Simulation moves from one scheduled event to the next, where simulation events are executed based on a preset schedule of activities where entities are routinely assigned to resources. The simulation clock is based on the current event's scheduled initiation, not elapsed clock time. Based on this paradigm, many internal events are generated for each external event. But events that are simultaneous, that is, events with the same initiation times, are processed sequentially but there is no time change to the simulation clock. In airport and airspace simulation, resources are considered objects like runways, taxiways, gates, and airspace links engaged in activities within networks of link-node structure where "aircraft" entities move between resources throughout this link-node network, or alternatively in the four-dimensional continuum of space and time.

The process of simulation model development includes the following steps, where each needs to be carefully complied with vis-à-vis certain parameters and statistical control:

1. System evaluation and the identification of the problem in a clear statement
2. Problem analysis, formulation, and variable relationship model building
3. Project scoping and planning, scenario building, and definitions of performance measures
4. Data acquisition and abstraction
5. Model translation into computer code
6. Model verification, or whether the model does what it is intended for
7. Model validation, or whether the model is an accurate representation of the real system
8. Planning, design, and execution of experiments, with proper statistical controls to determine whether the simulation runs satisfy the objectives of the study
9. Prototyping and experiment implementation
10. Simulation runs and the analysis of results
11. Study documentation and project implementation

The flow chart of the simulation development process is depicted in Figure 15.2.

Advantages versus Disadvantages of Simulation

Simulation has many advantages and disadvantages that have to be carefully weighed prior deciding on the simulation in light of the specific conditions of the project at hand.

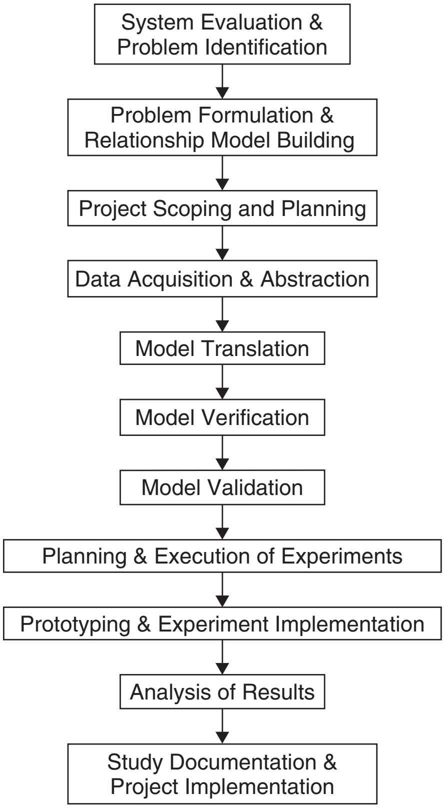

Figure 15.2 Simulation study development process.

Advantages of simulation include:

- It is always quicker and cheaper to develop a simulation than to build the real system.
- Once a model is built, it can be used repeatedly to analyze the proposed design, policies, or problem at hand.
- Simulation methods can be used to analyze a proposed system despite the scarcity of real-world data.
- Simulation data are typically less costly to obtain than similar data from the real system.
- Simulations are easier to understand and apply than mathematically advanced methods (e.g., queuing theory) and hence are attractive to users.
- Applying analytical methods usually requires certain simplifying assumptions to make then mathematically tractable; simulations normally do not need these restrictions.
- Simulation provides the flexibility of measuring a variety of system performance measures deemed necessary to monitor, while analytical methods may have a limitation on the number and kind of performance measures.

Disadvantages of simulation include:

- Simulation typically requires a considerable amount of data, whicht may be costly in terms of acquisition time and costs of collection and handling.
- Complex computer simulations may sometimes be costly as far as time, computer hardware and software, and development and validation of the model.
- Simulation runs required to build the necessary synthetic database of the problem have to be carefully determined statistically. This may imply a large number of runs, depending on the nature of the problem and accuracy required for the solution.
- In very special occasions, analytical techniques would provide the appropriate results whereas simulation would not.
- Simulation modeling requires certain investment in specialized expertise and thorough training.

To build efficient simulation models and run them effectively, certain capabilities and properties are desirable. These include:

- Flexible methods of describing state changes during an event
- Techniques for scheduling events to occur relative to the independent variable time or upon satisfaction of a set of logical relations of state variables
- Extended data structures such as lists and trees and capabilities to easily manipulate them
- Built-in capabilities for generating random variables and random functions, as discrete-event models are essentially stochastic Monte Carlo processes
- General arithmetic capabilities and methods for gathering statistics and controlling experiments in the system
- Interfacing capabilities with other segments of the legacy software (e.g., FOTRAN libraries, SAS standard statistical packages, and SIMGRAPHICS graphical objects)
- Advanced debugging capability
- Graphics capabilities to display output of statistical experiments
- Real-time animation graphics
- Programming, editing, and data coding and manipulation capabilities

15.3 AIRPORT SIMULATIONS

Typically, airport simulations essentially address three broad and distinct components of the airport: its subsystems—airside, landside, and groundside. The following simulations are used in airport studies to analyze the airport's functions independently:

- *Airspace* simulation of aircraft operating in the NAS airspace between airports
- *Airport airside* simulation of aircraft operating on the airfield and the terminal airspace
- *Environmental* modeling and simulation, including noise, air quality, and aircraft emissions

- *Airport landside* simulation of persons moving between different parts of the terminal building and vehicles at the terminal curb frontage

Each of the above is described in the following sections discussing evolution, basic construct and components, application for airport capacity and operation management studies, and state of the airport–airspace simulation industry. However, no attempt is made to provide an exclusive list of all brands of simulation models and systems available in the market.

In addition to these major simulation models, other applications of modeling and simulation related to the airport system are more related to airline operations. Models, while not categorized as simulation, have been covered in this book in relation to demand forecasts (Chapter 2), airport systems (Chapter 4), master plan analyses (Chapter 5), airport capacity (Chapter 7), environmental analysis (Chapter 17), and other subjects. Simulation models related to airline operations will be only briefly mentioned.

To provide continuity, versatility and across-systems solutions, integrated models may sometimes be devised. The common goals of these large-scale airport simulations include:

- Determine global airport measures of effectiveness.
- By interfacing the airside and landside, airport delays could be estimated for some airport schedule (demand) scenario, where delays represent the difference between unimpeded and actual travel times across the entire airport.
- Estimate utilization of specific airport resources (such as gates, runways, and taxiways) over time.
- Estimate capacity approximated in an airport system through estimating delay at all airport resources (facilities).

15.4 AIRFIELD–AIRSPACE SIMULATION

To conduct airport airside simulation adequately, the simulation needs interfaces with the terminal airspace (approach) and sometimes to en route as well. The airside portion of simulation (ground) would have to be integrated with the airspace simulation (airspace) in one system, as they cannot be separated in real-world environment.

This section covers both airport airfield and airspace simulations.

TAMS Simulation of DFW

The first airside–airfield simulation was conducted by TAMS Consultants in 1969 as part of the master planning for Dallas–Fort Worth (DFW) regional airport (5). TAMS was authorized to develop “a simulation of aircraft ground operations which would permit evaluation of the operational efficiency of the proposed airfield plan and determination of the optimum locations for the airlines within the passenger terminal modules.” The aircraft ground operation simulation (AGOS) is a time-oriented simulation of aircraft airfield ground movement used to evaluate time and cost parameters under various operational and environmental conditions through indicators of the effectiveness and efficiency of the airfield plan and its control procedures in order to select the optimal one.

The simulation model used the GPSS (General Purpose Simulation System) language. Each entity (aircraft) in the system is generated with a predefined set of rules and according to a predefined event schedule. The simulation included operational procedures and statistical distributions based on observed aircraft operations that are used to control assignment decisions. The simulation model logic relied on submodel rules and distributions of components, formulation of FAA ATC and ground control procedures, and the airlines' gate–runway operational procedures and future schedules.

As congestion builds up in certain airfield locations, aircraft routing assignments are changed, based on observed ground traffic controller's actions in these conditions. The model design had sufficient flexibility to permit assessment of effects of different airfield aircraft loading (demand) and variations in environmental conditions.

The output of the simulation, mainly aircraft delays and congestion points of the apron–taxiway–apron system, provided the airport planners with the necessary information to develop an operationally efficient and effective configuration plan of the airfield. This effort was the first to use simulation to actually assess airport plans and generate efficient airfield configuration. This study verified, through using this innovative technique, the merit and effectiveness of an all-parallel runway airfield system which four decades later became the optimum plan to follow. TAMS used the same approach to conduct passenger terminal simulation that would be covered under airport landside simulation.

FAA SIMMOD

SIMMOD is a fast-time, event-step simulation model written in SIMSCRIPT II.5 with a preprocessor and postprocessor in C language. It is designed to "play out" airport and airspace operations on a computer and calculate real-world results for user-specified operational scenarios based on a node–link network to represent the gate–taxiway–runway–airspace interconnected route system (6). SIMMOD is one of the first airport–airspace simulations whose development was spearheaded by the industry, supported by the FAA, and used by aviation planners. In 1978, industry, supported by the FAA, developed the airport/airspace delay model (ADM), the predecessor of SIMMOD, and since then, it has gone through several phases:

- Basic simulation engine development and validation (1978–1988): FAA provided low-level funding to this program, and in 1983 it was renamed SIMMOD:
  - Development of basic airspace and airfield logic, which included upgrades and modifications to simulation logic and enhancements to its pre- and postprocessors.
  - Airfield and fuel consumption modules were added.
  - SIMMOD validation test and evaluation were conducted during 1985 at several U.S. airports and ATC facilities by an FAA-sponsored committee of aviation and airport experts, with the developer of SIMMOD, ATAC Corporation, conducting the SIMMOD validation exercise for the FAA in 1988 (7).
  - FAA applications.

- Public release with FAA-funded user support (1989-1995): FAA provided high-level funding to:
  - Develop the graphic user interface (GUI), network builder, and animation
  - Official release of the PC version 1.2 (DOS) software to the public (1989)
  - Expand platform application from PC-DOS to PC-OS2 and workstation (UNIX) version 2.0 (OS/2) in March 1991 and an integrated noise model (INM) interface in December 1991
- Transition to industry (1995–1997)—The FAA transitioned the maintenance and development of SIMMOD to private non-FAA management with funding coming from industry through user-paid support, with oversight from a worldwide membership of users group. Eventually it evolved into multiple SIMMOD products.
- Transition to public–private (after 1998): SIMMOD witnessed more transition, including:
  - Core simulation engine management moved to NEXTOR: FAA Center of Excellence, which oversaw its research and management. Private organizations took responsibility for derivative development.
  - The future evolution of the model is being dictated by the SIMMOD Users Group in North America (NASUG) and Europe (ESUG).
  - Investment in specific research and enhancements was through user-paid support, and more choices of SIMMOD products became available to users.
  - Simulation logic was continually enhanced with change to the simulation engines.
  - More focus on realizing benefits accrued to users from integration of SIMMOD with contemporary tools and models.
  - Eventually, next-generation SIMMOD would evolve.

SIMMOD is possibly the most widely utilized airport and airspace simulation model in the world, with about 300 registered users worldwide, with 185 users from 35 countries (8). Of those perhaps a third are believed to be currently active. The FAA is providing partial support of the SIMMOD development effort, while the simulation industry is continuing to develop and market commercial versions—SIMMOD-Plus and SIMMOD-Pro, the current successors of the original FAA software. The new SIMMOD-Plus! includes the following new or upgraded features: new network builder, database editor, 2D animator, report generator, new data conversion and verification utilities, and upgraded simulation engine. SIMMOD is now a mature model, having undergone many revisions, upgrading, and improvement cycles over more than 25 years. Despite minimum funding to SIMMOD, its development is continuing through partial funding from industry and user around the world to ensure SIMMOD's future growth.

Typical simulation applications of SIMMOD include:

- Runway operations and capacity evaluation
- Airfield (gate–taxiway–runway) ground operations

- Terminal area traffic
- Multi-airport interactions
- En route airways traffic studies

Conducting SIMMOD Simulation

According to the SIMMOD training literature (9), SIMMOD enables the user to build airspace and airport representation for execution by the simulation from inputs that describe the airport physical layout. The airport flight schedules to be simulated are part of the input based on airline flights by unique flight schedule, schedule times, gate assignments, and flight plans to destination. The program executes both data inputs (airport layout and flight schedules) and uses external data to initiate flights and terminate them as the simulation clock specifies. SIMMOD uses the simulation clock to move from one scheduled event to the next, where several program-generated events are created for each external event, all depending on the simulation logic and procedures of operation. During operations, the program resolves all conflicts and monitors time, delay, and fuel consumption along each segment of the system around the clock.

The principal restriction with SIMMOD is that traffic must move on a pre-specified network constituted of nodes and links that reflects the airspace structure, the pre-specified operating procedures, and the ATC/ATM strategies. Therefore, SIMMOD essentially checks conflicts on the aircraft's longitudinal path along specified links only, with no possibility for lateral or vertical separation violations. This has always been SIMMOD's drawback versus its major competitors: TAAM and RAMS.

On the other hand, SIMMOD has two attractive features that allow it to be used with other simulations: modularity and flexibility. Early in its development, SIMMOD was interfaced and linked with the INM, so the noise impacts of aircraft operations at airports are evaluated using the output of the SIMMOD simulation.

NASA has worked on another effort to integrate SIMMOD and TAAM on a distributed network that is connected to the top NAS airports in the United States (10). This network (LMINET) is implemented in 64 U.S. airports that account for 85% of domestic passenger traffic and more than 80% of air carrier operations. These airports are a superset of the FAA's 57 "pacing airports" indicated in Chapter 7 in relation to NAS capacity studies. This effort, conducted by the Logistics Management Institute (LMI), was to explore, test, and demonstrate advanced ATM technologies required to enable safe and efficient air travel, as significant changes are expected in ATM technologies and procedures, and the roles and responsibilities of various parties involved. Establishing a modeling and simulation infrastructure to explore the multidimensional performance of proposed concepts and system technological changes is deemed necessary for such an effort.

Generally, LMINET models link the queuing network models of airports with the sequenced queuing models of their respective TRACON and ARTCC sectors. In this respect, LMINET could then offer a fast-time simulation of the NAS, a valuable air traffic simulation for NAS aircraft delays and traffic flow congestion. SIMMOD and TAAM (described later) are the two most widely used simulation models of the airport and airspace in the world with varying degrees of sophistication. These discrete-event simulations track all aircraft operations throughout simulated time clock with high fidelity; hence they are accurate in generating synthesized air traffic statistics. This

NASA effort integrated the NAS airport network (LMINET) with the high-fidelity TAAM and SIMMOD simulation models.

EUROCONTROL has also developed a SIMMOD-RAMS data interface (SIMBUS), so that RAMS and SIMMOD can be operated jointly as one simulation, with RAMS being the airspace component simulating aircraft final approach and departure and SIMMOD simulating the airport–airfield operations.

In order to conduct the SIMMOD simulation, the steps outlined below have to be followed.

Input. There are five categories of SIMMOD inputs: airspace definition, airfield definition, schedule events, flight banks, and aircraft definition. For each category, SIMMOD provides logic, procedures, and system operating rules governing the simulation and defines the simulated operation. Extensive data collection is therefore required to compile the input files for simulation, including:

- Preparing the airfield digitized input file, where the airfield components are expressed in a node–link construct. Each node (taxiway intersection or runway exit) and link (taxiway or runway) of the airfield is assigned a unique number by the program.
- Preparing the airspace digitized input file, where the terminal and en route airspace structure is expressed in a node–link construct. Each node (fix) and link (airway) is assigned a unique node or link number in the simulation input file.
- Matching airport–airspace interface nodes, that is, defining the runway threshold as an interface point unique to both the airspace network and airfield.
- Preparing the input file defining the airfield physical characteristics in terms of the components: runways, taxiways, taxi lanes, gates/aircraft stands, airlines and their gates (exclusive or shared use), and the runway holding areas and departure queues.
- Preparing the input file defining the airspace network characteristics in terms of airspace links (airways) and nodes (fixes) in terms of physical attributes and procedures for the associated airports.
- Preparing the "event file," which defines the flight schedule for simulation in terms of flight plans, type of flight [i.e., arrival, departure (enplane), multiarrivals, multidepartures, turnaround, or transit], special simulation instructions (e.g., trace), and end time of simulation.

Output. After the end of the simulation period, SIMMOD generates reports of all outputs required for analysis from an output dump file. SIMMOD provides highly detailed statistics on each aircraft simulated, with data obtained on aircraft travel times; traffic flows past specified points; delays by time of day and location on the airfield or in the airspace; throughput capacity per unit of time; and loading on the system links and nodes, along with aircraft fuel consumption. Reports are usually tailored by the user but generally include statistical summaries, graphics, and animation.

One of the first and largest applications of SIMMOD was conducted for the Chicago Regional Supplemental (third) airport study in two phases during 1990–1995:

1. *Phase* 1. Analysis of the Chicago regional airspace with the objective of selecting a site through evaluating the operational performance of the system with five alternatives for the new airport (11).
2. *Phase* 2. Evaluation of the terminal airspace structure and airfield layout plan of the site selected, and analysis of the airport airfield design based on simulation results of the long-term operational environment (12).

The Chicago region airspace study (13) covered nine counties in northeastern Illinois and northwestern Indiana comprising the Greater Chicago region, with two primary airports (O'Hare and Midway), nine reliever airports, five public general aviation (GA) airports, and more than 25 private GA airports. Table 15.1 lists the major airports in the study with their demand (aircraft operations in 1989) and nominal capacity (ASV).

Airspace included in the simulation extended 150 nautical mi from O'Hare and included 44 sectors of the Chicago ARTCC airspace (120,000 square miles), the O'Hare TRACON 40-mautical-mi radius divided into 13 areas of control, the Milwaukee overflight sectors, and the airspace of the satellite airports covered in the study. Table 15.2 lists the ATC centers covered in the study, with the 1989 annual operations, NAS rank, and average daily operations. The SIMMOD input database included a 1989 baseline where data were collected for one week in November:

- FAA-published flight procedures, terminal and en route sectorization, traffic control area charts, airspace route structure, standard instrument departures (SIDs)

Table 15.1 Chicago System Airports, Operations and Capacity (13)

Airport	Classification[a]	Based GA aircraft	Demand, aircraft operations	Nominal capacity (ASV[b])
Chicago O'Hare International[c]	PR_L	2	797,000	841,000
Chicago Midway[c]	PR_L	292	257,000	330,000
Lake in the Hills[c]	RL_BU	136	94,000	108,000
Waukeegan Regional[c]	RL_TR	261	131,000	220,000
Palwaukee[c]	RL_TR	460	207,000	275,000
Aurora Municipal[c]	RL_TR	276	146,000	160,000
DuPage County[c]	RL_GU	470	217,000	160,000
Lewis University (Romeoville)[c]	RL_BU	243	74,000	155,000
Lansing Municipal	RL_BU	158	39,000	155,000
Gary Regional[c]	RL_TR	115	106,000	220,000
Chicago Meigs Field[c]	CR_S	4	6,000	240,000
Clow (Plainfield)	GA_BU	141	37,000	150,000
Schaumburg[c]	GA_BU	141	83,000	215,000
Campbell (Round Lake Park)[c]	GA_GU	90	18,000	220,000
Joliet Park[c]	GA_BU	81	59,000	215,000
Frankfort	GA_BU	162	38,000	150,000

[a]P = commercial service-primary (L = long-haul, M = medium-haul, S = short-haul).
CM = commercial service-other, CR = reliever airport with commercial service.
RL = reliever (GU = general utility, TR = transport, BU = basic utility).
GA = general aviation.
[b]Annual Service Volume, in terms of aircraft operations.
[c]Airports included in FAA terminal area forecasts.

Table 15.2 Air Traffic Operations in Chicago Airspace (13)

Facility	Annual operations	NAS rank 1989	Daily average operations
Chicago ARTCC	2,499,252	1 (ARTCC)	6,847
Chicago O'Hare TRACON	1,179,889	2 (TRACON)	3,233
O'Hare ATCT	789,384	1 (ATCT)	2,163
Chicago Midway	316,041	34 (ATCT)	866
Chicago Palwaukee	250,101	53 (ATCT)	685
Chicago DuPage	217,515	74 (ATCT)	596
Aurora	140,567	179 (ATCT)	385

and standard instrument arrival routes (STARs) for the primary airports, and area navigational charts. The baseline traffic was projected into three future demand forecasts for the years 2000, 2010, and 2020 derived from the baseline traffic. Using this database, the simulation link–node network and all the simulation rule-based procedures were developed. To project a realistic system environment, the NAS plan was evaluated to examine planned system improvements and was covered in the simulation operation logic.

- Flight progress strips of the entire ATC system were collected for the seven days in November from the ARTCC, TRACON, and airports' ATC towers. A total of 80,000 flight strips were compiled.
- The selected representative day was analyzed based on the compiled flight strips and reflected on the Official Airline Guide (OAG) schedule to derive a "representative SIMMOD event file" that will drive the simulation.
- Realistic aircraft operational characteristics reflecting the actual fleet were included in the simulation. New aircraft technologies and operation characteristics for aircraft fleets in future scenarios were included based on the airlines' new aircraft that will be entering service in the future.

Based on the above, SIMMOD simulations were run representing combinations of three groups of scenarios:

- Baseline (1989) and three future horizons of 2000, 2010, and 2020
- Each of the five alternative sites (Lake Calumet, Gary, Bi-State, Kankakee, and Peotone) proposed as the third Chicago airport shown in Figure 15.3, with the location of O'Hare and Midway airports
- Certain operational scenarios that needed to be simulated separately.

These runs were designed to provide data to enable analysis of the operational performance of the regional airspace at different scenarios for the proposed site of the new Chicago regional supplemental (third) airport. The database required to conduct the analysis included the following: airspace structure, flow and loading; airport airfield operations data; flight scheduling (grouping of airline hubbing activities into flight banks, nonscheduled operations, GA routing, etc.); aircraft characteristics; and lists of events that drive the simulation.

SIMMOD simulations for the Chicago regional airspace study were run in three stages following FAA guidelines for SIMMOD applications (14):

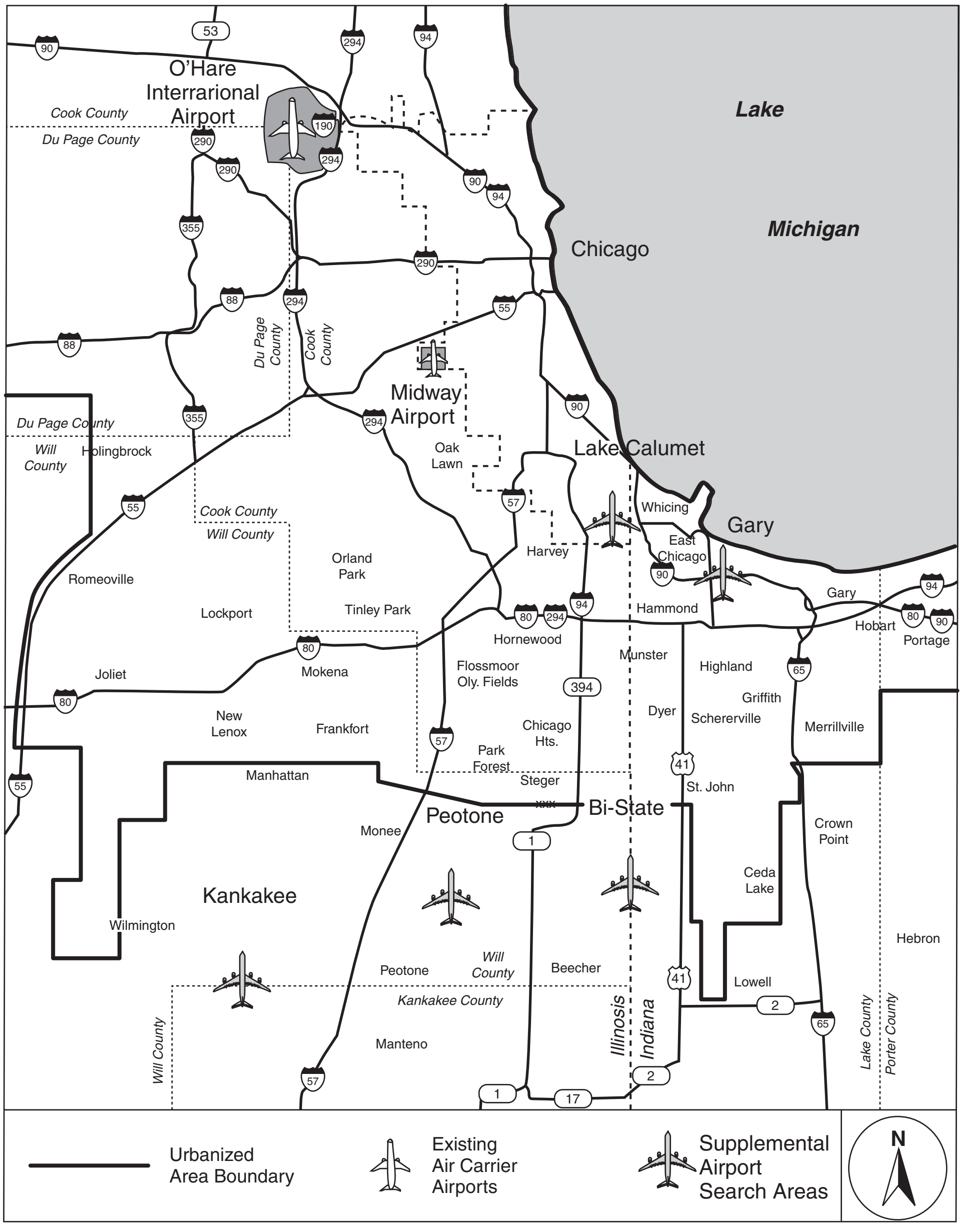

Figure 15.3 Chicago airports, existing and proposed (13).

Preprocessing. Data acquisition and compilation were integrated into specific SIMMOD format files for the preprocessor component of SIMMOD. These data included standard arrival and departure procedures and routes developed for each of the alternative sites, forecast air traffic demand for the airports coded in the "events flat file," and other airfield-specific characteristics of the five alternative sites.

Simulation. The SIMMOD events file drives the simulation and initiates the aircraft traffic arrivals and departures, both in the air (airspace) and on the ground (airfield).

Post-processing. After termination of the simulation run based on the simulation clock synchronized with the events file, an extensive digital file for all SIMMOD 'transactions', or the "log file", is created representing progress of the entire model through the designated simulation clock, executing events according to their scheduled time. The SIMMOD output units use the extensive data on simulated events compiled by the postprocessor to generate reports, graphic displays, and animations. The reporting unit provides comprehensive data logging and statistical analysis on aircraft fuel-burn, aircraft operations (takeoff, cruise, hold, landing, and taxiing), delay in different flight segments, and other operation performance-based data.

Simulation Results. For the first stage of this study, the simulation output indicated the following:

1. *Baseline Simulation*. For the two existing commercial (O'Hare and Midway) and satellite airports, there was a 22% increase in annual delays in the system for 2010 and 2020. This is associated with the forecasted increase in operations for a "no-build" scenario. The aircraft operation forecast grew by 8% for O'Hare and 11% for Midway for 2010, a level maintained at 2020 due to capacity constraints. Total system operations grew from 1,068,000 in 1989 to 1,164,000 in 2010. Only a modest, supply-driven growth in regional aviation activity is considered in the simulation, as it is constrained by the physical capacity of the airports.
2. *Simulation for Third Airport Scenarios*. With a supplemental (third) commercial airport included in the simulation, airport regional system demand was expected to increase to 1,700,00 operations by 2010, with the third airport capable of taking up to 530,000 operations. The 2020 demand at the third airport would increase to 665,000 annual operations, approaching that of O'Hare. Since there is a strong and direct interaction within the entire regional system of airspace and airports, the simulation indicated substantial increase in total delay and average delay per operation across the system. Airspace is limited and finite and the kind of close-in interactions of three close-by airports will continue to pose major problems within the simulated terminal airspace. One fundamental reason for this complex situation arises from the simple fact that the runways at these three urban airports (O'Hare and Midway airports, and the Lake Calumet alternative site) are not harmoniously aligned, a situation that would substantially complicate the arrival–departure procedures of the terminal airspace through its four corner posts.
3. This situation manifested substantial increases in delay for the closest site to Chicago proper (Lake Calumet site), which would result in a situation that may necessitate the closing of Midway Airport. A new scenario was therefore run with the closure of Midway Airport to commercial operations with Lake Calumet as the third airport site. However, this new simulation scenario indicated that little or no change resulted as changes in en route or terminal air

traffic procedures did not create more airspace or resolve critical interactions and coordination problems. The results of the two Lake Calumet sites with Midway Airport open and closed indicate an unacceptably high level of delay whether Midway is opened or closed:

(a) For the Midway Airport open scenario, the average delay per operation at the Lake Calumet site is excessive at 45 min/operation in 2010, reaching 61 min/operation in 2020.

(b) For the Midway Airport closed scenario, the average delay per operation at Lake Calumet is less critical, at 21 min/operation in 2010 and stabilizing at 20 min/operation in 2020.

4. The Gary, Indiana, regional airport site fared slightly better than the Lake Calumet site, but still resulted in high delay levels—it is still relatively close to Midway Airport as well as the departure/arrivals tracks. Therefore, full airport system capacity for Gary as the site would not be achieved, but the airspace situation would not necessitate the closure of Midway Airport. Under this scenario, simulation results indicated an average delay per operation of 11 min in 2010 and 15 min in 2020.

5. The three "green-field" sites, Bi-state, Kankakee, and Peotone, are grouped geographically farthest south at around 35 miles distance from Midway Airport. Despite this distance, while the sites are not completely free from airspace ATC interactions with Midway, they are not as adversely affected as the other two sites. Access to north tracks is somewhat problematic for departures, where such operations are likely to be delayed, rerouted, or restricted to low altitudes for longer distances. Simulation results indicate that the average delay per operation for these three sites ranged between 9.6 and 9.8 min/operation in 2010 and between 11.2 and 12.4 min/per operation in 2020.

6. In retrospect, the analysis conducted in this study proved, through simulation almost two decades earlier, the importance of harmonious runway alignment for efficient operation of the entire airport system in this active airspace and vibrant metropolis. The study proved that such a complex runway configuration of the existing airports of O'Hare and Midway contributed to the excessively high delay levels in the region's airspace, and this was evident even at the baseline analysis. It is interesting to observe that at present O'Hare Airport is currently undergoing an extensive and costly reconstruction program to realign its runway into an all-parallel runway configuration, which will result in considerable reduction of system-wide delay in the region.

7. In phase 2 of this study, the airfield configuration of the selected site was extensively tested through simulation to arrive at an efficient airfield design. Conclusions from the simulation results were (14):

(a) The all-parallel configuration proved to be the most efficient for ground operation. A single crosswind runway was included to accommodate smaller turboprop aircraft, which is a small percentage of the airport aircraft fleet mix.

(b) Simulation validated an important and new feature of the airfield–runway end taxiways. During peak periods, aircraft taxiing between runways and gates on hubbing "banks" experience delay when crossing one or two busy runways. Routing these aircraft around the ends of runways instead of crossing them reduced aircraft delays even though the taxi distance is longer. Airlines may find a trade-off between aircraft taxiing longer with delay crossing runways or at intersections versus experiencing ground delay waiting to cross runways streaming with almost continuous flow of takeoff and landing aircraft.

National Airspace System Performance Analysis Capability (NASPAC)

NASPAC was developed by the FAA Operations Research Service, FAA Technical Center and the MITRE Corporation in the early 1980s (15). It provided the first attempt to address NAS-wide system performance through total NAS capacity evaluation. The FAA has identified major airports in the NAS as pacing airports that are characterized by high traffic volume that frequently exceeds the operational capacity of the airport. The FAA used NASPAC to assess airport-based system-wide delays with the goal of minimizing effective delays at airports, hence reducing NAS-wide delay (16). It is a scalable model with entities representing NAS airports, airport arrival and departure fixes, sectors, routes, and restrictions. It was useful to evaluate the impacts of system improvements (i.e., new airports or expansion) and technology (e.g., ATM system automation, resectorization, GPS routes) on the capacity and delays of the entire system (see Section 7.2). It focuses on the interaction between terminal airspace and airport operations and provides procedures for both to be properly interfaced. Figure 15.4 provides a schematic depiction of the elements of the terminal airspace (TRACON) between the airport and en route airspace. As an example, Figure 15.5 depicts a flight between Chicago O'Hare and Atlanta Hartsfield airports and all the NAS entities it crosses.

As previously discussed in Chapter 7, the airport runway capacity model exhibits the relationship depicted in Figure 15.6, which establishes the relationship between aircraft arrival and departure capacities of the airport (17).

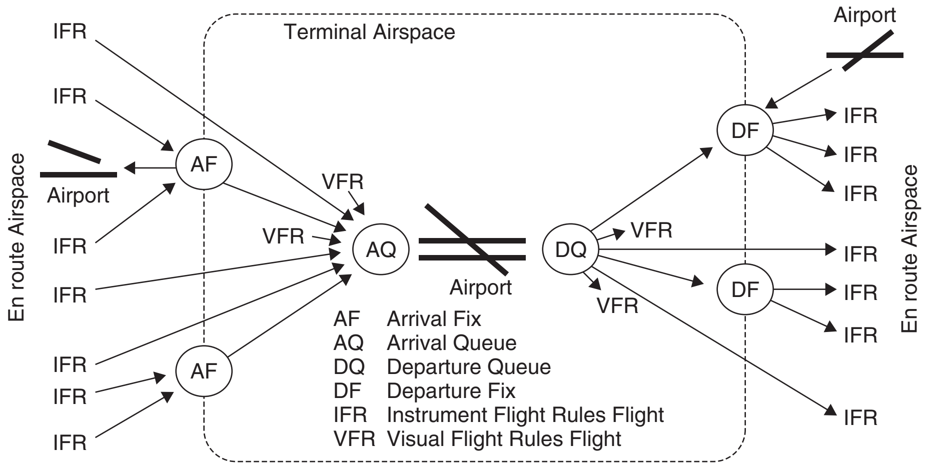

Figure 15.4 Schematic of terminal airspace between airport and en route airspace (17).

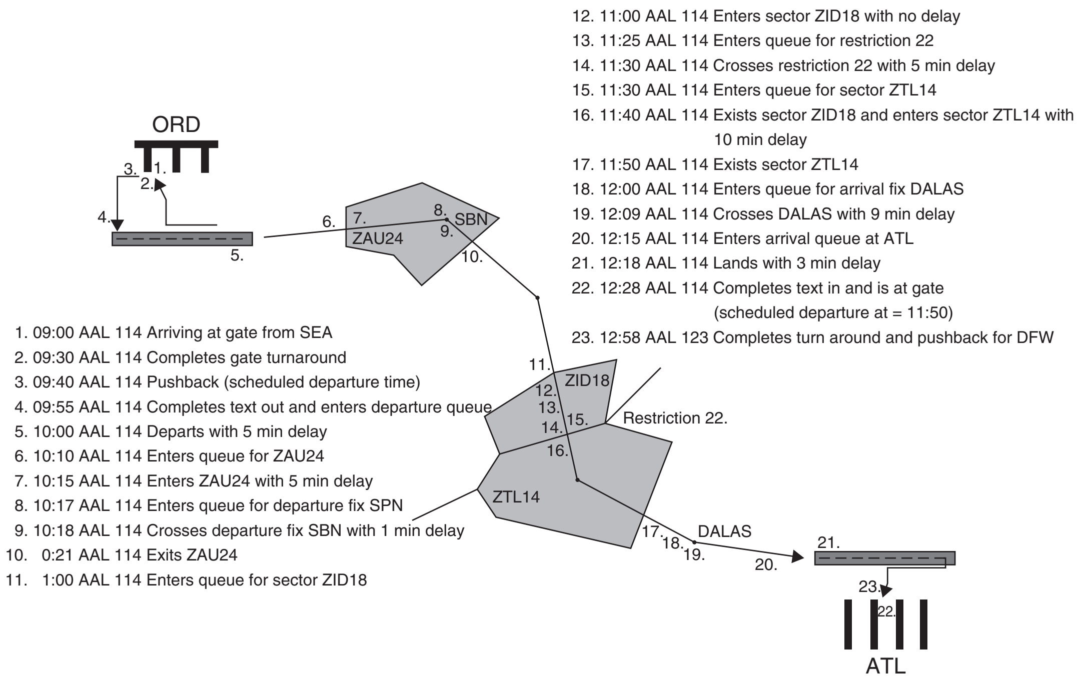

Figure 15.5 NASPAC flight log entry between ORD and ATL (17).

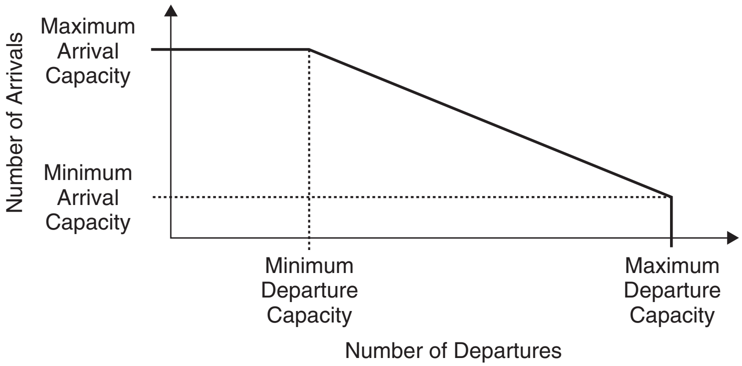

Figure 15.6 NASPAC airport runway capacity model (17).

Reorganized ATC Mathematical Simulator (RAMS)

The RAMS model is a fast-time discrete-event simulation system developed by EUROCONTROL Experimental Centre to provide functionality for the study and analysis of airspace systems, ATC systems, and future ATM concepts (18). It is composed of the typical structure of the simulation model with an input data preparation and display system, a simulation engine, and an output system with animation and reporting packages.

The main objectives of RAMS include:

1. Model a wide range of ATC/ATM concepts, synthesizing operational analytical results, that would offer ATM managers and aviation planners insights into assessing different scenarios and experiment with new concepts.
2. Provide a cost-effective, fast-time simulation tool to analyze a system, evaluate its operational performance, and assess modifications or state changes of the system.
3. Measure the workload associated with existing and proposed ATC systems and organizations. This is an important measure to increase airspace capacity through modifications of airspace structure, including air route reorganization and resectorization.

RAMS components and features include:

1. Integrated editor and display tool
2. Rapid data development module
3. Stochastic traffic generator
4. Four-dimensional flight profile calculator
5. Three-dimensional sectorization tool
6. Four-dimensional spatial conflict detection capability
7. Forward-chaining AI (artificial intelligence), rule-based conflict resolution capability
8. Four-dimensional conflict resolution maneuvering tool
9. Controller workload assignment module
10. Graphic animation
11. User-tailored reporting package

RAMS system software is written in MODSIM II, an object-oriented computer simulation language incorporating object-oriented programming (OOP) features, such as encapsulation, inheritance, and polymorphism, combined with a library of graphic objects programmed in SIMGRAPHICS II. The following RAMS functions are written in MODSIM II:

- Graphic editor
- Query module
- Rule-based system
- Simulation engine
- Dynamic graphic animation in simulation

The following functions are written in other programming languages but are integrated under the MODSIM II environment:

- Data extraction module
- Postprocessing reports

The RAMS system has the capability of simulating a variety of ATC functions and can be applied to a wide range of studies that include:

- *Sector Workload*. Study the variation and distribution of the workload given different tasks to perform.
- *Route Planning*. Conduct high-level route planning "top-down" ATC simulations using traffic display/edit features of RAMS and the conflict detection and resolution mechanism.
- *Airspace Resectorization*. Airspace resectorization and route reorganization using the graphical sector manipulation features to assess the effects of the changes proposed.
- *Free-Flight Routing*. Simulating continuous flight rerouting and graphical "dragging" of navigational aids would approximate free-flight routing.
- *Future System Capacity*. Simulating actual and forecast traffic sampling of varying density and composition generated in the airspace system to assess the effectiveness of proposed ATC/ATM refinement on the future capacity of the system.
- *Conflict Resolution.* Using RAMS rule-based conflict resolution capability to effectively and accurately model the different control areas without extensive reengineering of the simulation software.
- *Testing Future Procedures and Technologies.* RAMS would be effectively used to model the behavior of the new system operating under new ATC procedures and navigational technologies, such as RVSM, ADS-B, FMS–RNAV, RNP, etc., described earlier in Chapter 6.
- *Comparative Analysis of Proposed Changes.* RAMS could provide comparative analyses of proposed system changes and report on the distribution of controllers' workloads; traffic loading per sector, center, route, fix, and so on; and traffic penalty caused by imposing air traffic flow management measures, flight level changes, en route/ground delays, and arrival holding.

RAMS has been continuously refined to enhance its features and coverage taking advantage of the continued advancements in computer software and hardware technologies. It has been used primarily within EUROCONTROL to conduct airspace integration and airspace refinement.

Total Airspace and Airport Modeller (TAAM)

TAAM, a large-scale detailed fast-time simulation system used to model entire air traffic systems, was developed by The Preston Group in cooperation with the Australian Civil Aviation Authority (CAA) and Quantas Airlines. TAAM was later acquired by Boeing and now is part of Boeing-Jeppesen. In 1998, the FAA acquired several licenses of TAAM and has been using it mainly in the NAS airspace redesign effort and other large-scale studies. TAAM has been used throughout the world for more than two decades by civil aviation authorities, airport operators, airport designers, major air carriers, air navigation service providers, airspace planners, and others.

TAAM is a complex and sophisticated, yet flexible tool that can enable airport operators to accurately predict and analyze the impact of present and future airspace and airport operations and enhance the safety and efficiency of operations. This sophisticated simulation system presents realistic 2D, 3D, and 4D models of airspace and airports to facilitate decision support, planning, and analysis, particularly conducting multiple "what-if" studies for airport and airspace environments. TAAM simulations are processed in fast time enabling users to obtain results quickly and evaluate a wider range of scenarios.

TAAM can simulate most ATM functions in detail and conduct analysis and feasibility studies of ATM concepts. The simulations cover the entire gate-to-gate ATM process. With TAAM, airports and airspace can be modeled, and impacts of the changes to infrastructure, operations, ATC/ATM procedures, and schedules can be evaluated. TAAM simulation consists of a collection of user-provided data relevant to the problem at hand and its modeling requirements and takes air traffic schedule, environment description, aircraft flight plans, air traffic control, and output control rules as input and uses them in performing airport and airspace usage, conflict detection and resolution, and aggregate metrics calculations with its internal algorithms and user-defined rule-based logic.

TAAM modules include interactive graphical fast-time simulation tools which provide the user with a 2D or 3D view of the airspace or airport; a real-time air traffic monitoring tool with simulation capability; and a reporting tool which can be used to generate graphs and tables from data generated by the simulation. Simulations can be interrupted and restarted and key aspects of the model, such as conflict resolution and airport resource usage, are controlled by rule-based logic which may be edited by the user during a simulation run. "Live" graphical display of the simulation can be selected and customizable reporting is available. The simulation can also be run unattended in batch mode with no graphics. During the simulation, statistics are gathered by the reporting program and written to a report file. This file is used by the report presentation facility to construct the text and graphical reports desired by the user.

In general, useful outcomes of the TAAM studies to its users include:

- Increased financial performance as revenues increase with more productive use of resources
- Increased capacity from improved management of existing and future traffic
- Improved operational performance and utilization of ATC systems
- Better resource management of infrastructure and equipment
- Reduced operating costs through reduction of ground and airborne delays and reduction in operating and fuel costs
- Optimization of future investments in infrastructure and resources through better planning
- Reduction in workload through improved control of airspace

Since its development and entrance into the market, TAAM has been used for various airport studies, including (19):

- Airport capacity expansion (gate, taxiway, runway capacity)
- Planning airport improvements, extensions
- Airport deicing operations
- Aircraft noise impact studies
- Impact of severe weather on operation
- Design of terminal area procedures (SIDs/STARs)

- Design of terminal area ATC sectors
- Controller workload assessment
- Impact of new ATC rules (e.g., RVSM, RNAV)
- Airspace systemwide delays
- Project cost/benefit studies

In particular, airport planners and designers can use TAAM simulations effectively with the objective of:

- Reducing the costs of congestion and delays while maintaining safety
- Optimizing or enhancing the use of existing airport infrastructure and resources
- Capacity expansion programs, as increased capacity means greater revenues to the airport operator
- Planning for the introduction of new aircraft (e.g., new, larger aircraft)
- Evaluating the financial implications and cost-effectiveness of future infrastructure investments, including new terminals, additional gates, taxiways, or runways
- Improving irregular and inefficient airport operations
- Planning noise abatement, deicing, and other operations in the most cost-effective way
- Measuring the impact of disruptions, such as proposed runway works on airport schedule and normal operations
- Assessing the effect of changes in sequencing strategies and separation standards

Structure and Components

The TAAM model has four basic modules: the interactive data input system (IDIS), the simulation engine (SIM), the report presentation facility (RPF) to report output, and Gtool, the input mapping program (19).

Input. TAAM software comes with a supply of databases that are typically useful to users for modeling, and they should provide a good point to start modeling. However, input has to be customized to the specific model and files are created with the required accuracy, but level of detail can be varied for better modeling of critical areas.

As TAAM is a large-scale simulation, IDIS guides the modeler to create and edit the following essential classes of input:

1. *Airport File.* The airport (APT) file includes listing of latitude, longitude, altitude, and magnetic deviation of every airport as well as airport layout, SIDs, STARs, and runway usage. Airports are considered as "points" in the simulation unless the user specifies the ground layout in the input. The ground layout file is a digitized map of the airport complete with all details on runways, taxiways, aprons, gates, buildings, deicing stations, runway hold areas, and obstructions. It provides the programmed routes and taxi assignment of aircraft on the airfield and is also used as the graphical template for simulation display.
2. *Waypoints*. File containing locations, names, and capabilities of all navaid aircraft used to define, plan, and execute the flight plans.

3. *Routes*. File containing lists of waypoints defining routes for aircraft to use. They can be radio navigational or great circle between an origin and a destination. In addition, artificial waypoints can be created to reflect other permutations, combinations, and variations.
4. *Timetable*. File representing the flight demand or "events." It lists flight ID, day and time, origin and destination, aircraft type, route, en route altitude, SIDs, STARs, and runways used.
5. *Maps*. AutoCAD-generated maps showing functional structures and terrain features, where points are defined by latitude and longitude. Features include coastlines, rivers and lakes, airspace route and sector layout, geographical features around airports, airport geometric layout, and state boundary lines.
6. *Project File*. Every simulation is governed by its project file that TAAM uses to connect the simulation engine with specific data files entered into simulation memory to read from throughout the simulation run.

The above input classes are user defined and project specific, but the input also requires other data necessary to define general characteristics of the system environment. These "secondary" data items are not accessed through TAAM's IDIS and include:

7. *Aircraft Performance*. File containing flight performance of aircraft, including speeds (minimum, average, and maximum), fuel burn at 3000-ft-altitude increments, differentiated by phase of flight (climbing, cruising, and descending), and rate of turn, rate of climb, and taxi and takeoff speeds.
8. *Aircraft Cross-Walk File*. Provides generic aircraft performance characteristics model.
9. *Conflict Resolution Strategy*. File containing a set of 38 conflict resolution rules that TAAM consults when a conflict is detected. Resolution is situation specific, where TAAM searches the list of resolutions until one is found for the conflict described and the solution suggested is applied.
10. *Sector Separation Setting*. The setting specified for aircraft separation in the sector, as the air traffic sector is created in TAAM's GTool.

To facilitate the preparation of the above input datasets, TAAM provides additional features:

1. 2D/3D graphical editor (CAD tool) for entering and editing graphical data such as airport layouts and airspace sectors
2. Data entry and validation tools for entering and maintaining data such as waypoints and routes
3. Other data entry tools, for example, digitizer for digitizing paper maps, and an external data converter for importing maps in AutoCAD format and Jeppesen data format

For simulations that require aircraft noise impact evaluation, TAAM interfaces with the INM to determine the noise impact footprint on land uses on the ground. TAAM would then facilitate the building of airport approach and departure routes that avoid noise incursion on the noise-sensitive areas around airports.

Output. TAAM simulation output, in general, is made up of data records of operations measures and metrics generated that can be reported on any level of simulation to the system or on a sectorwide basis. Simulation output includes:

- System delays—total and average per operation
- Conflicts: counts by degree of severity, whether successfully resolved or not
- Airport movements, delays, operations on taxiways and runways, runway occupancy
- Airspace operation metrics such as usage of routes, sectors, fixes, and coordination
- Aircraft noise contours
- Total aircraft fuel burn
- Costs: aggregate, fuel, nonfuel
- Controller workloads
- Individual aircraft flight profiles
- Scenario generation, for example, for real-time ATC simulators or other playback
- "Show Logic" diagnostics, which gives the operator an insight into TAAM's decision-making process
- Text messages (extent and content user selectable) which contain further details of TAAM events
- Error identification, diagnostics, and resolution
- 2D or 3D graphical visualization of the simulation can also be generated. The graphical output can be viewed in several windows simultaneously, each window having an independent 2D or 3D view with the scale ranging from 30 m to 40,000 km.

Given the complexity and enormity of TAAM structure and composition, the FAA requested MITRE to prepare a document that provides guidance for TAAM users on best practices of conducting airport and airspace simulations (20). One of the important principles to conduct successful simulation is maintaining consistency in all aspects of simulation runs. It is particularly important to ensure that alternatives' input file definition and assumptions remain consistent with the baseline's, except for features that differentiate the alternatives from the baseline. Accuracy of the study results and findings could be compromised if this condition is not maintained. Therefore, it is good practice to use a common development path for the common features of both baseline and alternatives.

Important aspects to build the input files for alternative case studies are:

1. *Traffic-Demand Level*. Future alternative scenarios representing growth of traffic in a given airport where the infrastructure is not expanded, only the flights or "events" in the "timetable" file representing the flight demand is increased while keeping the other input settings unchanged.
2. *Airport Configuration*. It is particularly important to define alternative scenarios accurately for any changes in airport configuration [e.g., adding runway(s) to expand capacity, temporary closure of runways, changing taxiway structure to enhance ground movement, or other changes to airfield geometric layout or

operational procedures]. Evaluating the impacts these changes will have on airport operation, terminal airspace, and the regional airport system requires that the same traffic level and type are used.

3. *Aircraft Type and Equipage Mix*. Any change of the aircraft type mix in the scenario implies changes in performance and consequent changes in throughput or delay. Changes in aircraft navigation equipage between scenarios would result in the simulation confining or restricting aircraft from certain routes, altitudes, or airspace sectors, something that deviated from the real-world conditions. Also, in examining effects of severe weather on operation in airports/runways, for example, aircraft performance characteristics will exclude certain aircraft types from landing at particular airports/runways, resulting in altering arrival and departure rates at these airports/runways.
4. *En Route Separation*. In airspace simulation, reducing en route in-trail separation standards (lateral and/or vertical separation minima), it is important to express the valid separation standards for both baseline and alternative scenarios.

Equally important is to develop a detailed set of all underlying assumptions of the study and use them as part of the study scoping and definition. An accurate and complete set of assumptions that address the relevant aspects of the simulation and its indicators and metrics is critical to the success of the simulation study.

Such assumptions are categorized as:

1. *Scope of Simulation Study*. Mainly geographic boundaries, details of modeling the ground, terminal, or en route operations, the number and the level of detail of airports modeled in study, particularly in relation to configuration, procedures, and kind of changes to be simulated.
2. *Runway Use*. The static, dynamic, and operational preferences or restrictions to be included in the simulation and any runway dependencies.
3. *Taxiway Use*. Similar and directly related to runways, the static, dynamic, and operational preferences or restrictions concerning direction of aircraft movement, taxiing speed, hold lineup for departure, and runway crossing.
4. *Gate, Apron, and Parking Positions*. Similar and directly related to taxiways, the static, dynamic, and operational preferences, restrictions by airline (airline exclusive use), type of user, and aircraft type.
5. *Terminal Airspace Operations*. Arrival and departure patterns, preferences, restrictions, dynamic ATC changes and patterns, and ATM procedures.
6. *En Route Airspace*. Miles in-trail separation restrictions, altitude restrictions, effects on dynamic restricted airspace (i.e., restricted and special-use airspace), and conflict resolution rules.
7. *Traffic*. Mainly city-airport pairs and routes, timetable, future traffic projections, and aircraft fleet mix.
8. *Weather Conditions*. Mainly IFR versus VFR meteorological conditions, weather front specification, and weather as constant or variable vis-à-vis throughput.

Another important aspect of simulation is the identification of proper metrics that correspond to simulation indicators. Study metrics are quantifiable output elements that define certain performance attributes of the simulation. If properly selected, study metrics would provide accurate quantitative representation of differences between baseline and alternative scenarios and in support of the study analysis and its objectives.

These metrics would provide a quantitative discriminator between the system operation indicators (e.g., delay, throughput, flight-segment time, and number of conflicts) for the scenarios simulated. Figure 15.7 shows typical relationships between the system simulation indicators and their respective metrics that are used in TAAM simulation

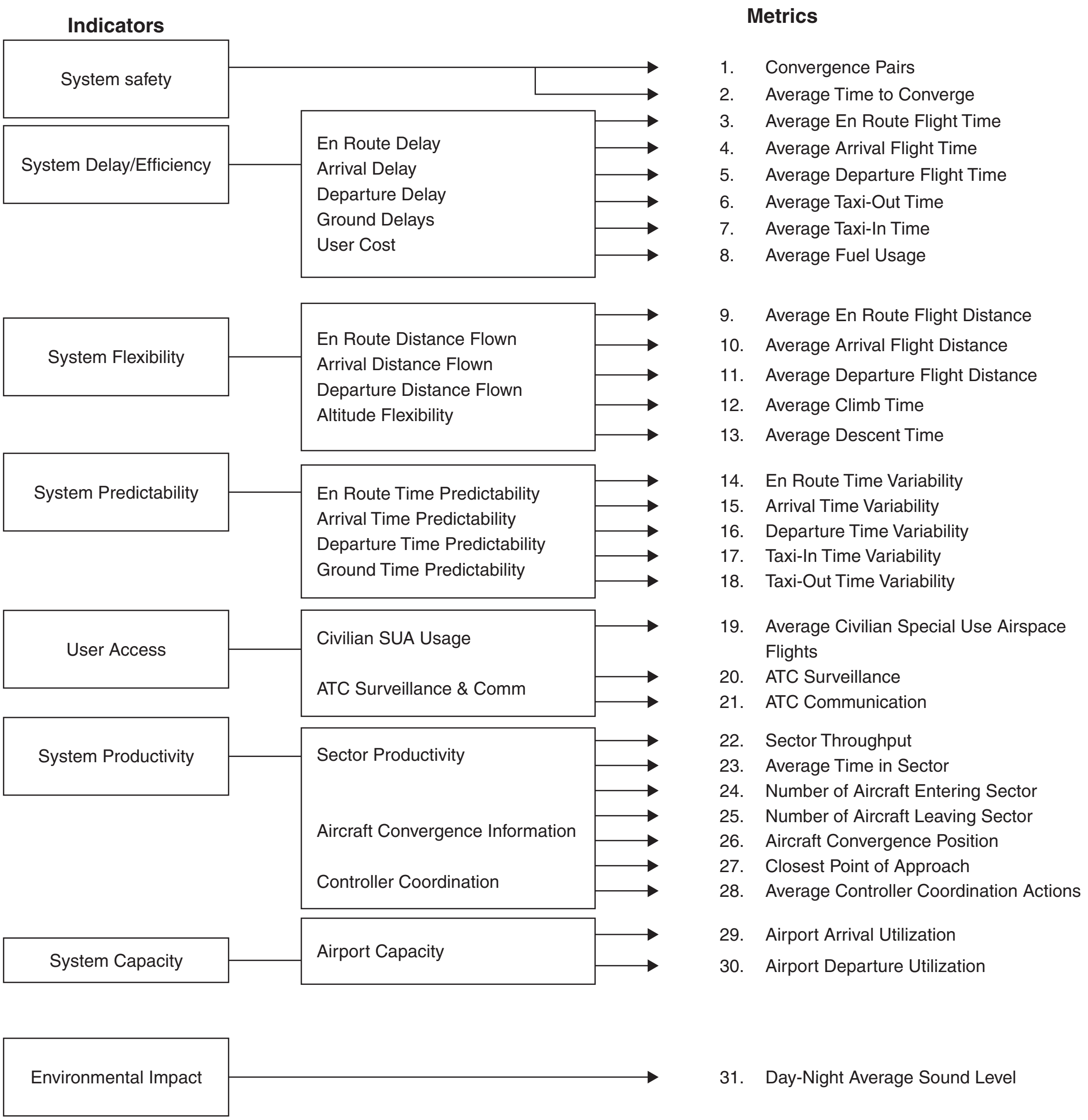

Figure 15.7 System indicators and respective metrics used in TAAM simulation (20).

(20). It may be necessary to combine several metrics to draw a conclusion of a primary indicator (the left column in Figure 15.7).

TAAM versus SIMMOD. Making direct comparisons of both simulation models is difficult, as they clearly belong to two different "generations" of airport–airspace simulations. A comparative study at early stages of their development reached certain conclusions on their features and practicality of use in different areas. Both models were used to conduct simulations for one project, and a general conclusion was reached by the user on using both models (21):

1. TAAM logic is more ATC realistic, powerful, and sophisticated in the terminal airspace and en route environments. Since it is 3D (i.e., aircraft moving in the *x-y-z* space), aircraft separation in TAAM takes all conflicts (vertical and lateral) into account and considers them as real conflicts. But since SIMMOD uses a link–node structure in 2D space, it considers only longitudinal separation along links and therefore it may consider certain encounters as conflicts.
2. SIMMOD is more appropriate and powerful with the 2D logic of simulation for ground modeling (runway–taxiway–gate).
3. In general terms, TAAM could perform certain simulation tasks that SIMMOD could not, and it is more user friendly.
4. Major variables used in the reporting of simulated operations, particularly en route, are air delay in SIMMOD and number and importance of conflicts.

Sector Design Analysis Tool (SDAT)

Other airspace and airport simulation models developed or supported by the FAA include the Sector Design Analysis Tool (SDAT). It is a computer program designed to assist airspace planners, procedure designers, and ATM analysts in optimizing the design of airspace. SDAT is in C language and operates in UNIX and X-Windows operating systems supported on Hewlett-Packard and SUN workstations. SDAT, however, is not a simulation model but is intended to provide the airspace designer with a fast, easy, and accurate way to develop and evaluate proposed changes to airspace structure and/or traffic loading. SDAT is easy to use and is compatible with many different types of airspace and traffic data. SDAT has been developed by the FAA as an analytic tool for assistance in the evaluation of changes in airspace design and traffic routing. The existing airspace and traffic data are examined and reduced to more manageable form by the specialist, and SDAT is used to select, modify, add, and display the data interactively. The conflict probability database is then used to provide performance metrics to the airspace, including conflicts, traffic loading, impacts on users, and sector controller task loads.

The major features of SDAT include:

- Graphical capability to view airspace structures and features in 2D and 3D representations and to rotate the entire display to be viewed from various angles
- Airspace features relevant to designing airspace and optimizing sector design (i.e., the FAA HOST computer adaptation data) that are viewed in 3D, including airways, adapted routes, navaids, fixes, and airports
- Flight plans and flight track data, provided from different sources, including HOST system analysis recording (SAR) of air traffic information, the Enhanced

Traffic Management System (ETMS) database, the Automated Radar Terminal System (ARTS) database, and the ability to modify, add, or delete "adaptation" and air traffic data

- Capability to retrieve and view multiple centers simultaneously, which allows performing airspace analyses across center boundaries, evaluating the impact of changes made in one center on another center
- Capability to perform various analyses required for sector design, such as conflict potential and fix and airspace loading, using either the original or modified adaptation data and/or traffic information
- Predictions of conflict potential within the sector, traffic and airspace loading, and their impacts on airspace operation, generated for any proposed combination of airspace and traffic data

The SDAT output module generates reports and graphics describing adaptation and traffic modifications and other relevant information of interest to the airspace planner. SDAT's adaptation modification report is produced in a format that is compatible with the HOST's Adaptation Controlled Environment System (ACES) and reduces the airspace planner's effort regarding data recoding and data entry.

SDAT generates the following reports and graphical output:

- Summary of analysis results, including reports and graphs on traffic, fix, sector, and sketch loading
- Adaptation and traffic modifications
- 3D conflict analysis showing potential chokepoints for crossing or merging paths where need for increased separation exists
- Location, frequency, and expected per-sector and per-flight conflict potential on screen and text output
- Traffic volumes in sectors: counts, durations, and throughputs as determined from sector boundary crossings
- Impacts on users from changes in flight time: based on average speed on each route segment, total flight distance, sectors traversed, and average hourly cost for aircraft
- Sector controller's task loads concerning actions, messages, time required, and so on, as calculated from exchanges of HOST data
- Impacts of all changes on all flights affected

FAA Airport Capacity Group Models. The Airport Capacity Group at the FAA Technical Center in Atlantic City, New Jersey, uses a suite of fast-time simulation models to conduct specific and focused airport capacity studies. The main models of this suite include:

- *Airfield Delay Simulation Model* (*ADSIM*). Calculates travel time, delay, and flow rate data to analyze airport airfield components, airport aircraft operations, and operations in the immediate terminal airspace focusing on delay as a measure of service.
- *Runway Delay Simulation Model* (*RDSIM*). A part of ADSIM that models the final approach, runway, and runway exits.

The group also developed a modeling technique to measure the *annual service volume* (*ASV*) of various airports throughout the NAS and has performed many such studies, initially, to provide localized improvements to airports as part of the NAS capacity enhancement program, but these studies have focused more on the effects of incorporating the NextGen technologies in NAS system capacity in the future.

FAA ATCSCC Models. The FAA Air Traffic Control System Command Center (ATCSCC) uses computer models to conduct its operation, including:

- *HARS.* The High-Altitude Route System is an airspace model and automated traffic planning tool that can help the center determine flight routes based on aircraft performance characteristics, changing weather conditions, traffic demand, and resource limitations. HARS produces alternate-route strategies for severe weather areas, special-use airspace, or congested sectors. It generates route revisions as changes in weather, user demand, or system capacity occurs. HARS could significantly improve the management of direct routing, severe weather avoidance routings, and nonpreferred route requests.
- *SMARTFLO.* The Knowledge-Based Flow Planning Tool is another model available to the center to generate traffic flow management (TFM) strategies to enhance TFM for the NAS. It adopts the artificial intelligence (AI) concept of "expert system" to capture the TFM specialist's responses to daily flow management situations over time to "learn" the expert techniques for the management of NAS aircraft flows across the system. It evaluates each day's set of conditions and analyzes the manner in which previous flow plans were successful in reducing system traffic delays. Based on AI principles, it matches current conditions to the best of similar past experience situations and recommends "intelligent" strategies to manage current flows.

MITRE's Center for Advanced Aviation System Development (CAASD) developed airport and airspace-specific models for the FAA. They include:

- *Detailed Policy Assessment Tool* (*DPAT*). A discrete-event, fast-time simulation capable of computing congestion-related delays on a per-airport, per-flight, or system aggregate basis for large-scale systems and can serve as a systemwide airspace congestion and delay analysis tool (22). DPAT is built on a parallel discrete-event simulation engine, which uses "optimistic" computing technology to achieve ultrafast run times. DPAT simulates an entire ATC system to predict the system-wide congestion and delay as a consequence of excessive traffic, poor weather, equipment outages, development of new facilities, or any other reason through propagating delays across the system. As such, it provides a fast assessment capability for quick turnaround studies involving thousands of parametric variations for more comprehensive sensitivity studies or as a decision tool for real-time aviation system decisions. The parallel computer simulation concept, optimistic simulation, efficiently simulates a large number of entities (flights) and computes throughput and delay at a large number of airports systemwide over a large geographic area. DPAT interfacing with the Web is another attractive feature that provides distributed processing capability to groups of analysts connected together through networks. In addition, DPAT can handle multiple "what-if" scenarios to achieve an optimal solution to help controllers and airspace planners assess the impacts of multiple decisions. Most input data on airports, flights, and airspace sectors included in the study and simulated real-time data are provided in text-based and simple traditional spreadsheet-type formats. Another attractive feature is that DPAT can be easily interfaced with and its output comparable to other NAS models, such as NASPAC, NAS Simulation (NASIM), and TAAM. DPAT models the time-based events of flights and sector handoffs, inspects queue and capacity change, and evaluates queuing delays and effective operational delays (deviating from published air carrier schedules, airport throughput, and sector counts and delays). DPAT was used to conduct capacity and delay assessment for large regions of the world, including North America, Asia Pacific, and Europe.

- *Terminal Airspace Visualization Tool* (*TAVT*). MITRE developed this graphic modeling tool upon direction from the FAA to generate 3D images of terminal airspace. Initially, it was developed for the complex Dallas/Fort-Worth Metroplex, the DFW TRACON airspace, but was eventually expanded to be an airspace planning tool to build entirely new approach and departure routes and procedures, expanding the evaluation and conformance functions to include new performance measures and TERPS standards (23). TAVT frees airspace planners from tedious manual methods of designing terminal airspace and provides them with an automated graphic modeling tool to generate 3D images of the airspace, animate the shape projection of airspace structures, and evaluate conformance with airspace design standards and operation procedures (TERPS). Components of TAVT include the TRACON and TCA boundaries, radar control volumes, instrument approach and departure procedures, navigational aids, intersection and fix identification, and other airspace features. To assist airspace planners in designing new or assessing existing airspace, TAVT has the capability to alter terminal airspace structure by modifying approach and departure components, changing their boundaries, measure the impact of proposed changes to airspace geometry, and determine whether TERPS standards have been violated by using the conformance evaluation function.

TAVT has the following basic capabilities:

- 3D display of STARs/radar approaches, SIDs/radar departures, navigation aids, intersection and fix identification, radar control volumes, satellite airfields within TRACON, runways, TRACON boundaries, and terminal control area
- Evaluation functions to measure distance flown along selected routes, traffic density along selected routes, and TERPS violation alerts
- Separate modules for visualization, airspace editing, and airspace performance evaluation of the airspace being designed
- Additional visualization functions that include 3D projection of restricted airspace, noise-sensitive areas, and route structure of nearby (perhaps conflicting) TRACON satellite airfields

TAVT has been incorporated in larger airspace simulation models as their built-in visualization and performance evaluation tool. Figure 15.8 depicts a TAVT-based -D display of a TRACON sector.

- *Enhanced Airfield Capacity Model* (*E-ACM*). A reengineered version of the program developed by the FAA during the 1970s called the airfield capacity model

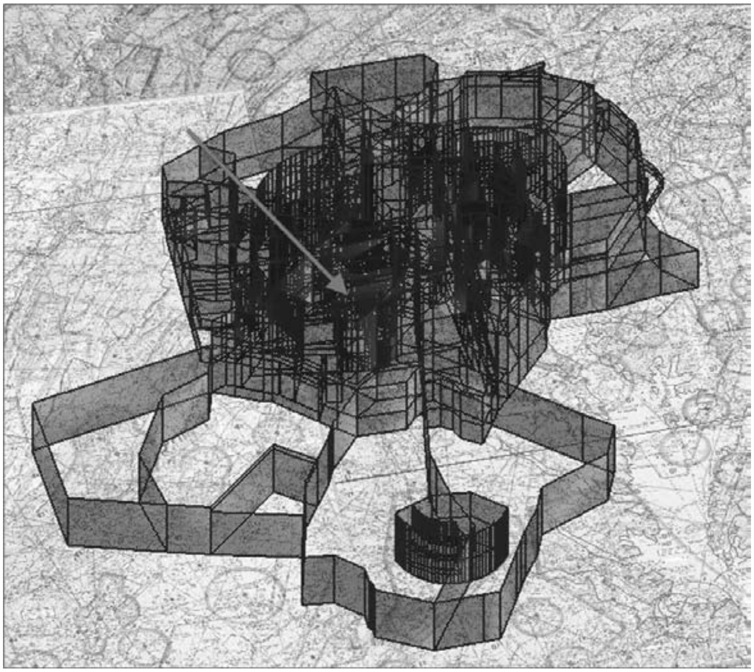

Figure 15.8 TAVT-based 3D display of sector in consolidated Potomac TRACON (arrow points to Washington-Dulles International Airport terminal airspace).

that analyzes runway system operation and calculates maximum runway throughput (see Chapter 7). ACM was a deterministic model based on the definition of capacity as maximum sustained throughput and was written in FORTRAN and was run on IBM mainframe computers. In 1980, the FAA requested MITRE to develop a personal computer model that was released to the public. The E-ACM provided upgrades, enhancement, and expansion to ACM with new capabilities that include:

- Extensive pre- and post-processing modules to improve user friendliness, flexibility, and practical use and implementation
- Web-based interface to facilitate distributed operation
- Program legacy software augmented with Visual BASIC to introduce graphics and improve computer-run efficiency
- Enhanced and more graphical user interface for input and output
- Improved ATC procedure logic providing better correlation and more realistic representation of operation, including wake vortex and triple parallel approaches
- Capability to provide necessary input to network models the FAA uses, such as NASPAC and DPAT
- Changing the program's modeling construct from a deterministic to a stochastic model using Monte Carlo simulation.

The program defines the runway operation strategy to be modeled, can provide more flexible representation of weather-based operation in terms of ceiling, visibility, and glide slope angle, is capable of representing realistic and user-defined arrival distribution, and can provide realistic separation standards at outer marker and at threshold. E-ACM handles simultaneous dependent parallel approaches for two or three parallel runways and other runway configurations, including intersecting runways, open-V runways, closely separated runways, and dependent converging instrument approaches.

15.5 ENVIRONMENTAL SIMULATION MODELS

Aviation environmental evaluation includes two major areas—aircraft noise and aircraft emissions. Simulation models have long been developed and used to address these two environmental impacts of aircraft. The most widely used models for decades are the integrated noise model (INM) and the emission and dispersion modeling system (EDMS). In addition to these two models, the FAA has recently initiated an integrated framework for available environmental software called the Aviation Environmental Design Tool.

Aviation Environmental Design Tool (AEDT). The FAA has developed AEDT, a comprehensive framework for environmental-based software to provide a single and integrated platform for thorough assessment of environmental effects of aviation, assess interdependencies of aircraft noise and emissions impacts on the environment, and facilitate comprehensive cost–benefit analyses of aviation environmental policy options (24). The major design goals of AEDT include: (a) ensuring scalability and distributed use, (b) flexibility and global use of legacy and new software within an integrated system, and (c) facilitating an efficient integrated development environment. The initiation of this effort was through a series of TRB workshops (25) where all stakeholders discussed enhancing and streamlining utilization of the existing legacy environmental models. All these models have unique historical development timelines, wide users' utilization, and their users have strong motivation for their existence.

The primary objective for AEDT is to integrate legacy software developed over the years that themselves are disjointed and inconsistent in their input–output interfaces into a unified framework. Inputs to these models are typically the output of airport and airspace simulation models, which adds to the interface format problems. Solving the intrinsic interaction of legacy software and interfacing problems will greatly improve user access and control and reduce application maintenance, data input collection and preparation, and distribution efforts. AEDT provides the framework for consistent modeling and assessment of aviation environmental effects by merging existing models and new tools into a publicly available, planning, regulatory, and policy assessment framework.

Four existing FAA environmental evaluation models are central to the AEDT architecture: INM to evaluate airport noise, EDMS for airport aircraft emissions, a model for assessing global exposure to noise of transport aircraft (MAGENTA) for global noise measurement, and a system for assessing aviation global emissions (SAGE) for global emission measurement. These core components of the AEDT architecture contain software implementation of best-practice environmental modeling and assessment techniques for environmental impacts of aviation. The long-term objective of the AEDT effort is to integrate these four core models into an integrated system. Figure 15.9

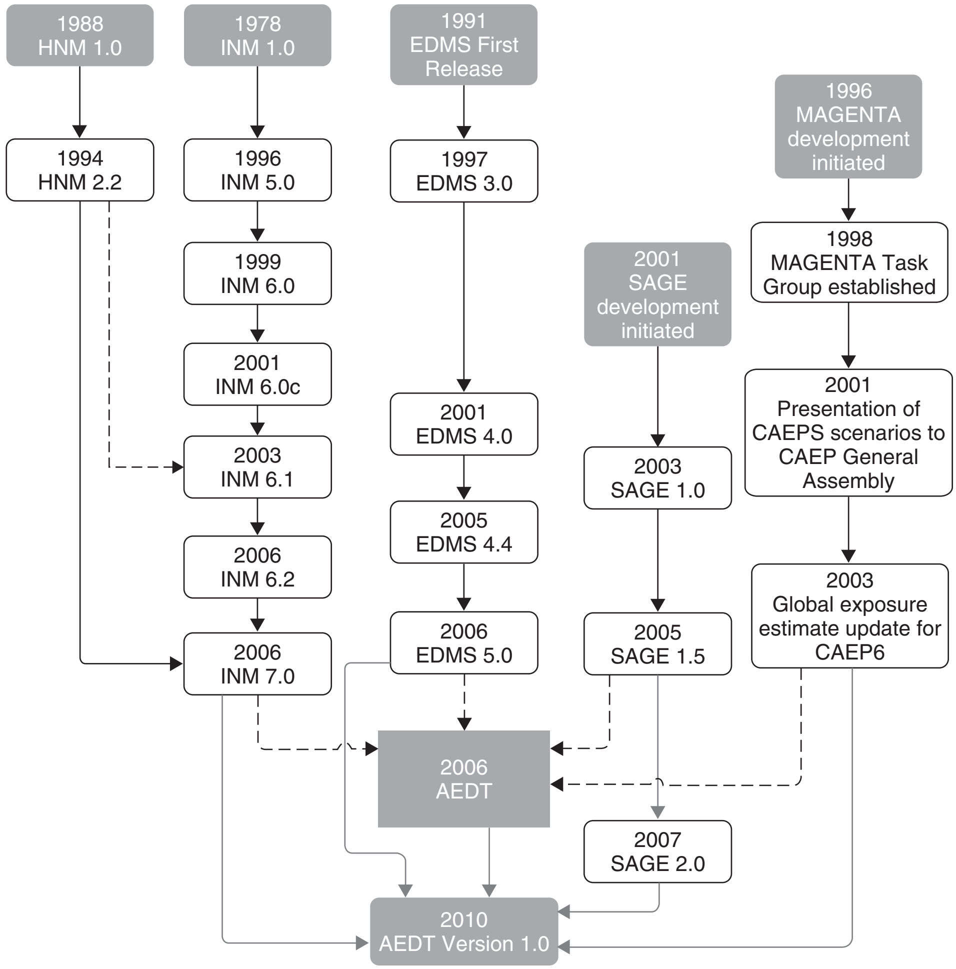

Figure 15.9 Development timeline of environmental models and integration into AEDT (25).

depicts the development timeline of the four core models into AEDT (Version 1.0) that will eventually culminate into an integrated AEDT framework (Version 2.0) which will contain the following components:

- Noise module
- Weather module
- Flight/service module
- Emissions inventory module
- Emissions concentration module
- Contour module
- Terrain module
- Common database
- Reporting module

- GIS import/export interface
- Study file database
- Trade-off analysis module

The AEDT system architecture includes input–output databases and individual system modules. System databases include:

- Airports: airport-specific data including runway layout, navaids, and local meteorological data
- Aircraft fleets: annual itemization of world aircraft fleets, performance, noise and emission generation parameters, and so on
- Aircraft movements/operations: flight schedule itemization, schedule or trajectory information, and so on
- Aircraft retirement/replacement: updated orders/retirement schedule to project future aircraft fleets
- Results inventory: database containing annual emission and noise assessment inventories

The AEDT modules are aircraft performance, aircraft emissions, aircraft acoustics, local/global GUI, database access, fleet operations, taskmaster (to coordinate internal interface/processes), GIS, fuel burn, interpolation (to undertake necessary interpolation and extrapolations), terrain, data validation, ground track, weather, and radar flight profile.

Integrated Noise Model (26)

With the advent of jet transport and the huge growth in air transport in the 1950s, there was a public outcry against airport noise that contributed to human annoyance and strong community reaction. As a result, government supported intense research on aircraft noise and adverse impacts on communities during the 1960s and 1970s that culminated in developing this program. The INM was first released in 1978 and was utilized in support of FAA Regulations Part 150 studies (Airport Noise Compatibility Planning), Part 161 (Notice and Approval of Airport Noise and Access Restrictions), and the National Environmental Policy Act (NEPA) of 1969. A companion model to the INM, the helicopter noise model (HNM), which was specifically designed to model noise of rotorcraft operations, was later integrated into the INM. The INM version of 2010 is INM 7.0. The INM is the most popular noise model of its kind in the world, and only in the United States, over 650 organizations use the INM for various purposes.

The INM was developed based on algorithms and a framework that used *noise–power–distance* (*NPD*) data to estimate noise accounting for specific operation mode, thrust setting, source–receiver geometry, acoustic directivity, and other environmental factors. The output would be noise contours for an area and/or noise level at preselected locations. The noise output can be exposure based, maximum-level based, or time based.

The INM has many analytical uses, including:

- Assessing current aircraft noise impacts around a given airport or heliport
- Assessing changes in noise impact resulting from new or extended runways or runway configurations

- Assessing changes in noise impact resulting from new traffic demand and fleet mix
- Evaluating noise impacts from new operational procedures
- Evaluating noise impacts from aircraft operations in and around national parks

INM Input. INM input data include:

- Airport elevation and ambient temperature
- Runway(s) configuration, orientation, and threshold displacements
- Aircraft definition, operation parameters, and INM noise curve database
- Aircraft approach and departure procedures and profiles, in terms of procedural/aerodynamic, and fixed-point profiles
- Airport approach and departure tracks and operations, including approach, departure, touch-and-go, circling, and overflights
- Terrain elevation and profile
- Flight operations, including numbers of aircraft assigned to each track and percent of aircraft assigned to each track
- Other aircraft operations (e.g., airport airplane ground run-up)
- The noise metric(s) used in the simulation: day-night level (DNL), community noise equivalent level (CNEL), noise exposure forecast (NEF), and others

Simulation. The process to set up an airport noise simulation includes the following steps:

1. Create a new or open an existing case study from the INM File menu and select the airport in Setup.
2. Verify required runway data (as indicated in Input above).
3. Select all aircraft included in the airport flight schedule and apply aircraft substitutions as needed.
4. Select the noise metric to be used (from Setup–Metrics).
5. Define the aircraft approach and departure tracks using Tracks.
6. Define aircraft operations using Flight Ops.
7. Define the ground grid using Grid Setup.
8. Under Run Options (Run menu) select the noise metric desired and commit record.
9. Set up the Output menu to view scenario results.

INM Output. Depending on the INM model definition, objective, and scenarios to simulate, the output typically includes:

- Noise contours (equal DNL contours)
- Metric population point calculations (i.e., DNL level at a specific city block with a specific land use)
- Population living within a given noise metric

To simplify the assessment step in determining the need for further analysis with the INM as part of environmental assessments and impact statements (EAs/EISs) and Federal Aviation Regulations (FAR) Part 150 studies, the FAA developed the area equivalent method (AEM). The AEM is a mathematical-based screening procedure that provides an estimated noise contour area of a specific airport given the types of aircraft and the number of operations for each aircraft. The noise contour area is a measure of the size of the landmass enclosed within a level of noise as produced by a given set of aircraft operations.

Emissions and Dispersion Modeling System—EDMS (27)

Parallel to the development of the INM, a similar effort was mounted in the United States to assess the emissions of mobile sources and the adverse impact on the environment. The government legislated laws to curb these emissions (e.g., Clean Air Act) that all organizations, public and private, military and civilian, would have to comply with. As part of the compliance effort, the FAA and the U.S. Air Force recognized the need to analyze and document air quality conditions at and around airports and air bases. In the early 1970s both agencies independently developed computer programs to address this need. The U.S. Air Force developed the air quality assessment model and the FAA developed the airport vicinity air pollution model. Both agencies agreed to develop a unified system that would have regulatory, operational, and economic benefits. The resulting system—EDMS—was developed in the mid-1980s as a complex source microcomputer model designed to assess the air quality impacts of aviation-related emission sources for proposed airport development projects. These aviation sources consist of aircraft, auxiliary power units, ground support equipment, airport ground access vehicles, and other stationary sources. It is utilized in support of the Clean Air Act, national NEPA, and state implementation plan (SIP) development analysis studies. EDMS has also been adopted internationally by the ICAO as an aircraft emission assessment tool. Functionally, EDMS estimates aircraft emissions and predicts emission dispersion. Today, the issue of "climate change," which covers all forms of emissions from various sources, is the foremost priority of the ICAO, where all countries have to show material compliance, quantitatively and qualitatively.

To ensure the consistency and quality of aviation analyses performed for the FAA, the FAA revised its policy on air quality modeling procedures in 1998 to identify EDMS as the "required model" to exclusively perform air quality analyses for aviation sources (28). In 2004, the FAA reengineered EDMS once again to take advantage of new data and software algorithm developments and released a new version of the software. The FAA continues to enhance the model under a government/industry advisory board to more effectively determine emission levels and concentrations generated by typical airport emission sources. Figure 15.10 presents the EDMS development timeline.

EDMS is one of the few air quality assessment tools specifically engineered for the aviation community, and it includes:

- Emissions and dispersion calculations
- Aircraft engine emission factors, based on the ICAO Engine Exhaust Emissions Data Bank
- Vehicle emission factors, based on the Environmental Protection Agency's (EPA) MOBILE6 model

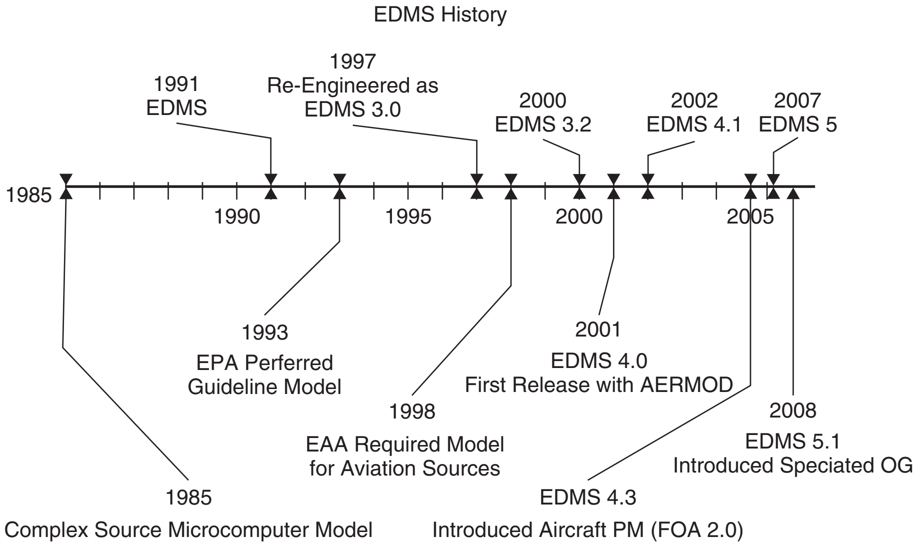

Figure 15.10 Timeline of EDMS development by the FAA (27).

- EPA-validated dispersion algorithms
- Emissions data for criteria pollutants and spatiated organic gas (OG) emissions

Structure and Components

The EDMS architecture is designed to offer functionality for performing both emissions inventory and dispersion modeling and analyses. The EDMS architecture consists of several layers of interaction between different components of EDMS within the framework of the integrated environment and, as Figure 15.11 depicts, the high-level representation of these interactions. This architecture is typical of current-day multi-tiered applications and allows for modularity of components by separating the database-related functions and the core business logic from the graphical user interface. Providing modularity is an important benefit as EDMS continues its transition into the AEDT environment in the future.

As shown in Figure 15.11, the EDMS architecture is composed of:

Graphical User Interface (GUI). The front end of the system, where the user interacts with the model and the database and performs data entry (with parameter validation), executes commands, and receives visual feedback of both data entered and results generated.

Database Layer. This layer contains data required for input to EDMS, including airport data, aircraft fleet, aircraft performance, aircraft engine emissions, and airport layout. Also included is data on EDMS emission sources, including aircraft, roadway vehicles, parking, aircraft ground service equipment (GSE), and stationary sources.

Database Interface. This is the middle portion in the architecture between the GUI and the database layer and the core of the EDMS application and contains the

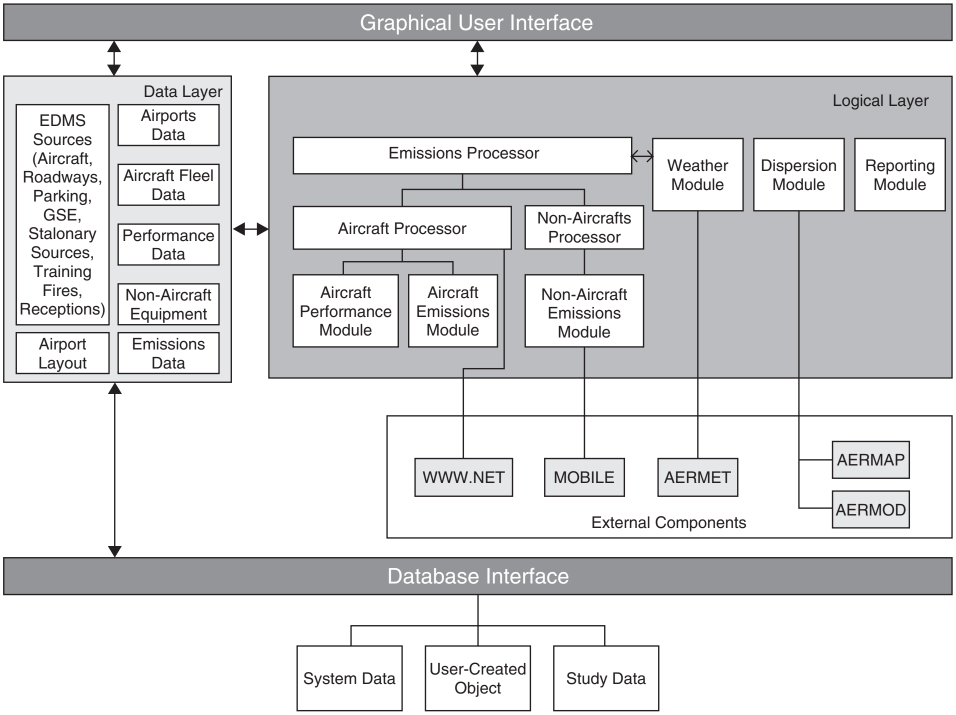

Figure 15.11 EDMS architecture showing components, interfaces, and layers (27).

set of classes and functions that represent each emissions source and dispersion object and its associated properties. The interface includes system data, user-created objects, and study information details. This middle layer allows for study and system data to be retrieved from memory while simulation is running to enable the user to interact with the system and make changes.

Logic Layer. This component of the architecture contains the logic (models) of all parts of EDMS modules, either within the architecture or placed externally, and includes: internal modules, the weather module (using AERNET logic), dispersion module (using AERMAP and AERMOD logic), and reporting module. This component also includes the emission processor for aircraft (using the aircraft performance module and aircraft emissions module through WWLMINET) and the non-aircraft emission (mobile) module.

External Interfaces. Shown as a dashed border in Figure 15.11 are programs that include AERMAP, AERMET, AERMOD, and MOBILE that are maintained by the EPA.

Inputs for the external interface programs are collected through the GUI, passed to the logic layer, and sent to the external program for processing. Once the run is complete, the results and associated messages are interpreted by EDMS and the output is displayed to the user through the reporting module.

The three independent aspects of a typical EDMS study are the scenarios, the airports, and the years. Each study must therefore have at least one scenario, one airport, and one year defined. These are arranged in a hierarchical manner to facilitate the design, programming, and maintenance of EDMS. Within the study the scenarios are given the highest rank followed by the airports and finally the years. A typical EDMS study has five levels:

- *Application Level*. User-created aircraft and airport sources are defined independently and are available to any study, permitting users to add custom extensions to the database layer.
- *Study Level*. As the entire scenario is defined and the study is selected, users access program features and data that apply to the study to update the emissions inventory and run other modules.
- *Scenario Level*. Sets the modeling options for the particular scenario, such as the choices for times in mode and taxi times, and where users create several scenarios, representing different modeling options for comparison and analysis.
- *Airport Level*. Includes properties of the particular airport that apply across all scenarios in the study and are associated with the scenarios of other airport combinations.
- *Year Level*. The lowest and most detailed level that contains information that varies for each year and is associated with operational usage data (such as number of operations and the duration of each operation) for emissions sources.

As the airport–airspace simulation generates huge amounts of synthesized data related to a particular airport, it would be advantageous to pool the simulated database and use it for a variety of other airport modeling and analysis studies. Moreover, as the airport simulation system is available and its input databases are improved and completed on a continuous basis, it would be advantageous to the airport operator and airport planner to conduct "annual system simulation" runs and assess operational changes that could be made to improve its performance in several areas. This "airport annual system use information" could be a useful tool for several analyses, including (29):

1. Regional aircraft noise analysis using INM and flight track noise impact model (FTNIM)
2. Pavement analysis to develop annual airfield pavement use profiles used in the airport pavement management system (PMS) and its annual maintenance programs
3. Airport aircraft emission evaluation using EDMS
4. Aircraft gate–runway taxi route profiles used to optimize aircraft ground movement and reduce fuel burn

Model for Assessing Global Exposure to Noise of Transport Aircraft—MAGENTA

The global noise model MAGENTA, first released in 1991, was recommended for use internationally by the ICAO for global noise measurement through estimating population in land uses exposed to a range of day–night average sound levels (DNLs) for various policy scenarios (27).

MAGENTA is a computer model used to estimate the number of people exposed to significant aircraft noise worldwide. The original MAGENTA model development was done with the ICAO Committee on Aviation Environmental Protection (CAEP) to assess the worldwide aviation noise climate. A U.S. version of the global MAGENTA model was developed to determine the noise exposure in the United States using data on aircraft and operations specific to U.S. airports. For the U.S. version, the regional forecast used in the ICAO CAEP version of MAGENTA was replaced by the FAA terminal area forecast (TAF), which provides current and accurate information on how traffic will increase at each U.S. airport. The U.S. version of MAGENTA has evolved over time as more comprehensive databases were incorporated to improve the accuracy of the model. The data source for airport traffic changed from the OAG to the FAA ETMS. Unlike OAG, the ETMS database includes unscheduled air traffic, which allows for more accurate modeling of freight, general aviation, and military traffic.

MAGENTA is used internationally in support of CAEP noise analysis as part of the Annex 16 requirements, and in the United States it is part of the Aviation Environmental Design Tool (AEDT) and is used to support the DOT Government Performance Review Act (GPRA) performance goal and FAA's own flight plan performance goal by tracking the number of people in the United States exposed to significant aircraft noise.

The INM constitutes the core of MAGENTA. Major assumptions on local traffic use come from getting INM datasets developed for an airport. The noise studies obtained from U.S. airports have gone through thorough public review either under the NEPA requirements or as part of a land use compatibility program.

System for Assessing Aviation Global Emissions—SAGE (30)

SAGE is a high-fidelity computer model developed by the FAA in collaboration with the Volpe National Transportation Systems Center (Volpe), the Massachusetts Institute of Technology (MIT), and the Logistics Management Institute (LMI). SAGE is used to predict aircraft fuel burn and emissions for all commercial (civil) flights globally, to analyze scenarios from a single flight to airport, country, regional, and global levels, and to model aircraft performance, fuel burn, and emissions.

The purpose for developing the program was to provide the FAA, and indirectly the international aviation community, with a tool to evaluate the effects of various policy, technology, and operational scenarios on aircraft fuel use and emissions. SAGE was used in the United States to develop global fuel-burn and emission inventories as well as specific data analysis for a global gate-to-gate airport–airspace simulation model. Taking advantage of its capability to predict global aircraft emissions, SAGE was used internationally by the ICAO and United Nations to assess climate change and set related policies. For air traffic management applications, SAGE was used to analyze the impact of reduced vertical separation minima (RVSM) on emissions through implementing SAGE's capability to change fleet-wide fuel-burn values relative to specific criteria.

SAGE has been incorporated into the AEDT, which dynamically models aircraft performance in space and time, as the aircraft fuel-burn and emissions analysis tool to produce fuel burn, emissions, and noise. Aircraft performance algorithms, emissions and fuel-burn calculations, and validated methodologies found in the SAGE model have been improved and assessed for stochastic simulation to reflect the probabilistic uncertainty effects.

SAGE is used to generate the global inventory database of fuel burn and emissions by modeling high-resolution gate-to-gate movements of all global commercial flights annually. The inventory report files present aggregate data as derivative metrics and comparative assessments.

Flight Track Noise Impact Model—FTNIM

This model was part of aviation system analysis capability (ASAC), which was developed by the LMI for NASA. FTNIM was developed jointly by LMI and Wyle Laboratories to examine the impacts of quieter aircraft technologies and the relocation of flight tracks over less sensitive land uses might have on air carrier operating efficiency around some of the busiest airports in the United States (31). The main objectives of FTNIM include estimating noise impacts for airports, examining the effects of changing an airline's operations or fleet mix, exploring the benefits accruing from using efficient flight procedures, and evaluating accurately reduced noise impacts on the ground from adopting different scenarios.

FTNIM is capable of adjusting aircraft operations to minimize noise impacts on the ground through manipulating three variables: flight track noise efficiency, source noise reduction, and varying aircraft operations levels. The model input that the analyst selects from includes the following input choices: airport, case year, flight tracks, scaled operations, and aircraft noise level desired. Model output includes noise impacts in terms of the magnitude of noise contour footprint, number of people (and land use) within the contour, number of homes located within the counters, and the time and distance saved for each aircraft operation on the more efficient alternate routes.

FTNIM noise calculations are performed using the core modules of the FAA INM model. Population and households are computed using a special algorithm which incorporates census data modified to account for distributed population in the region and integrated with the region's GIS system MapInfo.

15.6 AIRPORT–LANDSIDE SIMULATION

Simulation techniques run the gamut from the basic and rudimentary manual, pencil and paper, to simple spreadsheets, to the Monte Carlo random-number probabilistic models, to the mathematically sophisticated queuing theory, and to the computer-intensive discrete-event, object-oriented simulation with advanced animation and multimedia output. The trade-off in choosing any given technique is entirely related to practicality, cost effectiveness, and reliability of results vis-à-vis the level of accuracy required.

For a long period of time, airport planners were frustrated with lack of adequate tools to solve higher order problems and provide appropriate solutions. Airport planners and managers needed effective tools to solve such problems, assess system performance, and conduct planning tasks. Airport planners recognized that tools like nomographs, empirical data, and rule-of-thumb approaches were overly simplistic in the highly dynamic nature of airports, as they were based mostly on gross and generalized assumptions and unlikely to achieve effective solutions to complex problems in the dynamic environment of the airport landside (32).

Simulation came to quickly fulfill this void in terminal planning and analytical techniques and has satisfied airport planners with capabilities that yielded much more accurate results as well as practical and cost-effective implementation. Simulation is increasingly becoming an essential tool for planning, design, and management of airport facilities. Research in landside simulation started in the 1960s to investigate and try to better understand the problem of severe congestion and delay. Researchers considered using an analytical technique, later called simulation, because of its reliability, convenience of use, practicality, and efficiency in describing and explaining detailed activities in a manageable fashion (33).

During the 1970s, government provided support to academia and industry to develop landside simulations that would assist in solving terminal congestion, and subsequently several landside simulations were developed as research tools in academia and as industry products in the United States, Canada, Europe, and Australia. In the United state, the FAA supported landside simulation through development of the Airport Landside Simulation (ALSIM) program (34). Huge leaps in computer hardware and software during the 1980s followed by similar advancement in information technology provided the "critical mass" to push landside simulation forward by making it more efficient and reliable, yet affordable. Consequently, landside simulation was credited worldwide as the most promising method to cope with the time-varying, dynamic, and mostly behavioral nature of the terminal environment and became the method of choice in terminal planning and analysis studies.

In general, airport landside simulations were developed on three tracks: government-supported, academia-developed, and industry-built and marketed simulations; each track had a specific objective, but all were collaborating together (35). The three tracks share the same objectives of putting at the disposal of airport planners and operations managers a technique and tool that is balanced, cost effective, accurate, and truly representative of the terminal environment. At the same time its use is practical, easy, expeditious, and easy to understand and explain.

The purpose of simulation would define model functional characteristics, sophistication and fidelity levels, degree of representing the real-world system being modeled, and level of simulation precision desired. There are four levels defining simulation (32):

Level I. Simplest and most basic form that considers only fixed peak-demand patterns at individual parts of the terminal, not including the time-variant and stochastic nature of operation in modeling.

Level II. Accounting-type model that considers the time variation in average demand only. It does not follow queuing theory principles and demand and service, as both are non-stochastic.

Level III. Queuing theory based, where demand is probabilistic and the stochastic nature of operation is explicitly considered. However, the steady-state assumptions of queuing analysis hold that can prove to be impractical for computer simulation.

Level IV. Time-varying probabilistic queuing, where both demand arrival and processing are probabilistic and explicit functions of time. Calculations involve a high degree of mathematical complexity.

For the past two decades, landside simulation has been following in the footsteps of innovations in computer and information technologies to enhance its reliability, utilization, and efficiency. The resulting progress of landside simulation during this period changed the airport planners' perception towards it that resulted in an important shift to actually use this novice concept. From "black boxes," whose derivation is almost impossible to ascertain with extensive input and output that are difficult to accurately verify, to user-friendly programs running on highly efficient yet affordable hardware. These programs use more superior graphics, animation, multimedia interfaces, and most importantly efficient data storage devices and data manipulation software (35). Today's landside simulation offers fast, flexible, transparent, animated, and accurate tools to the airport planner. Some of the major technological innovations that helped in this include:

- Object-oriented programming (OOP) structure that is far more superior in programming efficiency and reliability
- Enhanced graphics, animation, and interactive user interface
- Wider use, more efficient, and reliable operating systems, environments, and platforms
- New-generation programming languages that are more efficient and can generate more representative and realistic simulations

Industry-Developed Landside Simulations

Industry initiated pioneering landside simulation development efforts to implement in actual airport planning and design using commercial off-the-shelf (COTS) simulation software available at the time. These COTS simulation language software were developed in other environments, mainly industrial and system engineering. Major pioneering industry-developed landside simulations include:

TAMS Landside Simulation. A pioneering landside simulation and probably the first simulation model developed and used for airport terminal design was the Dallas–Fort Worth regional airport simulation conducted by TAMS Consultants that ran parallel to and interfaced with the airside simulation discussed earlier (5). The simulation used a level III SLAM programming language to simulate terminal operations and activities to generate synthesized data to assist airport planners in fine-tuning their design of terminal facilities. The model was also used for the planning and design of Pittsburgh and Caracas, Venezuela airports (36).

Airport Landside Simulation—ALSIM. Bechtel originally developed a similar level III GPSS-based, with FORTRAN subprograms, interactive, time-oriented queuing model capable of simulating up to 50-gate terminals that was used for the planning and design of airport terminals in Saudi Arabia (32). The FAA later acquired the model and supported its expansion and improvement through research and later became ALSIM (34).

ALSIM is a macroscopic, probabilistic, discrete-event, fast-time computer simulation model capable of producing flow and congestion parameters and statistics on simulated passenger facilities. As seen in Figure 15.12, the model structure is composed of (34):

- Main and auxiliary programs in the GPSS-V simulation language which create transactions representing passenger and visitor movements and transactions inside the terminal and direct these entities through the model blocks that describe the simulated system

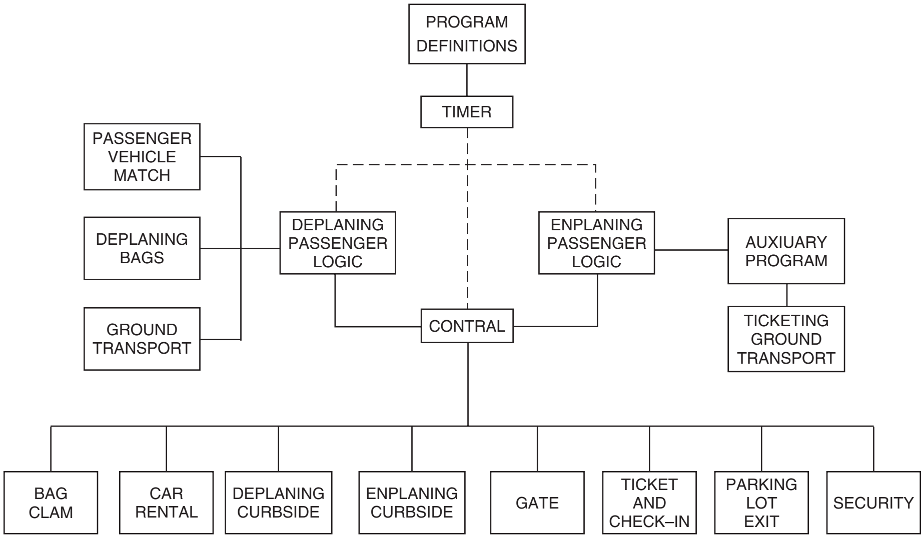

Figure 15.12 ALSIM model structure (33).

- Supporting subprograms to provide flight schedules, airport configuration, data matrix manipulation, and assignment of entities to facilities written in FORTRAN
- Computer assembly language subprograms to provide linkage between the GPSS-V and FORTRAN components of the program

ALSIM input is grouped into four major categories (37):

- *Flight Schedule*. Including flights number, airline and sector (domestic, international, charter, or commuter), arrival/departure times, aircraft type, passengers per flight, transferring passengers between flights, and bag claim identification.
- *Passenger Characteristics.* Including percentage of passengers pre-ticketed or using express check-in, passenger routing in landside, ground transportation modal choice, passenger group size, visitors per passenger/group, distribution of number of bags per passenger, arrival distribution prior to standard time of departure for originating passengers, visitor arrival distribution, arrival distribution of vehicles meeting passengers, car rental agency selection distribution and number of car rental companies, and percentage of visitors accompanying passengers to gate and other parts of the terminal.
- *Airport Geometry*. Including terminal flow node number, x–y coordinates of node, node facility type, and facility number by type.
- *Facility Characteristics*. Including facility operational type, service time distribution for processing facilities, number of servers (agents) of processing facility or size of holding facility, ground transport vehicle loading and unloading times, and baggage transport time from plane to claim area.

ALSIM output is contained in a statistical report for each facility simulated. The report includes total number of persons (passengers and visitors) served, maximum and average number of servers (agents) in processing facilities busy and the percentage of time they were idle, occupancy per facility, and flow statistics of persons through the system.

Major assumptions of using the ALSIM simulation include the following (37):

- Passenger and visitor processing facilities are similar and independent of airport types.
- Random-number generated (through Monte Carlo simulation) functions govern transfer flight selection and baggage delivery times. However, transfer flight selection could be tied to the airline hubbing operation via the flight schedule.
- Passenger service time distributions are independent of time and server workload.
- Single-queue waiting lines can be represented as single line per server or single line per pool of servers, depending on facility type and airline policy.
- People proceed directly from one facility to another, unless otherwise specified as per actual condition, particularly for the case of duty-free utilization.
- Exogenous flight schedule provides the time-varying demand.
- Arrival rates to and operations of facilities are determined by the model itself, except the first node in the model for arrivals and departures specified by the exogenous flight schedule.

Other industry landside–terminal flow simulations include the following:

- An airport terminal simulation model was developed by the Preston Group in Australia (TMS).
- TransSolution of Fort Worth, Texas, developed a terminal passenger and baggage flow simulation based on ARENA, a COTS simulation package.
- Leigh Fischer Consultants, San Francisco, California, developed a terminal simulation model (TERMSIM) that is based on the ACAP research effort discussed later.
- Arup/NAPA developed several landside simulation tools applied in many airports around the world that were originally based on Transport Canada research efforts to develop landside simulations (38).

Airport Passenger and Baggage Flow Model (APBFM) (39). The FAA funded the development of a computer simulation model of the movement of passengers and baggage through the airport terminal building. This model allows the measurement of the operational impacts of the alternative placement of security screening equipment and the security procedures required and administered by the U.S. Transportation Security Administration (TSA). It determines through simulation the operational effectiveness of security screening device processing times and false-alarm rates. The primary objective of this model is to explore alternate configurations and procedures for the security screening operation that would improve the passengers and baggage flows at equivalent and varying security measures.

APBFM is used to simulate passenger and baggage flows by:

- Technical and security analysts, responsible for developing and maintaining basic, general, and airport-specific databases for airport layout, airport processes, and passenger demand

- Airport and airline operations analysts, responsible for operations management, who use it to explore alternative what-if scenarios
- Managers, the model "information end users," who would initiate studies and use results as the basis to make changes in the airport terminal operations, layout plans and security technologies and measures, and conduct analyses of airport operation and security procedures to assess performance

The model is composed of the user input interface, demand generation module, simulation engine, performance measures evaluation module, and output statistics report generation module.

Airport Landside–Ground Access Simulation

Passengers going to/coming from airports have to use the airport ground transportation system and its terminal interface—curbside. While it is not directly related to airport operations, the airport access and ground transportation system directly affects passenger perception of the overall LOS and their satisfaction service in general. Overall airport capacity may be limited by not only the airport functional components but also the capacity of the airport ground transportation system.

Therefore, the terminal roadway and curbside are critical determinants in integrated airport system capacity. In such an environment, and in order to provide comprehensive assessment of terminal roadway curbside capacity, simulation modeling is used. While conventional highway traffic simulations have long been used, these models do not have the airport roadway and curbside element typically represented, and they do not have the appropriate resolution to model airport access roadway and terminal curbside; therefore, they are not applicable to conduct airport access evaluation.

Landside–terminal roadway and curbside simulations developed by consultants include:

- TransSolution of Fort Worth, Texas, developed a terminal roadway and curbside simulation that was used for the planning of Las Vegas McCarran Airport (40). It is a stochastic, discrete-event simulation model to replicate the behavior of vehicles on the airport terminal roadway and curbside and is composed of the following major components:
    - Data generator, which applies operational characteristics of all modes and vehicles, passenger characteristics, and flight schedules to derive vehicle traffic using the airport curbside.
    - Traffic simulator, which provides the logic and procedures for entities to conduct activities and includes six elements: vehicle movement logic, lane changing logic, pedestrian crossing logic, passenger pick-up logic, parking space selection logic, and double- and triple-parking logic. With these logic subprograms, the simulation uses applicable data from the data generator and "move" vehicles throughout the airport terminal roadway and curbside to perform the parking, passenger pick-up, and drop-off operations required following the flight schedule pattern.

- Interactive GUI input, which allows users to manually change input data to respond to special conditions and particular situations or adapt to scenarios as it is capable of recording a multitude of user-defined variables to be input to the simulation model.
- Output report generator, which provides the output database after the end of simulation, with statistical processing, in a tabular or graphical format and prepares data for post-processing animation. The statistical reporting of pre-selected performance measures assists the airport planner in conducting short- and long-term planning studies by evaluating sets of performance indicators and measures of traffic operation at the roadway and curbside, depending on the relative importance of the terminal roadway/curbside and the specific objective desired by simulation (e.g., planning, design, capacity evaluation, assessment of scenarios, or alternatives analysis).

- JHK Mobility Consultants developed ALPS (Airport Landside Planning System), a landside simulation model for roadway–curbside, terminal flows, and pedestrian-assisted mobility (41). The ALPS model was used in several airports, including Washington, Houston, and Detroit.

Academe-Developed Landside Simulations

Universities pioneered and initiated original research to develop landside simulations.

Massachusetts Institute of Technology (MIT). MIT first drew attention to future problems facing air transportation in an environment of unprecedented huge growth in air travel demand and the introduction of much larger aircraft with airlines adopting the hub-and-spoke concept that subjects airport terminals to demand load and congestion for which they were never designed. MIT initiated research into this subject and convened a workshop in 1967 to discuss the issues. Odoni and De Neufville (42) led the research at MIT on the simulation of terminal processing facilities using analytical queuing principles of terminal design (43) and to evaluate alternative terminal designs (44). While the MIT research effort helped in understand the complexity of operational interactions of terminal operations, no complete and stand-alone landside simulation model was developed.

University of California, Berkeley (UCB). Horonjeff (45) led extensive research effort at UCB to model airport terminal facilities using deterministic analytical models, not probabilistic or queuing based. This effort included modeling of gate utilization, baggage claim facilities (47), passenger movement in piers (48), processing facilities of departing and arriving passengers, passenger aircraft enplaning and deplaning, airline check-in counters, passenger security, and terminal departure lounges. Again, while UCB research efforts enriched the understanding of the landside research community and helped in understanding the operational interactions of different terminal facilities, no complete and stand-alone landside simulation model was developed.

University of Texas, Austin. Federally funded research to analyze terminal operations and evaluate landside capacity was conducted at the University of Texas, Austin (48).

The focus of this research was to develop the Airport Capacity Assessment Program (ACAP) simulation model, a level II, FORTRAN-based, event-driven, accounting-type model to evaluate the capacity of the terminal building (49, 50). The structure of ACAP is composed of the main program and auxiliary component modules that simulate individual facilities based on deterministic core regression-based models derived through airport surveys. In essence, these models draw their predictive power only from survey data where and when collected; otherwise they lose their explanatory value and predictive power. The model was improved and changed to a probabilistic model by replacing the regression-based core models with Monte Carlo–based models capable of simulating passenger processing using the appropriate mean service time selected at random from a negative exponential distribution (32). This modification changed ACAP from a level II to a level IV model. An airport terminal simulation similar to ACAP was used by consultants and airport planners (Leigh Fischer Consultants).

Object-Oriented Program Simulation—OOPS

A new concept and advanced computer programming simulation approach, OOP simulation, has been gaining wide popularity and coverage for the broad advantages it can offer to landside simulations. Conventional programming languages (e.g., FORTRAN and BASIC) and simulation programs (e.g., GPSS, SLAM, and SIMSCRIPT) have been used historically to develop landside simulations. But with the growing complexity of the landside as a system, the multiplicity of the passenger population categories, and diversity of passenger facilitation procedures at terminals, these conventional languages have reached their limits. Moreover, for the kind of solutions sought to the problems of such dynamic, probabilistic, and extreme loading environments, these languages and programs are no longer viable or useful. However, the landside design and capacity problems neither are well understood nor can be strictly formulated. Instead, they tend to be formulated in reaction and response to parameters that emerge gradually (51).

The OOP structure is not new and first appeared in the 1960s, but it did not see wide-scale application until the monumental development of computer hardware and software of the 1980s. The computer and software engineering industry introduced the OOP paradigm, where declared objects interact among themselves and constantly acquire changing characteristics during simulation, which affected simulation results to reflect this interaction more accurately. Developed in the domain of artificial intelligence (AI), the OOP paradigm presents the unique and particularly “intelligent” characteristics of class representation, inheritance, message transfer, and perspectives, and can provide a level of detail for simulated systems that was unavailable to users before (35). Inadequacy of current approaches requires that landside simulation software designers have to resort to using more precise, systematic, and easily manageable models and methodical constructs with hierarchical programming. Here, procedures are constructed in a way to make assumptions, report what is relevant, and seek information on the basis of hierarchy (51).

What makes OOP more superior to conventional languages is that the latter essentially stores, recovers, and manipulates data mathematically, treating data, procedures, and functions separately. OOP, on the other hand, treats all data as one entity, only conceptually different in properties and attributes, but all with an established ancestor-descendent hierarchy. Consequently, hierarchy, relationships, and abstract concepts can be easily, conveniently, and neatly represented with compact and concise code (35).

OOPS is written in object-based programming language (e.g., C++, Object-Pascal, or Visual BASIC), where the object is defined as a generic data structure. The principal properties of an object-oriented language are:

- *Inheritance*. Property that allows creation of a hierarchy of objects and descendants of objects inheriting the characteristics and properties of the ancestor.
- *Encapsulation.* Property that allows the orderly, structural arrangement of internal data of an object and the associated actions on the manipulation of these data.
- *Polymorphism.* Concept referring to sharing action throughout an object hierarchy.

An advantage of OOP is ease of designing a far advanced GUI than in traditional languages. But more importantly, from an airport simulation perspective, generic landside simulation models and respective facilities can be easily formulated due to this robust, flexible, and truly representative concept. The generic model can be tailored to the specific airport situation with slight modification to objects without actually changing the source code of the simulation.

Typically, the OOP simulation model consists of the following object types:

- *Event Object*. Updates the simulation clock and schedules changes of states throughout the simulation period.
- *Pax Object*. Holds the main parameters of passenger arrival time and location, departure time and location, passenger attributes, and assigned route taken in simulation, and it is linked to at least the transition, transaction, and process objects to cover the entire simulation.
- *Transaction Object.* Represents the processing unit in terminal and holds the logic of necessary processing.
- *Transition Object.* Represents the simulated passenger movement, where the passenger transitions from one processing/holding facility to another
- *Process Object.* Superclass of transition and transaction objects which defines the logic of traversing throughout the processing network.
- *Demon Objects.* Objects that are dormant in simulation and are evoked only when they are needed to accomplish some task.
- And many more objects, as simulation logic requires.

To develop an object-oriented airport terminal simulation, the following subsystems are modeled:

- Access interface
- Processing interface
- Passenger path interface
- Flight schedule interface
- Airport parameter interface
- Simulation environment in three modes: representative, evaluative, and optimization
- Output control interface

This OOP framework can enable the development of a completely integrated and seamless airport–airspace simulation system that would include airspace, airfield, and landside components in a single system (51). This unified integrated simulation would create a powerful planning and analytical tool to provide a more comprehensive and realistic representation of the entire airport–airspace environment and interpret the existing intricate system interactions far better.

An OOP application to landside simulation was first prototyped as a demo-simulation that was later developed into a stand-alone simulation model in the mid-1990s. One of the major features of this application is that it was LOS responsive throughout simulation, where it features continuous evaluation of operational performance against predefined LOS standards. LOS-responsive simulation mainly entails utilizing simulation as a system decision tool to adapt the system supply side (facilities and staffing) to the dynamics of demand within the LOS standards specified for the operational performance indicators, for example, space occupied/density, waiting time, and walking distance (52).

This approach was applied in the planning and design of a new terminal building for a major U.S. airline at its hub with good results. Airport planners and terminal architects were able to fine-tune the allocation of space where it was really required, proper location and sizing of facilities, and optimal location of people mover stops and provide adequate spatial exposure of passengers to duty-free shops, better planning of vertical and horizontal mechanical-assisted movement devices and optimizing corridor widths, and accurate evaluation of the evacuation population for fire code purposes (52).

This LOS-capable landside simulation could be easily extended to groundside and airside by linking the three subsystem simulations (groundside with vehicles, landside with passengers, and airside with aircraft) using objects and attributes that interface their basic entities with respective transition objects.

15.7 AIRPORT GIS

Geographic information systems (GISs) are computerized relational database, digitized mapping, and functional analytical tools within a workstation platform. With airports becoming larger and more complicated, with facilities that are increasingly interrelated in their functions and interdependencies, airports increasingly require the GIS for their management and development. How the GIS is central to the effective, comprehensive, and integrated airport development process—the planning, design, construction, and operations management is discussed.

GIS is an integrated computerized mapping and relational database system designed to support the capture, management, manipulation, analysis, and display of spatially referenced data to perform spatial analysis of graphics and attribute data for solving complex planning and management problems. The primary sources of graphical data in GIS include digital map databases, digital aerial photography, satellite photography, and CAD drawings.

Modern airports are essentially a huge and complex real estate endeavor and should be managed as one. As such, to be a successful business generating income and running the real estate cost effectively, infrastructure management should have a high priority. McNerney (53) conducted research to explore the utilization of GIS in U.S. airports and develop standards for airports to optimize GIS as the core for a multi-system airport infrastructure management system. This study included a survey whose findings had determined that airports used GIS for:

- Airport infrastructure management of:
  - Airport properties and buildings
  - Leasable space
  - Utilities
  - Airport PMS requirements, including pavement condition surveys, visualization of pavement data, and PMS spatial analysis and optimization
  - Aircraft apron–gates
  - Aircraft ground support equipment
- Environmental analysis and management (see Chapter 17):
  - Mapping of the airport EIS-related studies, planning permit and FAA requirements, and other EPA compliance requirements, including clean-air compliance
  - Storm water system and storm water pollution plans
  - Noise impacts and community complaints
  - Aircraft noise analysis and respective changes in noise contours
  - Noise monitoring, mitigation, and abatement programs
  - Off-airport properties under noise mitigation programs
- Airfield aircraft movement planner, including:
  - Airfield aircraft ground movement on taxiways and runways
  - Navigational aid airfield locations and analysis of potential interference (see Chapter 8)
- Airport airspace safeguarding and management, including:
  - Conducting Part 77 obstacle limitation analysis on natural or man-made obstacles (see Chapter 9)
  - Airport airspace relation to ground terrain and geographic features of the region
  - Terminal airspace route structure display, planning, and management, including management of terminal airspace capacity by ATC controllers and ATM managers, and mapping and spatial studies for planning of new airspace procedures (see Chapter 6)
- Intrinsic GIS capability, including:
  - Geographic and spatial data analyses
  - Display and public presentation of airport region geographic mapping

According to the GIS airport survey conducted by McNerney in the mid-1990s (53), of 81 responding airports, only 15% said they were using GIS, but 52% said they would acquire and implement GIS within three years. Today, even small airports use GIS for a variety of purposes.

The FAA is recognizing the value of GIS as a system-wide multipurpose resource for NAS and is encouraging NAS airports to utilize GIS in their planning and operations management functions. For this, the FAA has issued documents (54) to provide specifications for collecting airport data under the FAA's Airport Surveying–GIS Program, which provides guidance on submitting GIS-compliant data. The FAA would forward safety-critical data to the National Geodetic Survey (NGS) for independent verification and validation. This FAA document provides critical information to airport operators for the operation and safety of the NAS that are classified as critical by the ICAO (55). ICAO Annex 15 defines data as critical when "there is a high probability when using corrupted critical data that the continued safe flight and landing of an aircraft would be severely at risk with the potential for catastrophe." The information furnished under these standards covers the entire spectrum of the FAA's airport data requirements.

It is outside the scope of this book to provide further detail on technical features, composition, and use of GIS at airports. The reader can refer to the major developers of GIS systems to provide online literature on their GIS, general use, hardware and training requirements, and brief descriptions of specific applications of GIS in airports. The Environmental Sciences Research Institute (ESRI) is the leading GIS developer and provides several products in the '* *Info*' series tailored for specific applications and use, for example, ArcGIS, ArcInfo, and MapInfo (56).

Beyond airport operators, airport engineers and planners today have adopted GIS and find it indispensable and useful as a tool to conduct airport planning, expansion studies, and facility design reviews using GIS capabilities. GIS mapping data from local municipalities, such as current roadway/railway access to the airport, utility location and alignment, neighborhood constraints, geotechnical inventory data, and environmental sensitivities, are all critical and may have certain complexities and can seriously hinder airport expansion plans in densely populated urban areas without use of GIS to integrate these databases with that of the airport. Airline planners and ATC regulators use GIS for airspace planning and route structure modifications to improve operations and increase airspace capacity, but the list of GIS users for airport planning and operations management is long: for example, airport facilities management, capital planning, property/lease management, land acquisition, security and risk assessment, flight path management, airport layout planning, capacity planning, pavement management, parking management, courtesy vehicle management, utility maintenance, lighting management, noise monitoring and modeling, and environmental assessment.

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16

Airport City

16.1 INTRODUCTION

In the era of globalization, where the entire world has become a "global village," thanks to major technological breakthroughs in communication, mass media, and finance and the changing geopolitical landscape, the single means of actually bringing people from around the world together remains to be air transportation. The above breakthroughs provided the incentive and impetus to travel by air to leading cities of the world enjoying safe, efficient, and cost-effective operations at and between airports. The concentration of internationally oriented urban activities seems to take place in a limited number of highly competitive "global city regions." Global city regions are increasingly facing a highly dynamic global competition for economic activities, where they benefit from their position in the global network of great strategic importance strongly supported by the direct destinations their airports offer to major economic, cultural, business, and population centers of the world.

Before that, deregulation and liberalization influenced the world airline industry in many ways. They led to the rise of low-cost airlines and the formation of worldwide alliances of traditional airlines. These alliances organized their networks into global hub-and-spoke systems with a central role for the hub airports as point of interchange. Influenced by competition in a deregulated market, giant global alliances thrived, and partnerships between the airline, its hub airport, and local business community and industries turned hub airports into formidable business, financial, and technology urban centers in their respective regions centered on airports. These global alliance hub airports could offer a truly competitive intercontinental network to their global city regions, and these airports grew and expanded as the airline alliances developed their international and regional networks.

Since its inception, the airport's primary role was merely a facility to change travel mode of passengers and freight between air and land modes. With time, airports eventually got larger, more sophisticated in design, and quite busy and congested, but its primary function did not shift from its basic role, that is, until the early 1990s, at the dawn of globalization, the Internet, satellite telecommunication and navigation, and the seismic shifts in global geopolitics.

With the onset of deregulation, liberalization, and globalization, many airports outgrew their role as just transportation centers and became major urban intermodal nodes. Such concepts and brands as "airport city," "aerotropolis," and "airport corridor" indicated that these airports can generate urban and economic development as well through a synergetic and symbiotic relation between the commercial development on the airport landside and the networks of the airlines at the airport. Global city regions with major hub airports provided substantial benefits from their airports. Airports' success with the airport city development depended on such factors as availability of development space on the airport, location of the airport within the landside infrastructure networks, the socioeconomic structure of the region, the institutional setting of local government, and the planning framework.

This chapter describes the evolution of the concept of the airport city, how it prospered and expanded around the world, the symbiotic relationship with the airport, and forms of its implementation.

16.2 GLOBAL CITY

Before delving into the concept of the airport city, or *aerotropolis* and its building blocks, the higher level concept of the global city must be discussed first. A global city (also called world city or sometimes alpha city) is a city deemed to be an important node in the global economic system. The concept has its roots in geography and urban studies and rests on the idea that globalization can be understood as largely created, facilitated, and enacted in strategic geographic locales according to a hierarchy of importance to the operation of the global system of finance and trade. In global cities the linkages binding a city have a direct and tangible effect on global affairs through socioeconomic means (1).

There have been many studies on this subject worldwide to define the concept and identify its attributes. One of the first attempts to define, categorize, and rank global cities was made in 1998 by the Globalization and World Cities Study Group and Network (GaWC) of Loughborough University in the United Kingdom (2).

The basic characteristics of the global city are as follows:

Economic Characteristics

- Based corporate headquarters for multinational corporations
- International financial institutions
- Leading law firms
- Financial conglomerates
- Stock exchanges influential over world's economy
- Significant financial capacity/output for city and region
- Gross domestic product (GDP), stock market indices, and market capitalization
- Financial service provision, for example, banks, accountancy
- Costs of living
- Personal wealth, for example, number of billionaires

Political Characteristics

- Active influence on and participation in international events and world affairs
- Hosting headquarters for international organizations
- A large proper, population of the municipality (the center of a metropolitan area, typically several million) or agglomeration

- Diverse demographic constituencies based on various indicators, such as population, habitat, mobility, and urbanization
- Quality-of-life standards or city development
- Expatriate communities

Cultural Characteristics

- International, first-name familiarity, whereby a city is recognized without the need for a political subdivision
- Renowned cultural institutions (often with high endowments), such as notable museums and art galleries, notable opera, orchestras, notable film centers and festivals, a thriving music scene and nightlife, and influential media outlets with an international reach
- A strong sporting community, including major sports facilities, home teams in major league sports, and the ability and historical experience to host international sporting events such as the Olympic Games, World Cup, and major tennis events
- Educational institutions, for example, renowned universities with prominent research centers and diverse international student attendance
- Cities with sites of pilgrimage for world religions and world heritage sites of historical and cultural significance
- Thriving tourism industry and active round-the-year convention and conference industry
- City as site or subject in arts, media, television, film, theatre, music, literature, and magazines
- City as an often repeated historic reference, showcase, or symbolic actions

Infrastructural Characteristics

- Advanced transportation system that includes several highways connected with the regional highway network and large mass transit network offering multiple modes of transportation (rapid transit, light rail, regional and high-speed rail, ferry, intercity bus, etc.), that provide extensive and popular mass transit systems, prominent rail usage, road vehicle usage, and major seaports
- Major international airport(s) that serve as an established hub for several international airlines with significant volume of international passenger traffic and international air cargo activity
- Advanced communications infrastructure on which modern transnational corporations rely, such as fiber optics, Wi-Fi networks, cellular phone services, and satellite telecommunication
- Health care facilities and medical research centers, for example, hospitals and medical laboratories
- Prominent, world-class urban skyline

The 2008 GaWC world's global city rankings are depicted in Figure 16.1, based on GaWC four-level categorization of alpha cities. The ranking evaluation considered 24 metrics in five areas: business activity, human capital, information exchange, cultural experience, and political engagement.

Figure 16.1 GaWC 2008 ranking of global cities (2).

The evaluation of the parameters included in the ranking of global cities could assist in projecting the success and future of airport cities. The close and active relationship between the global city and its airport will undoubtedly assist in the evolution of an airport city, subject to availability of space, infrastructure, and congregation of business and industry close to the airport.

Numbers shown above the legend of Figure 16.1 indicate the global cities in that category that have actually adopted the airport city concept.

With a cursory assessment of airports known to have adopted the airport city concept and the global city ranking in Figure 16.1, it is curious to observe that none of the alpha++ global cities indicated actually has its own distinct airport city. Except for Hong Kong and Singapore for the alpha+ category and Seoul and Kuala Lumpur for the alpha category, airports of the other global city categories do not have airport cities. This is probably due to the fact that large global cities have functions subsumed by airport cities diffused in their urban mass. Airport cities tend to grow around international airports in a symbiotic fashion, and therefore the size of the immediate metropolis would have a certain impact on the creation of an airport city.

16.3 BUILDING BLOCKS OF AIRPORT CITY

The airport city has evolved in subtle and gradual ways to represent the spatial manifestation of interactions of certain airport-centered economic sectors, such as commerce, real estate development, select service industries that are dependent on airports. These service industries include convention and hospitality, and multimodal transportation shaped by contemporary financial, marketing, and strategic management processes. These have all coalesced together to position airports as distinctive new urban growth centers. The airport-centric development initially started ad hoc but then evolved to a point where the airport and its surrounding areas have morphed into major business, shopping, working, trading, meeting, and entertainment destinations. In such a process, airport cities have taken on many of the characteristics (both spatial and functional) of central urban districts, in addition to those of global cities discussed earlier.

In an environment of strong air traffic growth that is only steadily rising and the role airports are now playing as both catalyst and magnet of global economic activity, airport cities will continue to play a central role in accommodating growth in economic and cultural activities around the world. On the local level, the spread of this global phenomenon and the leading global role of airports brought new dynamics to airports and what they can do for their own communities.

Communities and local governments where airport cities were developed are embracing them and providing positive contributions that stimulate and energize them. These multifaceted contributions by local government and the airport business community are synergetic and attract new business, create new jobs, and open new commercial possibilities, introducing a vibrant business model that can accommodate intensive air travel needs in an environmentally responsible way (3). In this respect, airport cities are integrated into an urban planning development scheme, where airport cities and local authorities are partnering to ensure wise and mutually beneficial land use management around the airport to limit noise disturbance for residents and preserve local air quality. From another perspective, with the insertion of high-speed public transportation into this integrated urban mass, travelers, visitors, workers, and airport staff would have an efficient alternative for reaching city centers and the chance to reduce road traffic and congestion around the site. Airports that pioneered the implementation of the concept of the airport as a magnet of urban activities in addition to its typical intermodal function were influenced by the work of McKinley Conway (4)—a U.S. multidisciplinary visionary and pioneer in many areas: aeronautics, urban development, environment, and transportation. His creative concepts transformed transportation from unimodal to multimodal, intermodal, and trans-modal systems. He foresaw adoption of creative geoeconomic principles and development market models into airport projects in ways not considered before. He first initiated the "fly-in park" concept, whereby a corporation would park its airplane at its doorsteps, and "fly-in communities," whereby pilots and aircraft owners could keep their airplanes at home or residential airparks.

He later visualized the airport city concept (5) in more detail, where aviation-linked commercial development would evolve, grow, and prosper around airports in synergy through incorporating business, residential, industrial parks, logistical facilities, and cargo distribution centers all integrated into the conventional airport.

On the other side of the Atlantic and perhaps unrelated to Conway's inspiring concepts but as a precursor to the airport city was the experience of Shannon Airport, Ireland. Shannon Airport established the world's first airport duty-free shop in 1951. Airlines would offer extensive duty-free shopping to passengers on trans-Atlantic refueling "stop-over" flights.

Seen as an alternative source of income in the face of declining revenues due to competition with other airports, caused by the introduction of trans-Atlantic long-range jet aircraft, the Shannon free zone was established in 1959 by the Shannon Free Airport Development Company, or Shannon Development, as it is known today. The objective was to "initiate, participate in and support integrated development that will achieve sustained economic growth in and throughout the Shannon Region" (3).

Another objective was to improve the airport's global competitiveness with a generous corporate tax rate incentive offered that was much lower than other states in Europe and the United States. By 1960, Shannon Development housed 10 overseas companies with 580 employees, and today its size has increased to 600 acres, housing 120 international enterprises and employing more than 7500. Shannon Development's strategy was to focus on manufacturing in high technology and trade. It is now comprised of the Innovation Centre for High Technology Firms, National Technology Office Park, Shannon World Aviation Distribution Park, telecommunication companies, plus other aerospace and aviation-related businesses and tourism and entertainment (golf course and hotels).

With this background, the airport city was conceived as a successful concept when implemented properly. One of the early advocates of the airport city concept is John Kasarda, who advocated the concept and added the term aerotropolis, which essentially refers to the airport city metropolitan area when put in an urban design context. A generic schema for this concept, as envisioned by Kasarda, is depicted in Figure 16.2.

Airports, like cities, are never static; they are constantly evolving in form and function. Historically, airports have been understood as places where aircraft operate and passengers use just for this purpose. But this is now giving way to a much broader, more encompassing concept—the airport city. This concept is predicated upon the fact that all functions of modern metropolitan centers are evolving on and immediately around their major airports transforming them from city airports to airport cities.

For the airport city model, in addition to their core aeronautical infrastructure and services, major airports have developed significant non-aeronautical facilities, services, and revenue streams. Indeed, the daily consumer population at many airports is actually larger than midsize cities. This model has become the twenty-first-century way forward for many airports.

At the same time, airports are extending their commercial reach and economic impact well beyond their boundaries and toward the metropolis. Arterial spines and clusters of aviation-linked businesses are now radiating outward up to 20 km or more deep into the metropolitan area along and near airport access corridors forming the greater airport region, or aerotropolis. As central cities are the functional core of the metropolis, airport cities have the same relation to the aerotropolis.

Airport Metamorphosis into Airport City

Airport terminals are fast becoming luxurious shopping malls and artistic and recreational venues and convention forums. No longer restricted to magazine shops, fast food, outlets and duty free shops, they now feature brand name boutiques, specialty retail shops, and upscale restaurants along with entertainment and cultural attractions. In their transformation into the airport city and aerotropolis and beyond, most airports are diversifying, expanding, and upgrading their retail offerings, often incorporating shopping arcades, galleries, gourmet and culinary clusters, and arts, entertainment, and cultural zones. These are complemented by local-theme merchandise and dining outlets.

Given the significantly higher incomes of airline passengers, which are typically three to five times higher than the national averages, and the huge volumes of passengers flowing through the terminals (up to 85 million annually compared with 8–12 million annually for a large shopping center), it is not surprising that major airport retail sales

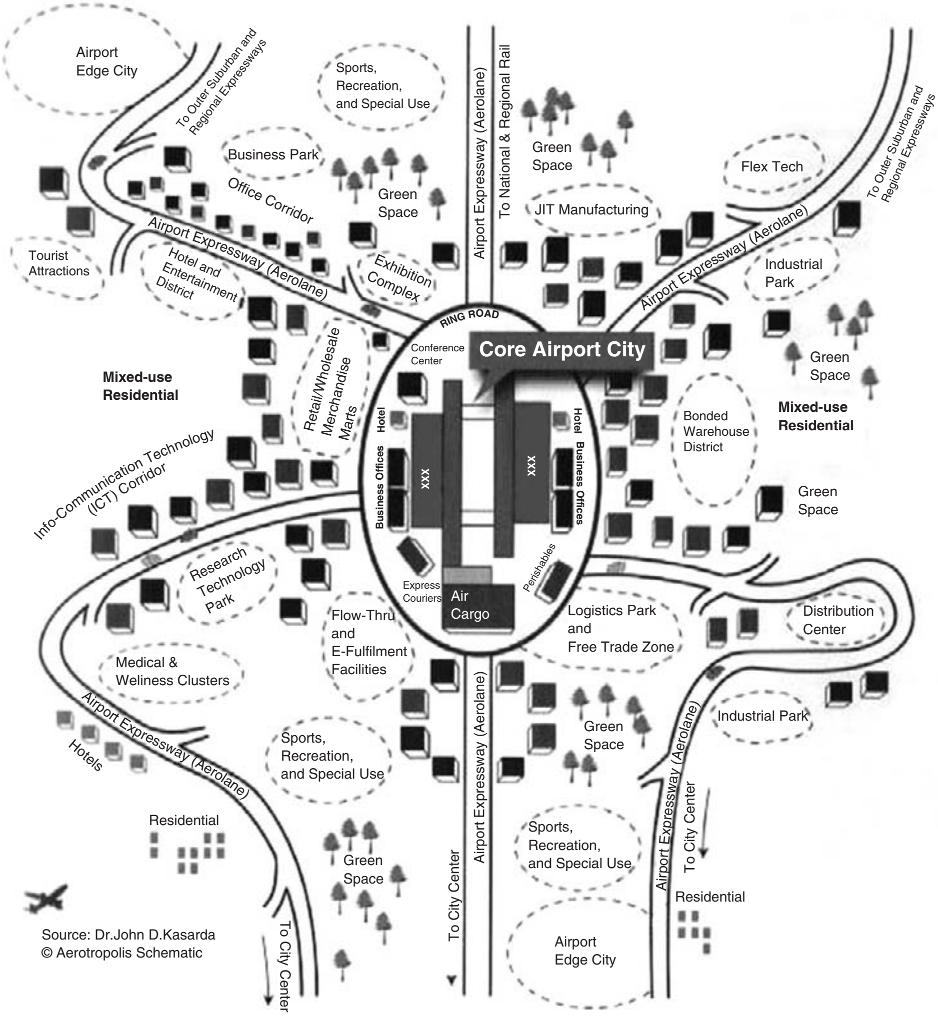

Figure 16.2 Schematic of typical airport city, or aerotropolis (3).

per square meter are on average three to four times greater than shopping malls and downtown shops. As a result, terminal commercial lease rates tend to be the highest in the metropolitan area.

In addition to incorporating a variety of commercial and entertainment venues into passenger terminals, airports are developing their landside areas with hospitality clusters, office and retail complexes, conference and exhibition centers, logistics and free-trade zones, and facilities for processing time-sensitive goods. Revenues from such developments are being reinforced by major financial streams from advertising and parking. Many airports now receive greater percentages of their revenues from non-aeronautical sources. For example, two-thirds of total airport revenue for Atlanta, Dallas–Fort Worth (DFW), Hong Kong, and Schiphol comes from non-aeronautical activities.

Another feature includes the generation of new revenue stream for the airport. The non-aeronautical revenues have become critical to airports, where their facility expansion and aeronautical modernization needs could be met along with needs to be cost-competitive in attracting and retaining airlines. Since non-aeronautical revenue flows are rising and are relatively predictable, there is emerging interest in securing them for major up-front airport capital infusion. This together with airport monopoly or oligopoly positions in major markets has made them favorite venture targets of investment funds, which typically upgrade and expand airport commercial development to meet both user and shareholder expectations.

Such rapid expansion of airport-centric commercial development is transforming today's gateways into leading urban growth generators as they become significant employment, shopping, trading, business, meeting, entertainment, and leisure destinations in their own right. These airports are taking on many features of the metropolitan central business districts, increasingly operating as regional and national points of multimodal surface transportation convergence and commercial development. This evolution in function and form has essentially transformed numerous city airports into airport cities.

16.4 ANATOMY OF AEROTROPOLIS

While the aerotropolis has evolved gradually over time and not in a structured manner, it does have certain characteristics and features that could guide its successful implementation. Its evolution manifested different spatial forms depending on certain parameters related to available land and ground transportation infrastructure, yet virtually all airport cities emerged in response to four basic drivers:

1. Need for airports to create new non-aeronautical revenue sources, both to compete and to better serve their traditional aviation functions
2. Commercial sector's pursuit of affordable accessible land
3. Constant growth in air passenger and air cargo traffic
4. Airports serving as a catalyst and magnet for landside business development

Functionally, these drivers induced an entire array of activities performed within and around airports seldom known previously to take place at airports.

Airport City Activities

Aeronautical and non-aeronautical activities at and around airports are classified in terms of three distinct functional categories of activities based on the extent to which they are related to aeronautical and airport activities:

I. Core aeronautical activities conducted as part of the technical operation of the airport directly supporting the aeronautical functions.
II. Airport-related activities that have direct relation to air freight or air passenger movements. Their competitiveness and/or business revenues are closely tied to the scale of the aeronautical activities.

III. Airport-oriented activities choose the airport area because of the airport's image and its typically excellent ground accessibility. The prices of land and surface connectivity, rather than the relation to aeronautical activities, are key factors in determining those activities locating in the airport area.

The functional schematic of the airport city activities inside and outside the airport boundary is depicted in Figure 16.3.

Airport City Commercial Activity List

The most common airside and landside airport city commercial activities include (3):

- Duty-free shops
- Restaurants and specialty retail
- Cultural and entertainment attractions
- Hotels and accommodations
- Banks and currency exchange
- Business office complexes
- Convention and exhibition centers
- Leisure, recreation, and fitness
- Logistics and distribution
- Perishable goods and cold storage
- Catering and food service
- Free-trade and custom-free zones
- Golf courses
- Factory outlets
- Personal and family services such as health and child care

Rapid commercial development at and around gateway airports is turning them into major urban growth generators as airport areas become significant employment, shopping, trading, and business destinations in their own right, and airports are developing a "brand image" to attract non–airport-linked businesses.

Attributes of Function and Form

The nature of the local market in terms of the industrial and commercial landscape always plays an important role in the development of the airport city and its activities. Airports that inherited limited developable land throughout the decades due to disorganized urban encroachment have compensated that with substantial airport-centered commercial development outside their fence. Moreover, as areas around airports attract business, professional workers, and residents more than other areas, commercial development in the airport district reflects the needs of employees, employers, and residents for incidental services offered by airport-centered businesses. These services include housing, recreation, food services, retail, health, child day care, and veterinary services. Indeed, urban research in the United States has shown that growth in employment near airports has been growing considerably and faster than the airport's other metropolitan suburbs. The needs for airport-centered business communities are now provided in large

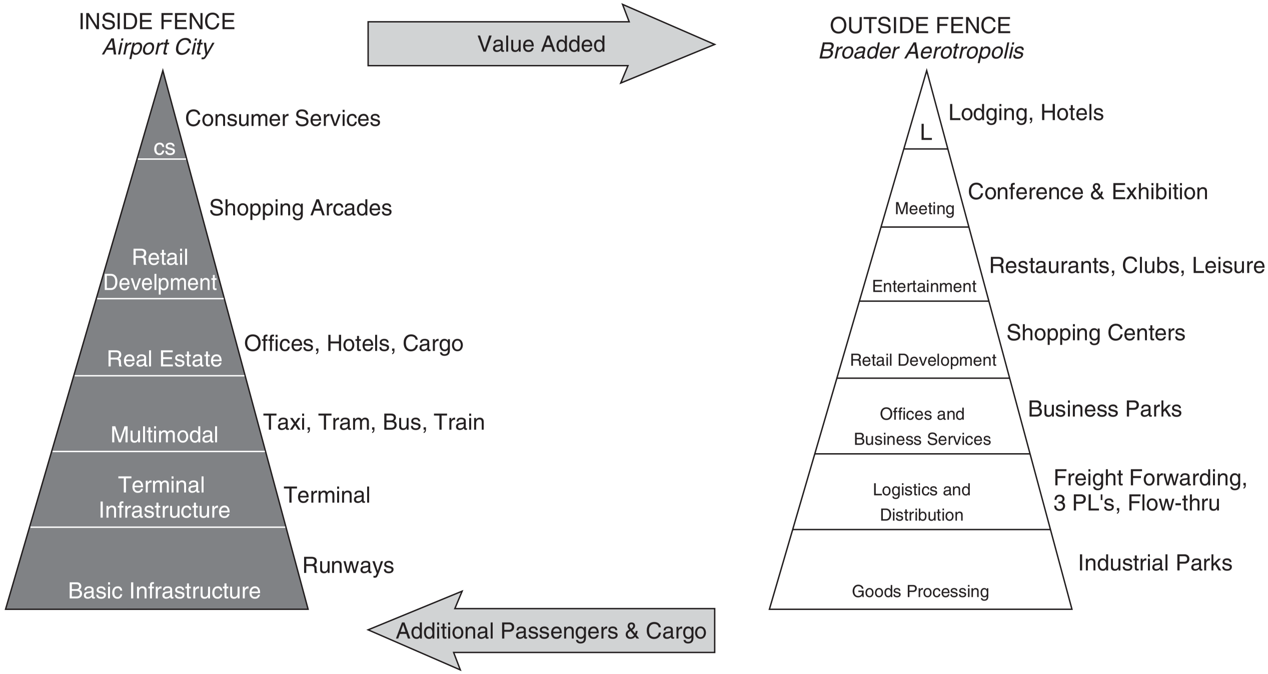

Figure 16.3 Typical airport city functions schematic, inside and outside airport boundary (3).

mixed-use development in the airport area, as metropolitan population growth centers. This shift requires the airport city functional development is based on creative planning models and different management attributes (3).

New Management and Planning Models

Airports are altering the operational management functions as their role shifts more towards non-aeronautical functions. Major airports around the world, including Paris (ADP), London (BAA), DFW, Frankfurt (FraPort), Schiphol, and Singapore, have actually established commercial real estate divisions to develop landside areas as well as fostering commercial development beyond their boundaries.

Through special operational financial structures and corporate ventures, airports are now evolving into complex multifunctional enterprises serving aeronautical needs as well as profitable commercial development under the airport city new business model. This enterprise model, which was not familiar just a decade or two ago, has become the norm for international airports in the twenty-first century.

New Operating Model. The airport city operating model is quite distinct from the more traditional civil engineering/aeronautical system airport operating model guided by public-sector principles. Its equally important commercial development role requires different strategies and operational skill sets driven by private-sector principles, fusing together innovative management, finance, marketing, and commercial development principles. In the airport city model, airports must do business the way businesses and corporations typically do business. This is a paradigm shift from the way airports were managed 20 years ago. In this new environment, parallel shift is therefore required in the way airport development is planned. Airport master plans are now focused on the layout of commercial entities and their efficiencies as well as on the aeronautical plans; ideally, both should be synergized.

Rise of Aerotropolis (3). With this innovative strategic approach, airports started to embrace the airport city model as an effective means of generating revenue to develop terminals and landside areas, as well as financing aeronautical functions and contributing to their profitability, competitiveness, and public satisfaction. In this shift, airports are undergoing significant transformation into commercial functions previously reserved for private enterprise, and spatial forms reserved for urban clusters. This transformation is bringing passenger terminals closer to commercial and cultural functionally, essentially resembling downtown central business districts (CBDs). This is particularly true when the airport is also a multimodal node on the transportation network with highway and rail connections. As a regional multimodal transportation and commercial nexus, strings of clusters of airport-linked business, logistics and industrial parks; information and communications technology complexes; retail, hotel, and entertainment centers; wholesale merchandise markets; and residential developments are forming along airport corridors up to 20 mi outward. Airport economic impact studies have measured impacts up to 60 mi away from the airport core infrastructure.

This dispersed and defused airport-centered development and airport–urban mass interdependencies are giving rise to a new urban design form—the aerotropolis, similar to the traditional metropolis. It is an urban form made up of an airport city core and extensive outlying development of aviation-oriented businesses and their associated residential developments. Corridor and cluster development of the aerotropolis reflects the new economy's demand for connectivity, speed, and agility that is optimized by corridor and cluster development, wide lanes, and fast movement. This urban form follows distinctive functions expressed as "aerolanes," the airport expressway, "aerotrain," and the airport express trains that bring cars, buses, taxis, trucks, and rail together with the airport infrastructure at the multimodal commercial core—the airport city.

Because of the advantages airports are providing in the fast-paced global network economy, the aerotropolis is becoming attractive to businesses, particularly those dealing in international business and trade. Most corporations and manufacturers today use advanced information technology, air transport, and high-speed transport systems to be efficiently connected globally for executing swift and agile communication on business transactions, trade, and manufacturing. Invariably, the business ability to meet such requirements would have to rely on a comprehensive and efficient ground–air shipping network of air cargo/express package carriers, trucking companies, freight forwarders, and logistics providers. As demand for time-sensitive manufacturing and distribution grows, so does this global network that, by its nature, is airport centric and therefore must be optimally located close to the airport. Such a global network provides manufacturers to minimize their inventories (just-in-time concept), shorten production cycle times, and quickly access novel inputs for custom products that create additional value.

Advanced High-Technology Convenience. Airport cities are becoming increasingly recognized as attractive locations for more than just global shipment networks. They are perceived as magnets for regional and international corporate headquarters, conference and exhibition centers, trade representative offices, and IT-intensive companies that require executives and staff to engage in frequent long-distance travel to conduct business. Business travelers benefit considerably from quick access to international hub airports offering greater choice of flight frequency, more worldwide destinations, and enhanced flexibility in flight rescheduling as needed. In particular, professionals from IT, telecommunication, and other high-technology industries tend to travel by air around four times more than others. In the United States, this fact is manifested by successful airport cities that are home to IT, telecom, and other high-technology corporations located next to airports known as active international hubs, for example, O'Hare, Washington Dulles, and DFW airports. This is yet another manifestation of the synergetic relationship between airports, airport cities, and high-technology industries and their reciprocal benefits. The high-technology corporate move to the airport city served as a catalyst to the move of other businesses seeking additional business and attracting a duet clientele of local high-technology and frequent-traveler customer base. For that, clusters of hotels; restaurants; retail; health, wellness, and fitness centers; entertainment facilities; and other incidental businesses have developed along the corridors of the airport city, hence creating thousands more local jobs. This healthy job market stimulates residential development and will definitely add more to the induced indirect economic impacts of the airport on the regional economy. This has fueled healthy competition for lucrative real estate development in the airport city with their respective metropolitan CBD—Dulles with Washington, D.C., center; O'Hare with Chicago Loop; and Atlanta-Hartsfield with Atlanta CBD; many more similar examples exist.

In terms of the international distribution of successful airport cities, while western airports conceived the concept (mainly, Amsterdam and DFW), it was the Asian airports that turned it into a successful universal phenomenon (mainly, Hong Kong, Singapore, Kuala Lumpur, and Seoul, and most recently Dubai).

Land Use Planning Needs. Most of the land use and infrastructure planning requirements for the aerotropolis have evolved ad hoc and spontaneously as part of the highway and municipal development planning regulations applied locally. With such random development underway, urban problems started to surface: traffic congestion, parking shortage, inefficiency of public transport, and safety concerns. What was required then was comprehensive and integrated localized infrastructure and urban planning of the airport city with enhanced connectivity, speed, modal compatibility, and agility. Implementing local and regional transport, urban and economic planning considerations to airport cities ensured they would grow according to a system of time-cost access gradients rather than spatial distance, and certainly are not ad hoc. Building appropriate multi-modal ground transit systems and locating commercial facilities consistent with the form and function of the Aerotropolis would contribute substantially to the emerging needs of business, more efficient cargo and passenger flows, and the future competitiveness of urban areas.

To meet this objective, it is in the interest of the airport that the master planning of the aerotropolis is conducted integrally and as part of the airport development plan. This effort requires that the airport work interactively and proactively with several stakeholders, including airport planners, urban and municipal planning agencies, government agencies, economic development commissions and chambers of commerce and industry, land developers, regional planning organizations, the business community in the vicinity, transport companies, local community groups, and environmentalists. This collaborative effort would bring in functional synergy, economic efficiency, collaborative development, and sound urban and transportation planning concepts, in addition to an aesthetically pleasing, socially acceptable, and environmentally sustainable airport city. But all recognizes that the airport city is still in the early stages of evolution. Proven and sound management and planning strategies must be adopted, not the ad hoc, spontaneous, and unplanned development.

Challenges and Shared Values. To ensure success of the airport city within its environment, it is important for planners and urban designers to consider potential challenges that may be facing the long-term existence of the airport city as well as some of the values shared between the major stakeholders in such an enterprise.

Air transportation and airports have matured as businesses. It is a challenge to position them more integrally within the society for them to be more compatible with their urban setting, and to ensure their congruence with their environment. The main challenges faced and critical issues to be considered include:

- *Synergy*. Develop the synergetic relation between the interest of the major stakeholders, namely, the region, city and local communities, airlines, and airport. A primary objective is to consider this to improve the position of the city and region to achieve the broader goal of sound international competitiveness.
- *Governance*. Involvement of all stakeholders to cooperate and organize development power and maintain public support. Developing airport corridors is intrinsically governmentally difficult, as it cuts through several jurisdictions in the city and region. It is therefore crucial for key stakeholders in government, the

business community, and public groups to share a common vision and participate actively in the development process.

- *Sustainability*. Although it is very difficult for an airport or an airport city to position itself as "green" and a "good neighbor," the challenge is to make it truly environmentally sustainable as society expects
- *Spatial Integration*. Airport cities are essentially spatial enclaves within a larger urban mass in the metropolitan area. It is particularly important for their success to ensure their proper integration in the urban setup and with seamless connectivity to the urban transportation network. To maintain public support, it is therefore crucial that this kind of development be connected physically and socially to its environment.

A broader and more strategic challenge is to instill collaboratively social values shared by the stakeholders in a meaningful and practical manner in the high-level planning of the airport city and airport corridors. Traditional planning instruments struggle with the challenges of developing airport cities and corridors. Seemingly contradictory development goals have to be addressed in a governmentally fragmented environment and in an environmentally responsible manner. However, attaining these goals may prove to be expensive, complicated, and in ways confusing to the different stakeholders. It is here that the "*shared-values*" concept can help airport planners and urban developers garner the local support needed to get the license to operate. Applying shared values would improve the economic and societal effects of the airport by improving the environmental performance and enhancing social acceptability. Porter (6) criticizes corporations and businesses that develop corporate social responsibility programs which are not integrated in the core business and are not compatible with environmental policies.

From a purely business perspective, corporate social responsibility is a costly constraint and more of a charitable deed with little long-term reward. The challenge here is to turn corporate social responsibility into a source of opportunity for innovation and a competitive advantage. It is argued, however, that for a sound long-term perspective both business and society must benefit from the choices offered. Improvement in sustainability is complicated and expensive and will never be achieved when it is not considered as part of the corporation's business plan.

Therefore, business decisions and social policies could harmoniously coexist by following the principle of shared value. In this respect, two elements of corporate responsibility are distinguished:

- *Responsive Corporate Responsibility.* Brings in good citizenship to mitigate the harm from value chain activities, such as noise, air quality, and congestion issues.
- *Strategic Corporate Responsibility.* To transform value chain activities in such a way that some benefit to society is accrued while reinforcing the company's strategy.

This is not an easy task to accomplish without creativity and being proactive towards corporate social responsibility.

16.5 AIRPORT CITIES OF THE WORLD

The airport city as a concept has proliferated around the world since the model prototype succeeded and gained recognition with pioneering airports in the three geographic regions (and generations): Amsterdam in Europe, Inchon in Asia, and the Gulf airports.

Europe

The primary hubs for the airlines' global alliances are all located in Western Europe. These major hubs, their respective global alliance, and owners are as follows: London-Heathrow—OneWorld (BAA), Frankfurt—StarAlliance (FraPort), Amsterdam—SkyTeam (Schiphol Group), and Paris—SkyTeam (ADP). The secondary hub airports in Europe include Vienna, Munich, Zurich, Madrid, and Istanbul.

Schiphol Airport has been the pioneer in adopting the airport city model and was very successful in this endeavor. Schiphol first implemented the brand name MainPort as a concept in the 1980s, serving as a major economic driver and magnet of airport-centric businesses and employment. It later branded its development scheme with its airport city. The Schiphol Centrum District, in synergy with the terminal, with its Schiphol Plaza, its World Trade Centre, and its CBD skyline, has become the most attractive business district in the entire Amsterdam metropolitan area. The airport has based its communication on the motto "Creating airport cities."

Today, this development, leader in European airport cities, is going on with the Amsterdam Airport Corridor (7). The progress of Schiphol Airport in adopting this concept since the 1980s is as follows:

1. *Airport*. Air transport infrastructure from 1920s to present.
2. *MainPort.* Engine for economic impact on the region from 1980s to present.
3. *Airport City*. Business model for aviation and non-aviation functions and businesses from 1990s to present.
4. *Airport City Corridor*. Positioning the airport in society and urban landscape.

Amsterdam Schiphol Airport does not function as any other airport—where passenger and freight change travel modes between land and air. It functions as the duo of a modern multimodal transport hub and a modern city of selective high-valued business, industry (logistics IT and services), and entertainment land uses. The progress of this transformation was natural and logical. At Schiphol, the conditions have been good for airport city development—space is available at the airport, it is located centrally in a densely populated metropolitan area, it is well connected to the road and rail urban networks, and it is recognized as part of an open economy. So, when it adopted "*creating airport cities*" as its motto, it was not too farfetched. The vision was that terminal, parking, retail, and real estate are spatially and conceptually integrated. Therefore, creating added value by developing the airport landside and supplementing that with commercial real estate would contribute to and enhance the airport role as a multimodal transportation node.

Historically, the vision started in the 1960s (Figure 16.4) with the development of Schiphol International Airport on the far southern part of the city of Amsterdam. In the 1980s the government initiated a program called MainPorts to enhance the Netherlands' stature in international trade that gave an impulse to the country's two major modal

Figure 16.4 Schiphol Airport between 1967 and 2005.

gateways–Port of Rotterdam and Schiphol Airport. Both were to be the cornerstones of the government strategy to improve the position of the country internationally, based on the historical role of the Netherlands as a nation of international trade, commerce and business and the strong international positions of both seaport and airport. In this context the local government and Schiphol Airport decided to cooperate more closely on the development of a logistic complex around the airport. A government commission (Bestuursforum Schiphol) and the Schiphol Area Development Company (SADC) were founded. The National Investment Bank was invited to participate, which established one of the first successful public–private partnerships (PPPs) in airport development. The area around the airport was planned to be developed under the airport city context and model. This development succeeded in attracting logistic facilities and head offices from Asia and North America to establish business and start operation. This organization still exists, but the emphasis on development around the airport shifted from logistics to services and from goods to people.

The proximity of Schiphol Airport to the city of Amsterdam had a significant advantage for urban economic development. The city of Amsterdam took the decision to develop a new business district at Zuidas, south of the city, only 6 km from Schiphol Airport along the ring road and the regional railway. The Zuidas development started small in the 1980s, but soon head offices of major companies and, from the 1990s onward, the financial and legal sectors moved to Zuidas benefiting from its ideal location. Indeed, the proximity of the airport and the central business district is ideal, and it was internationally unique at the time offering great opportunities for international trade, business, and technology development, and in turn, chances to improve the competitive stature of the airport, city, and region.

After World War II, Schiphol Airport was redeveloped, and development planning went through several cycles between 1967, 1980, and 2000. Both the airside and landside were developed and expanded to accommodate the huge increase in traffic at the airport, particularly its international operation. Figure 16.5 depicts the airport layout during the three periods showing its main runway configuration shifts. Recently, more emphasis was placed on the airport landside and groundside development in line with the plans set to develop and expand the Schiphol airport city. Airport terminal development has taken place in two areas of the airport: the airport central area and on the northwest side of the airport, as shown (Figure 16.6).

Amsterdam Schiphol Airport City Development. Amsterdam Schiphol Airport introduced and started implementing the airport city as a concept in 1998. In implementing the plan for the airport city, Schiphol developed a total of 600,000 m^2 of offices (operational and commercial) and almost one million square meters of industrial real estate at the airport:

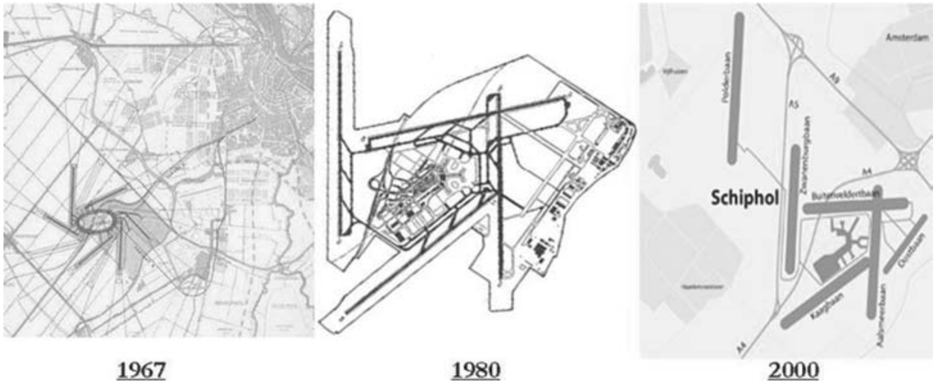

Figure 16.5 Schiphol Airport airfield plans between 1967 and 2005.

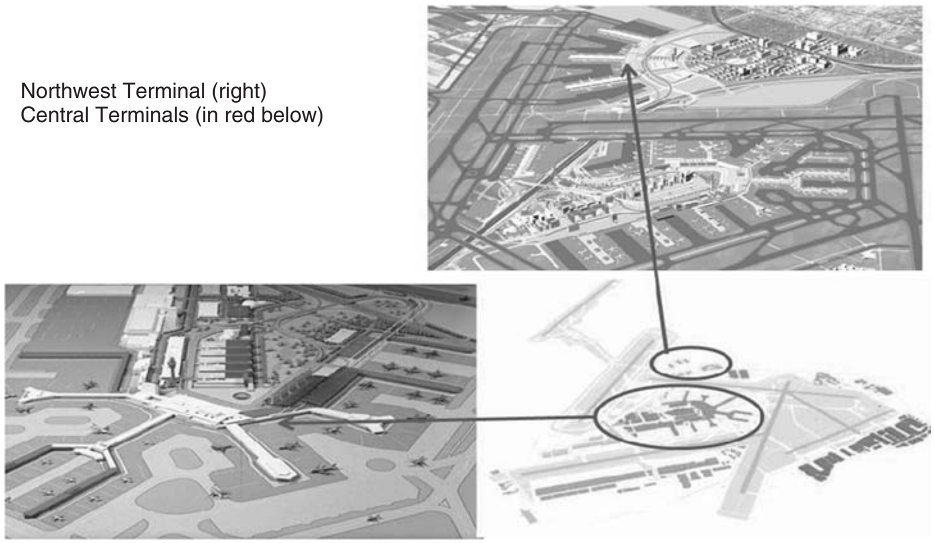

Figure 16.6 Schiphol Airport terminal development, 2020 (8).

- Airport Plaza. At the heart of the airport city and just outside the airport terminal area is Schiphol Plaza. The terminal and the railway station come together in Schiphol Plaza, where the transportation links connecting the airport to the multimodal regional network meet at and under a large covered square, served with multistory parking garages. Around the plaza are a shopping mall, the underground railway station, the food and beverage outlet, two hotels, a casino, and several communication centers. All this is directly adjacent to the terminal arrival and departure halls, where arriving passengers can easily use all the commercial facilities once they are out of passport and customs controls.
- Schiphol Centrum. Most value is created at Schiphol Centre, where the integration of activities withflows and spaces is optimum. The airport hotel, World Trade Centre, and parking are directly connected to Schiphol Plaza and the terminals via a covered passageway. Real estate connected to this passageway is considered part of the core of the airport city.
- Airport City Proper. Immediately outside the Schiphol Plaza lies the airport city proper with high-quality, carefully planned real estate and commercial development that includes the World Trade Center complex, business and commercial office buildings, and hotels. The airport city development eventually employed 60,000 people that worked at companies located at the airport, not counting off-airport developed land uses. Spatially, Schiphol as a “city” is defined as an urban cluster of areas comprising a “city center” and themed precincts. These include the Aerospace Exchange in Schiphol East (Figure 16.7), Schiphol Cargo World with truck, and rail terminals and logistics park in Schiphol Southeast (Figure 16.8), and the “grounds”—a concept for a knowledge cluster with universities, institutes, and private companies that is being developed around the

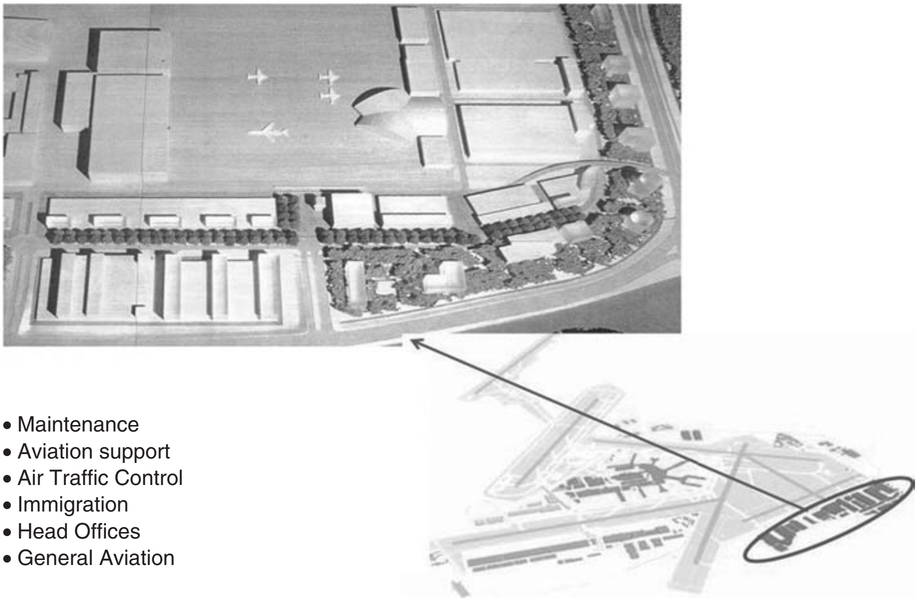

Figure 16.7 Schiphol East—maintenance and aerospace exchange (7).

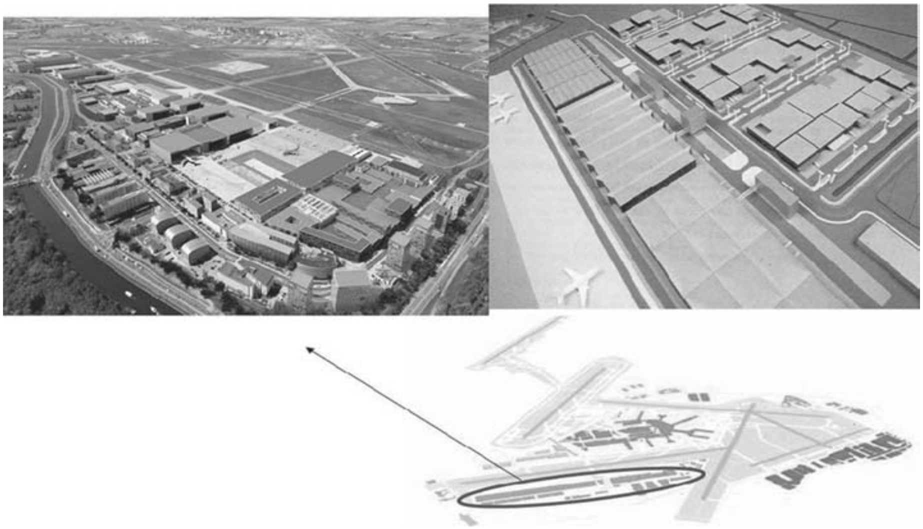

Figure 16.8 Schiphol Southeast—cargo world and logistics park (7).

themes of "sustainable airport" and "water management" located north of the airport. One of the pioneering concepts developed is the Eco Barrier to reduce aircraft noise from surrounding communities (Figure 16.9). Another precinct is the Elzenhof development in Schiphol Northeast (Figure 16.10), a mixed-use development with hotels and a golf course.

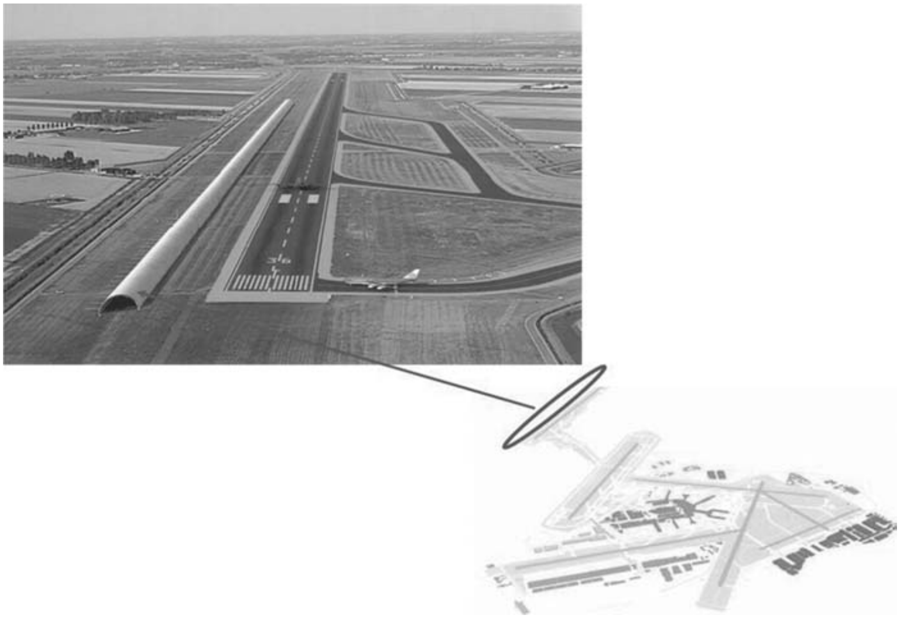

Figure 16.9 The "grounds" eco barrier (7).

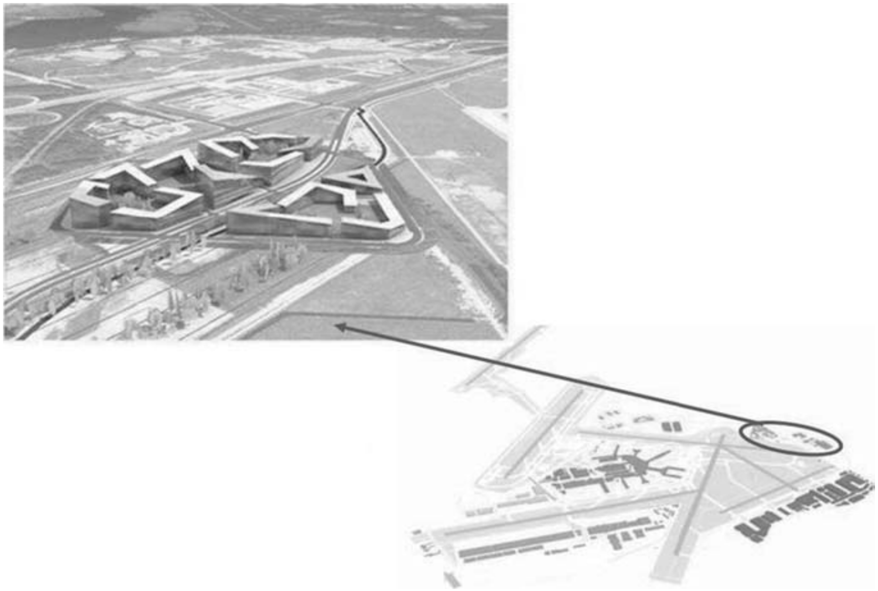

Figure 16.10 Schiphol Elzenhof Development with golf course and hotel (7).

Amsterdam Airport Corridor (Schiphol-Zuidas). Beyond the airport city, the next step in the Schiphol Group plan was to consider the potential of spatially connecting and functionally integrating Zuidas (the Amsterdam suburb) and the Schiphol airport city within the urban landscape and transportation nodes. Both urban nodes actually serve the same market of the high-yield business traveler, of crucial importance for the city, airport, and airlines as well as international technology and trade corporations. It was therefore ideal to develop the corridor between both nodes of urban development with an international focus, where SADC offered the governance structure necessary for a coordinated development along the airport corridors—the airport city corridor was created.

Today, the Amsterdam airport corridor can distinguish itself as a critical component of the concept of a unique accessibility profile, with seamless traffic flows serving the airport city. Figure 16.11 depicts the airport corridor within the Amsterdam metropolitan area. Figure 16.12 provides the long-term urban development context centered around the airport city and airport corridor.

Schiphol Shared-Value Principles. Bestuursforum Schiphol, SADC, and their participation in the development of the Schiphol-Zuidas airport corridor follow the adoption of the shared-values principles in planning. The airport is actively participating with government authorities in the economic development as a step toward increasing the influence of the airport in the entire metropolitan area. This strategic partnership aims at improving the competitive position of the airport city region as an optimum location for business, culture, international trade, sports, events, and so on. The goal of this strategic partnership is: (a) directly to generate more traffic at the airport, and, (b) to create more commercial and economic opportunities for real estate and consumers for airport-centered businesses.

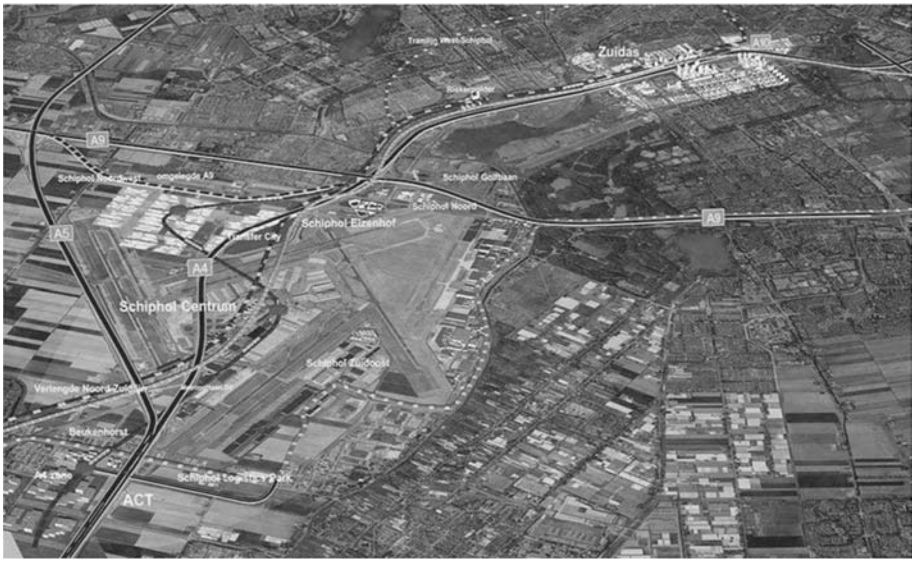

Figure 16.11 Schiphol Airport City and Airport Corridor. (7).

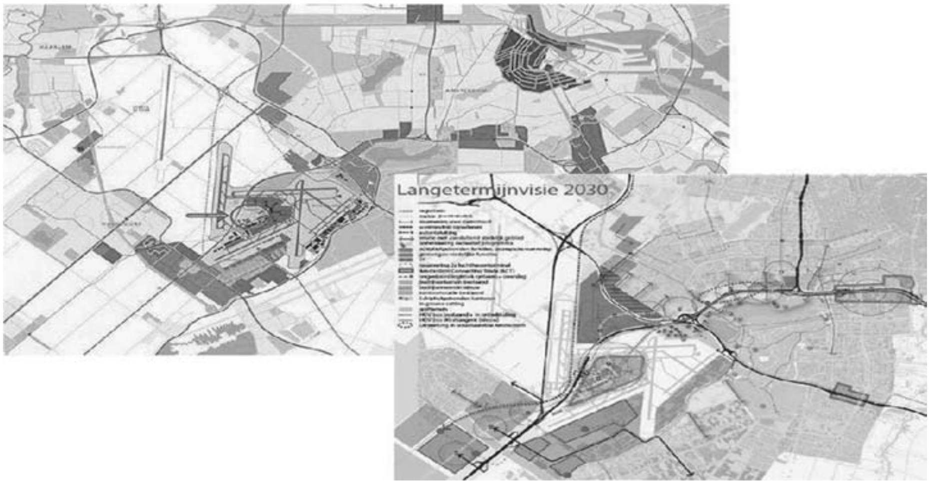

Figure 16.12 Metropolitan Amsterdam Long-term urban development centered around Schiphol Airport city/corridor (7).

Since these objectives may not address social or environmental issues, Schiphol included social and environmental initiatives in the development planning framework, including:

- Knowledge Clusters. In teaming up with universities, research centers, knowledge institutions, and private companies, Schiphol is investing in development that focuses on the innovative power necessary to prove the airport's environmental sustainability. In a shared-values approach, communities around the airport might be more directly involved in initiatives to develop recreational amenities of all kinds. One such example that Schiphol introduced is "GROUNDS"—a creative environmental object that acts as sound barrier against "ground noise" generated by aircraft on the airport grounds. This concept can be used as an "open-source" approach to sustainability. Schiphol's objective in adopting these concepts is to encourage these parties to locate parts of their organization at the airport and so work together on solutions that further environmental benefits to society. These concepts and their respective benefits can be applied to other airports worldwide as well as to municipalities and cities.

- Schiphol College. Amsterdam metropolitan municipalities and Schiphol are working collaboratively to provide educational programs to communities with predominantly lower class and immigrant population to assist in technical jobs placement at the airport. With this shared-values approach, interpreted as a shared-interests approach, the airport works proactively on a critical issue facing all airports—airport operation training and the engagement of local communities. In this way, providing trained workers to the traditional airport operation and business can be approached differently with benefits shared by all, and new business at the airport is generated in a better relationship with society.

Economics of Airport City. The strength of the airport city concept, which is inseparably linked to non-aviation, airport-centered activities, can be measured by the operating income it succeeds in generating. This success is reflected by the fact that 77% of the Schiphol Group's operating income in 2007 came from non-aviation revenue, with an overall annual percentage increase of 33% on operating results. More specifically, the return on net assets (RONA) for non-aviation business areas was 9.1% in 2005 and 11.6% in 2007, which indicates steady growth. On the other hand, aviation business areas indicated RONA was 41% in 2005 but declined to 29% in 2007 (8), while total annual investment was higher (55%) than non-business areas during the same period.

Sharing the Experience Globally. The Schiphol Group started to take opportunities worldwide as part of its core business. Successful partnerships were pursued worldwide building on its experience and management expertise in developing airports with the PPP model and the airport city. Some examples of these partnerships are:

Airport operation management of:

- Stockholm Arlanda Airport, Sweden
- Guangzhou Baiyun International Airport, China
- Sukarno-Hatta International Airport, Jakarta, Indonesia

Commercial airport development using the airport city model to develop and manage airport facilities at:

- JFK terminal 4, New York, with 40% stake
- Brisbane International Airport, Brisbane, Australia, with 18.7% stake
- Reina Beatrix Airport, Aruba

With the acclaim and stature achieved thus far in pioneering the airport city concept, the Schiphol Group is now looking ahead to more lofty goals, including:

- Caring equally for people and the environment
- Connecting people with organizations
- Teaching, learning, and technology development
- Innovation, discovery, and institutional research
- Marketing the Schiphol brand and the Dutch style
- Demonstrating openness and transparency to stakeholders
- Fine-tuning the economic engine
- Creating jobs for its community, the region, and the nation
- Collaborating with government and corporations to further the successful PPP model
- Maintaining the legacy of pioneering innovation and creating opportunities

North America

Several airports adopted the airport city concept on the other side of the Atlantic, particularly those functioning as hubs for the global airline alliances. These major hubs, their respective global alliances, and owner are: DFW—OneWorld (DFWIA), Chicago O'Hare—OneWorld (City of Chicago), Washington Dulles—StarAlliance (MWAA), and Atlanta-Hartsfield—SkyTeam (City of Atlanta), and on the West Coast, the major hubs include San Francisco and Los Angeles. North American secondary hub airports include Charlotte, Pittsburgh, Miami, Newark, Denver, Detroit, Toronto, Houston, and Salt Lake City.

The leading airport adopting the airport city model in North America is Dallas Fort Worth International Airport. This was the first new-generation airport planned and developed in the United States after Word War II; other new-generation airports are Washington-Dulles (1962), Atlanta-Hartsfield (1982), and Denver (1995).

The plan for Dallas Forth Worth 'regional airport' was conceived in the 1960s with innovative concepts and methods used in its planning, design, construction, and finally commissioning in 1969. According to its environmental impact statement (EIS) (9):

> The primary purpose of the Dallas-Fort Worth Regional Airport project is to provide an adequate facility to accommodate the ultimate air transportation demand of the two cities, and the eleven surrounding counties that constitute their tributary market-base region. The airport will also serve as a new international port-of-entry to the United States.

DFW had the hallmark of a mega international airport serving a sizable hinterland in North Texas. Total airport area is 17,250 acres, it has six instrument runways and a 250-gate passenger terminal complex formed of five dual-semicircular buildings with a spinal urban freeway running through their center, and it was one of the first to use a people-mover system (Sky Train) to connect the functional nodes of the landside with the terminal complex. In addition to airport acreage dedicated to aeronautical activities, the airport negotiated 1800 acres of compatible land use zoning with the municipalities at its periphery.

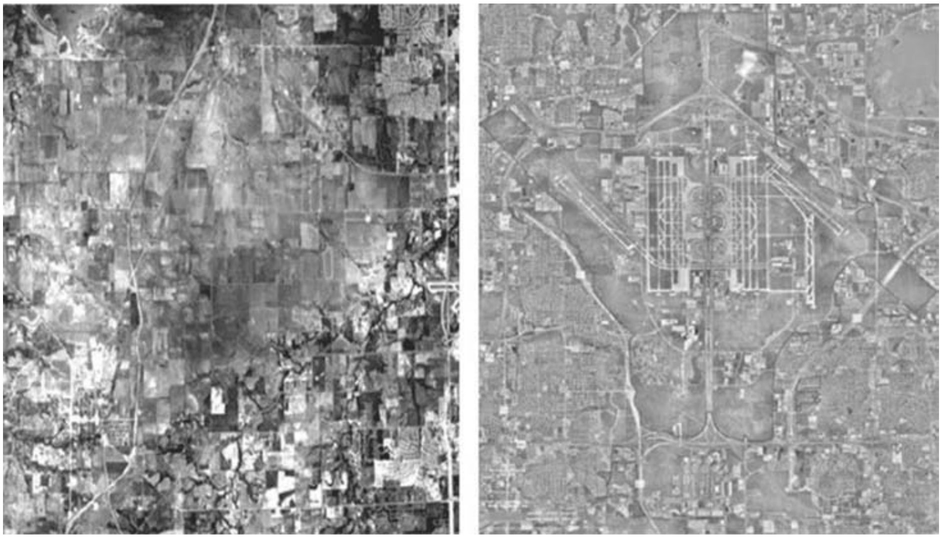

Figure 16.13 (a) Dallas–Fort Worth region and (b) DFW Airport 40 years later (10).

Forty years later, DFW still bears the traits of its founding planners. Figure 16.13 depicts the change in the region in four decades. Today, DFW is operated in many ways like a small city, with its own post office zip code and its own official city designation—DFW Airport, Texas 75261. It has local government status, where the members of the airport's board of directors are appointed by the "owner cities" of Dallas and Fort Worth and the cities of Irving, Euless, Grapevine, and Coppell of North Texas. As shown in Figure 16.14, the airport itself is inside the city limits of the four local jurisdictions, a situation that was legally challenging over jurisdiction but proved to be a blessing in disguise! The airport serves the entire metropolitan area of North Texas—aka the 'Metroplex'. Encompassing 12 counties in the State of Texas, the Metroplex is the term given by the U.S. Census Bureau to the DFW–Arlington metropolitan area since 2003.

The Metroplex population in 2009 was close to 6.5 million, the fourth largest in the United States, and is growing at the highest rate of any metropolitan area in the United States (10). The entire Metroplex has experienced a 200% population increase during these four decades, during which the communities of DFW have nearly tripled. The Metroplex is comprised of a total area 9286 mi^2 (24,100 km^2)—the largest in Texas and the fourth largest in the United States. In terms of total economic product, the Metroplex is the sixth largest in terms of gross metropolitan product (GMP) in the United States and the tenth largest in the world. DFW International Airport is the second busiest in the United States and third busiest in the world, with the second largest area in the United States and the third in the world.

In terms of economic impact, DFW is the primary economic engine in its region, which extends far beyond its fence, employing 305,000 with a total payroll of \$7.6 billion and a total economic impact of \$16.6 billion. With such a portfolio, DFW updated its land use plan in 2007 to ensure the airport's continued success in providing a cohesive, global, and cost-effective approach to the industrial, commercial, and urban

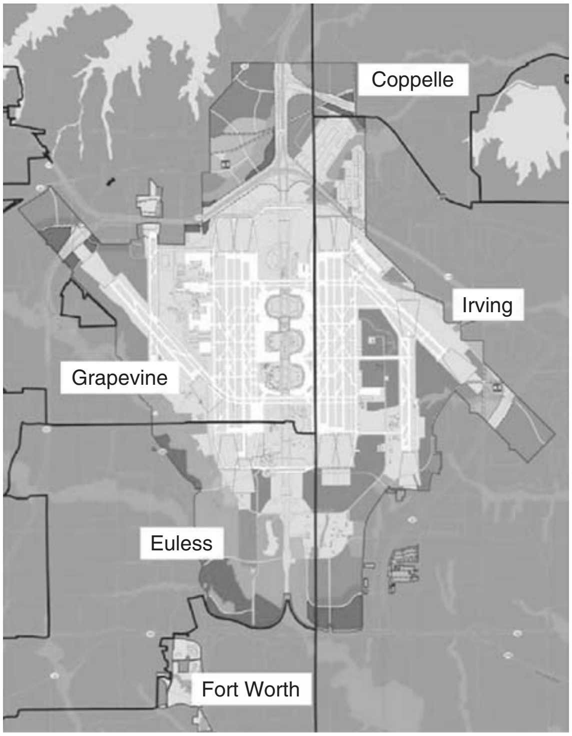

Figure 16.14 DFW airport and its local jurisdictions (10).

development outside its boundaries. DFW has been in the integrated commercial and urban development business since its inception, and it continues to have one of the United States's and indeed the world's most ambitious airport commercial development programs.

On-Airport Commercial Development. With its large acreage and within its own boundaries, the DFW International Airport Land Use Plan included several developments of commerce, entertainment and business. The long-term DFW Land Use Plan envisages more than 5200 acres of multiple mixed-use developments (see Figure 16.15) that would complement DFW's stature as an international transportation hub on a global scale, including (10):

- *International Commerce Park* (Figure 16.16)—428 acres of industrial and warehousing campus located within the foreign (free) trade zone that provides international opportunities in trade import/export focusing on aviation parts distribution, aviation cargo, and logistics industries. It was developed in 2001 as a logistics center that would attract tenants reliant upon DFW's cargo warehouse distribution centers.
- *Passport Park* is a long-term mixed-use development that offers unmatched opportunities for prime real estate development located on approximately 600 acres at the southern end of the airport and easily accessible from the regional highway network.

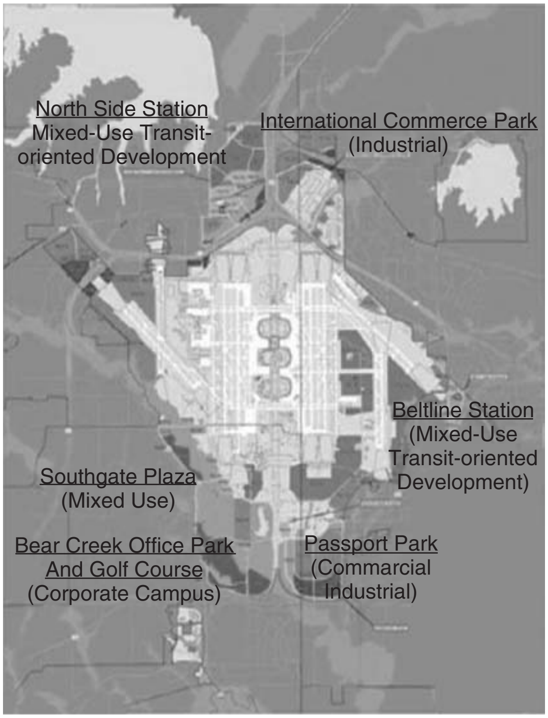

Figure 16.15 DFW Airport land use plan developments (10).

- *DFW Foreign Trade Center* (155,000 ft^2)
- *DFW Logistics & Distribution Center* (500,000 ft^2)
- *Bear Creek Office Park and Golf Club* is a scenic 1800-acre land accommodating a spacious corporate office park campus overlooking grounds of award-winning Bear Creek Golf Course in a rolling, wooded setting with ample green space.
- *DFW Convention Center* is located at two on-site fivestar hotels.
- *Beltline Station* (Figure 16.17) is a 23.5-acre transit-oriented development that will eventually incorporate a Dallas Area Rapid Transit (DART) rail line station.
- *North Side Station* is a mixed-use transit-oriented development that will eventually incorporate another DART rail station.
- *Southgate Plaza* (Figure 16.18) is located at a major highway interchange where more than 90,000 daily airport passengers and traveling public use the transport network. It covers 33 acres of mixed-use development focusing on "destination" commercial, retail, and office development with a pedestrian-oriented design.

On-Airport Oil and Gas Production (10). Under DFW lies the Barnett Shale—one of the largest shale-gas deposits in Texas that may have the largest producible reserves of any on-shore natural gas field in the United States. Recent technological advances in hydraulic fracturing technology and horizontal drilling since 2007 made it economical to mine shale and extract natural gas.

Figure 16.16 DFW Airport International Commerce Park (10).

This unorthodox airport revenue will undoubtedly generate additional income into the coffers of DFW. Exploration in DFW has progressed under this lease, and drilling commenced after confirming there would be no adverse impacts on airport operations or on public safety and the environment. DFW has secured the single largest natural gas lease in all of Texas. On-airport natural gas drilling is expected to last at least

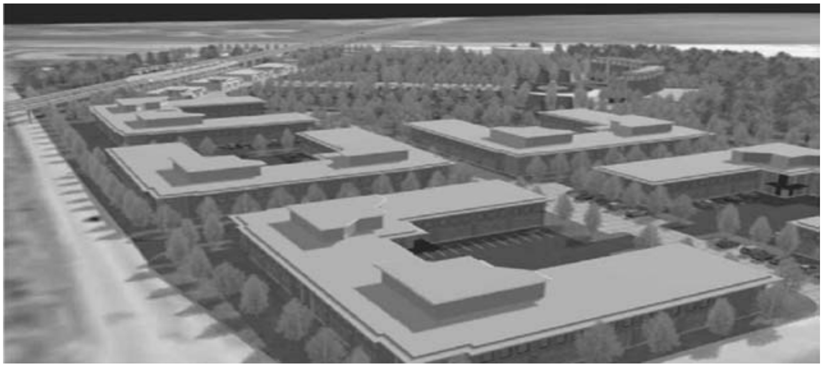

Figure 16.17 Rendering of Beltline Station (10).

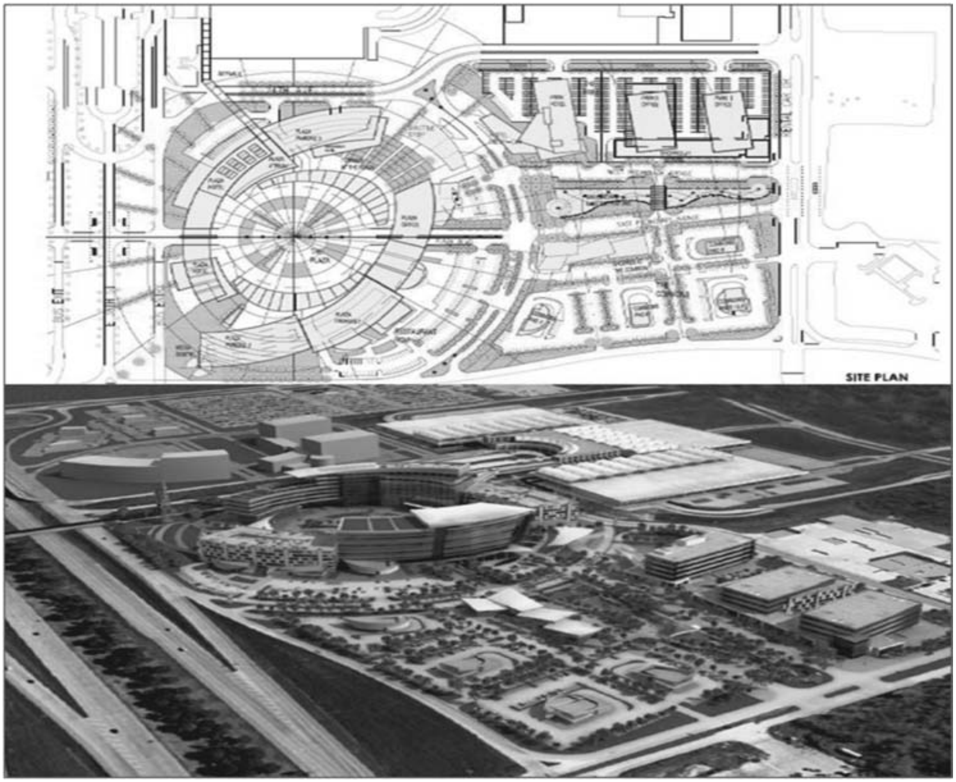

Figure 16.18 Plan and rendering of Southgate Plaza (10).

10 years and it will support economic development activities in the entire North Texas region. For DFW, the natural gas revenue will be used for on-airport capital projects and the reduction of airport debt and costs to airlines.

The DFW Airport corridor includes such activity centers as the Dallas Trade Mart, the Dallas Medical District, Texas Football Stadium, the Trinity River (with an environmental and water management project), Dallas Love Field [an active low-cost carrier (LCC) airport], and the University of Dallas and Texas–Arlington.

Off-Airport Commercial Development. The extended airport city associated outside DFW's boundaries is Las Colinas, a developed area in the Dallas suburb of Irving. Due to its central location between the cities of Dallas and Fort Worth and its proximity to DFW, Las Colinas has been a viable place in the Metroplex attractive for corporate and business relocation. As a planned community, it is synonymous with corporate offices, luxury hotels, landmark office towers on shining lakes, private country clubs, gated executive enclaves, and urban lofts.

Las Colinas was developed in 1972, when DFW started operations, as part of the specially zoned compatible land use development the airport negotiated with the neighboring municipality, the City of Irvine. As one of the first planned communities developed in the United States, Las Colinas was once the largest mixed-use development in the Southwest United States. Urban planners designed the entire town, and in the 1980s building boom, Las Colinas became a popular location for relocating companies and office developers, attracting many corporations, including the global headquarters and regional offices of major Fortune 500 companies. In 1985, financial trouble hit Las Colinas due to real estate market crash, but it made a remarkable comeback immediately afterward. In the boom of the late 1990s, 6,500,000 ft^2 (604,000 m^2) of prime office space was built, and residential real estate prices rebounded and have been rising steadily ever since.

By the end of the first decade of the twenty-first century, Las Colinas is a prestigious planned community housing business and residence, which contains high-rise office towers, retail centers, upscale residences, apartment complexes, and leisure facilities and is currently home to more than 2000 corporations and hi-technology companies, occupying 22,300,000 ft^2 (2,070,000 m^2) of office space, of which 1.3 million ft^2 (121,000 m^2) is for retail.

Las Colinas also features three private country clubs and four championship golf courses surrounded by prestigious gated residential communities built along tree-lined fairways and large and undulating greens and around lakes, creeks, and ponds. The residential part of Las Colinas includes 3400 single-family homes served by two independent school districts. A 40-acre (160,000-m^2) tract in Las Colinas has been developed for a major regional convention center.

In terms of transportation, Las Colinas is served by a 13-city regional transit system, DART, with an integrated bus and transit system providing direct bus and rail service to DFW Airport and Dallas CBD. More importantly, Las Colinas is served by the APT system, a unique people mover system linking businesses and entertainment areas of the Las Colinas urban center.

In summary, the Las Colinas fact sheet reads as follows:

Development. More than 2.3 million m^2 of office space, 4220 hotel rooms, 4630 single-family homes, and 13,900 multifamily homes.

Corporate Presence. More than 2000 companies, including more than 45 Fortune 500 companies, and 4 Fortune 500 global corporate headquarters.

Amenities. Four championship golf courses and three private country clubs, among other attractions.

Demographics. Employment of more than 120,000 and 38,000 residents.

Asia

The major airports in Asia have adopted the airport city concept and incorporating it in their long-term plans. Emerging Asian airport cities bring a new definition to the flying experience. Passenger terminals are turning into shopping havens with items from electronics and household items to consumables. Hotels, offices, conference and exhibition facilities, free zones, and logistics facilities are all becoming essential components of the airport. Beyond the airport city, more growth becomes visible with industrial, logistics, and business parks; IT complexes; retail and entertainment centers; and residential and sports complexes. As with pioneering airports before them, the aerotropolis has become the new urban form for Asian airports (11).

One only needs to take a quick tour of emerging markets to have a better view of this construction boom (11). The airport city at Beijing Capital International Airport, worth \$12 billion, aims to handle 80 million passengers in 2015. Hong Kong International Airport (HKIA), an aerotropolis that cost \$20 billion to build, offers a quadra-modal transportation system (air, highway, rail, and sea) to millions of airport users. Kuala Lumpur International Airport (KLIA), which cost \$4 billion to build, is providing the "'aviation foundation" for the Multimedia Super Corridor (MSC), which integrates two cities, Putrajaya—the relocated government capital—and Cyberjaya, or Cyber City. But the airport that provides comprehensive integration of the airport city principle with airport long-term development is South Korea's new Incheon International Airport and international free enterprise zone. The Inchon development plan brought about a new term to this field—*PentaPort*, a combined air–sea–land port with integrated business–telecom–leisure development.

Seoul-Inchon International Airport (12). Seoul-Inchon International Airport is located 70 km (43 mi) from Seoul, the capital and largest city of South Korea. The airport is currently Asia's eighth busiest airport in terms of passengers, the world's fifth in terms of cargo and freight, and the world's eleventh in terms of international passengers in 2006. In 2009, Inchon International Airport became the world's third in air cargo and was voted as the best airport overall. The airport features many luxury facilities unique to airports, including a golf course, spa, private sleeping rooms, a casino, indoor tropical gardens, and most notably a national museum—Museum of Korean Culture.

The airport is built on reclaimed land between two islands west of Seoul: Yeongjong and Youngyu. Figure 16.19 depicts the airport region, the transportation network, and the important features of the airport site. The entire development of the airport took more than eight years, with an additional six months to test and operate (ORAT). The airport master plan was approved in early 1992, design followed, and by end of 1992 phase I of construction and site preparation started. The airport passenger terminal construction started in May 1996, and runway construction began later in June. In June 2000, the construction of the airport basic components was completed, and the airport

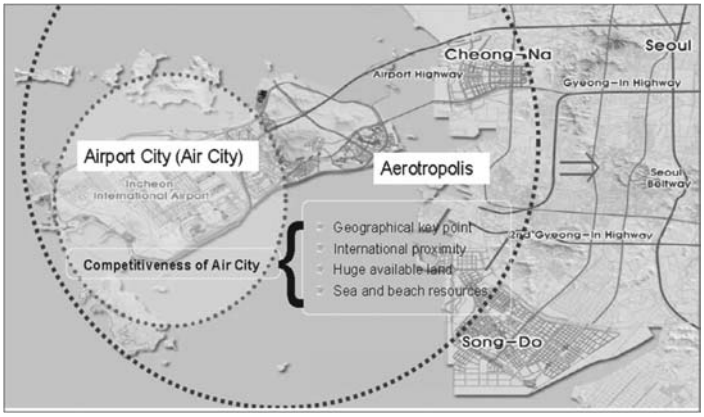

Figure 16.19 Inchon International Airport region and transport network (12).

was officially opened in March 2001. Phase I could accommodate 40 million annual passengers and 2.5 metric tons of cargo. Figure 16.20 depicts the Inchon International Airport airfield and the runways, and Figure 16.21 depicts the airport terminal area.

Later, in March 2007, the airport railroad station opened, and in June 2008, phase II of the airport construction was completed. Development of the airport will continue in the future with phase III by 2015 to bring capacity to 62 million annual passengers and 5.8 million metric tons of cargo, and ultimately phase IV by 2020 with a total capacity of 100 million annual passengers and 7 million metric tons of cargo.

The master development plan for Inchon Airport incorporated the diverse development (aeronautical and non-aeronautical) in phases. It also adopted a three-pronged developed plan for the airport city that relied on three non-aeronautical function hubs: leisure, logistics, and business located around the airport at the core providing the aeronautical infrastructure, as shown in Figure 16.22. Parallel to the aeronautical development indicated above, the "air city" is developed in three phases: Phase I is the

Figure 16.20 Inchon International Airport plan showing terminal area and runways (12).

Figure 16.21 Inchon International Airport terminal area (12).

airport support community consisting of airport-related industries (primarily logistics) commercial services, and a town of 100,000 population housing for airport employees. Phase II involves expanding the airport support community (functionally and spatially) and transforming it into the international business center (IBC) comprising a 360-acre commercial multiuse development in four clusters and a 220-acre airport free zone. Both parts are planned to be doubled in size in five years. Phase III is a complete aerotropolis with an extended international free enterprise zone.

As depicted in Figure 16.22, Inchon's airport city includes:

1. *Leisure Hub*. As shown in Figure 16.23, Inchons's leisure hub, or as commercially known Dream World, is composed of six clusters as follows:

(a) Fashion Island, a French–Korean joint enterprise built on an 180-acre site at a cost of $1 billion (see Figure 16.24). It will be comprised of a fashion convention center, fashion academy and design school, and a shopping

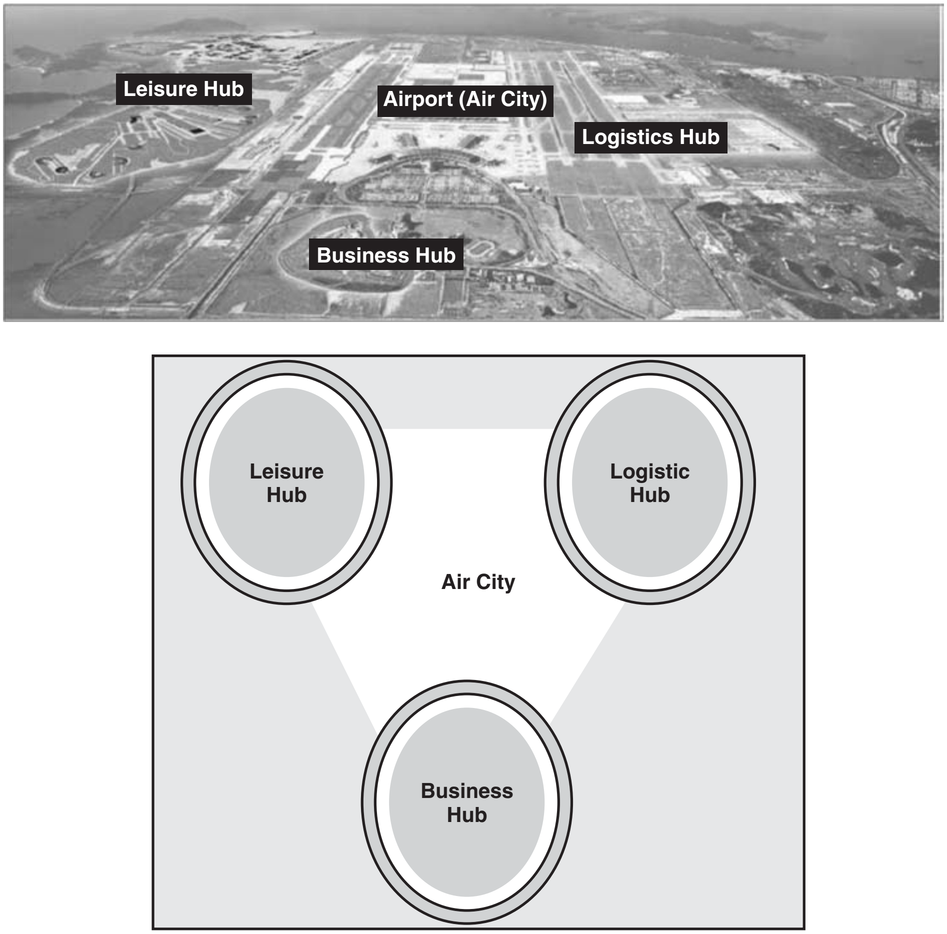

Figure 16.22 Inchon International Airport development components (12)

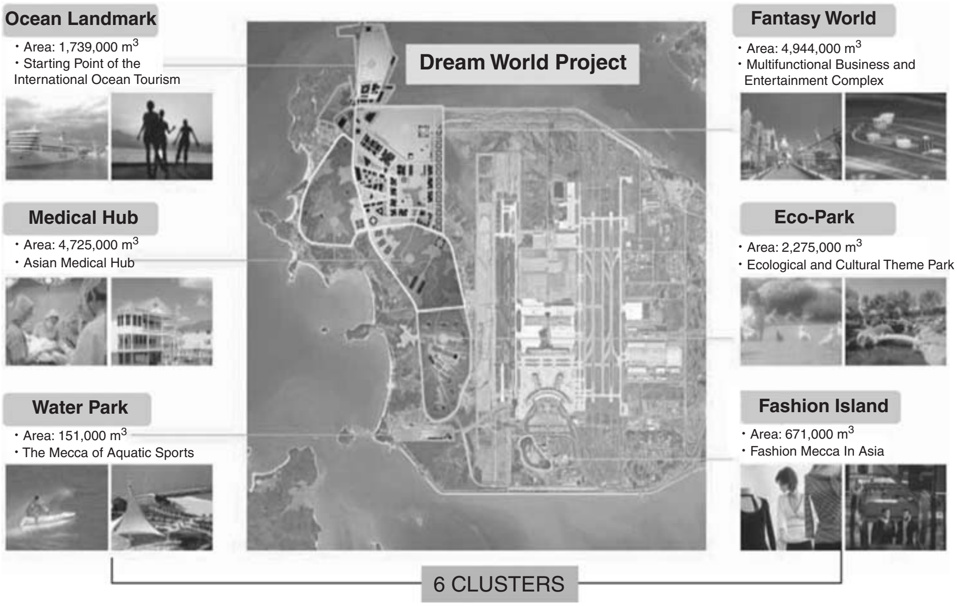

Figure 16.23 Dream World in the leisure hub (12).

Figure 16.24 Fashion Island (12).

mall with suitable supporting facilities totaling 671,000 m^2 for a world-class fashion hub.

(b) Fantasy World, a 4.5 million -m^2 multifunction business and entertainment complex.

(c) Ocean Landmark, a 1.75 million -m^2 complex for international ocean tourism.
(d) Medical complex of 4.75 million m^2 housing an international medical center and related facilities.
(e) Water park for aquatic sports on million m^2.
(f) Eco-Park, an ecological and cultural village with a theme park occupying 2.25 million m^2.

2. *Business Hub*. It includes:

(a) Free-trade zone
(b) IBC for tourism and trade that includes convention and exhibition centers, hotels, and related amenities
(c) Commercial areas, including shopping malls, leisure facilities, a casino, and sporting facilities

3. *Logistics Hub*. Figure 16.25 shows the components of Inchon's logistics hub, current and future, including:

(a) LogisPark, a 1-km^2 logistics center that would be expanded by 40%
(b) Airport cargo terminal, with phase I providing 1.1 km^2 space and phase II another 1.1 km^2
(c) Aviation Town: Phase I (1.7 km^2) and phase II (1.1 km^2)
(d) IBT Valley: Phase I (1.3 km^2) and phase II (1.5 km^2)

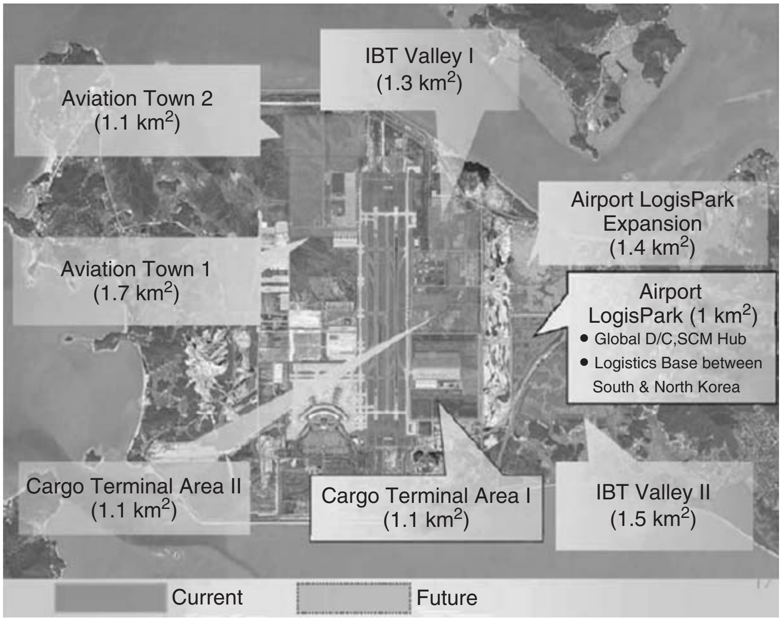

Figure 16.25 Logistics hub component and phasing (12).

Inchon's Air Transportation Center is connected to the capital and other cities via three expressway-standard airport access roads and a rail line with an airport railway station, as shown in Figure 16.19. In the future, other transit systems will include a low-speed maglev rail link.

The Gulf

From fishing villages in the eighteenth century, to pearl-diving centers in the nineteenth century, to major seaports and trading centers in the twentieth century, to major financial, business, urban development centers and air transportation hubs during the first decade of the twenty-first century, the cities of the United Arab Emirates (UAE) and Qatar are writing a new chapter in aviation-centered economic development.

In particular, the phenomenal growth of Dubai in general and its tourism, air transportation, and hospitality industries in particular, presents a model to explore in implementing the airport city concept. Dubai and the UAE came to assert this country's popularity as a preferred year-round business, tourism, and leisure destination with the following characteristics (13):

- Strategic location between east and west
- Political and economic stability
- Extensive foreign trade network
- World-class tourism facilities and business destination.
- High quality of life, with superb and excellent living conditions
- Highly developed transport infrastructure
- Safe and friendly environment
- Variety of natural assets and attractions
- Sophisticated financial and service centers
- Top-notch international convention and exhibition venue
- State-of-the-art telecommunication and services

The UAE's GDP reached $200 billion in 2008 with a diverse economy: crude oil 35%, manufacturing 13%, trade 11%, building and construction 8%, real estate 8%, government services 7%, transport and telecom 6%, with other sectors of the economy the remaining 12%.

The Dubai International Airport (DXB) has been showing very impressive growth to accommodate the significant economic growth. During 2007, it handled more than 34 million passengers at 19% rate of annual growth, more than 17 million tons of cargo at 11% rate, and more than 260,000 aircraft movements at a rate of 10% growth, with an annual income of $712 million from its duty-free sector at a rate of increase of 20%. Based on ACI statistics, Dubai International Airport ranked 27th in the world in passengers, 13th in air cargo, and 7th in international aircraft movements in that year.

However, despite the airport's aggressive and phenomenal growth and the large capital development program to ensure that it will continue to satisfy the future demand at such high growth rates, Dubai envisaged that another airport must be developed to maintain the growth. The new airport would implement creative measures to integrate the airport city concept in its plans. Dubai International Airport is essentially landlocked, as seen in the airport plan in Figure 16.26. Even with the large capital

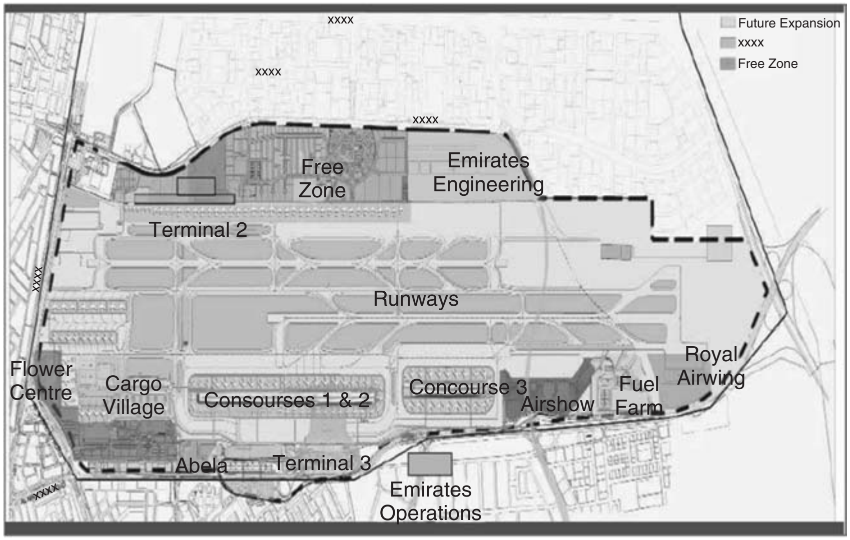

Figure 16.26 Airport layout of Dubai International Airport (13).

Figure 16.27 Concourses 2 and 3 of Dubai International Airport (13).

development program of $4.5 billion expansion of the airport landside that included construction of Terminal 3 which is composed of the new Concourses 2 and 3 (Figure 16.27), the airport would still be unable to support extensive non-aeronautical activities as those of the airport city.

To demonstrate the capacity constraints and the lack of space for future development at the airport, Terminal 3 is designed to expand the airport's capacity within the current airport area. This expansion is a multilevel underground structure and as follows:

Total built-up area for departures is 515,000 m^2 on 6 floors with 168 check-in counters and 60 self-serve kiosks, 48 departure passport counters and 16 e-gates, 3 airline passenger lounges, 4800 m^2 of 3 duty free public shops, and 2000 m^2 food court. Concourse 2 is 924 m long and 670000 m^2 built up area over 10 floors (4 underground) with 26 contact gates with 59 loading bridges (including 5 A380 gates) plus 14 remote stands. For arrivals, there are 52 arrival passport counters and 12 e-gates, 18 baggage-claim devices that are actually located 20 m below the apron and taxiways! Three 4/5 star hotels are integrated within Terminal 3.

The Dubai government initiated the development of the second airport at Jebel Ali within a 140 sq km multi-phase development. The selected site is remarkable in that it was actually an exercise of major urban design and development, as well as a long-term development plan for a new airport that will ultimately be one of the largest in the world by mid-2020 with a total capacity of 160 million passengers and 12 million tons of air cargo per year.

It is Dubai World Central (DWC) located on the southern outskirts of the Dubai metropolitan area at a distance of 40 km from DXB airport across Dubai Metro and 10 km east from Jebel Ali Seaport, one of the world's best managed seaports, and the Jebel Ali Seaport Free Trade Zone (JAFZA). Figure 16.28 portrays the metropolitan positioning of the three primary transportation hubs in the metropolitan area: DXB, the new Jebel Ali al-Maktoum International Airport (JXB), as part of the DWC block, and JAFZA. The location of the new DWC development within the metropolis is clear. Also clear is the difference of the area between DXB (only 14 km^2) and DWC with JXB at its heart (140 km^2).

DWC's urban design concept reflects the development of the new sprawling airport at the center of and spatially integrated with six "precincts" of different functions surrounding it, including Logistics City, Commercial City, Residential City, Aviation City, and Golf City. Figure 16.29 depicts the ultimate development plan for JXB.

Phase I of the airport was inaugurated in June 2010 with one 4.5 km runway, 5 million passengers per annum terminal, and 250,000 tons per annum air cargo terminal.

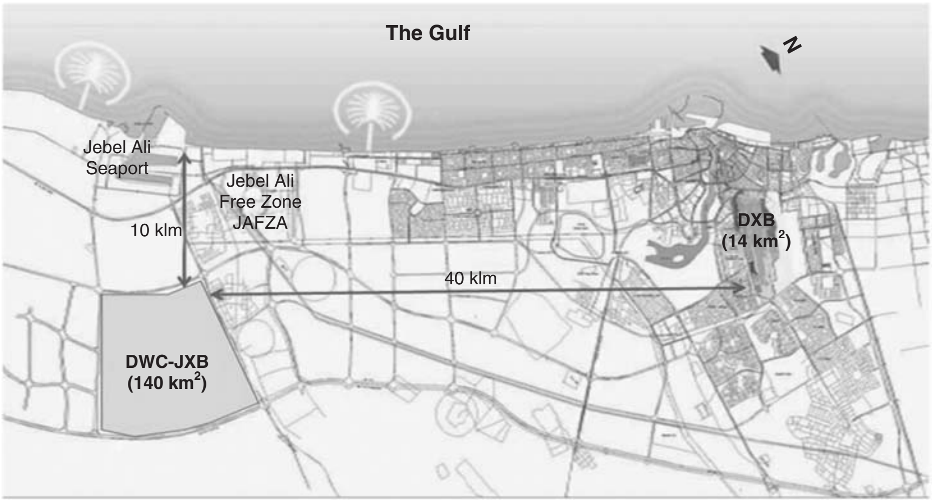

Figure 16.28 Position of Dubai World Central in Dubai metropolitan area (13).

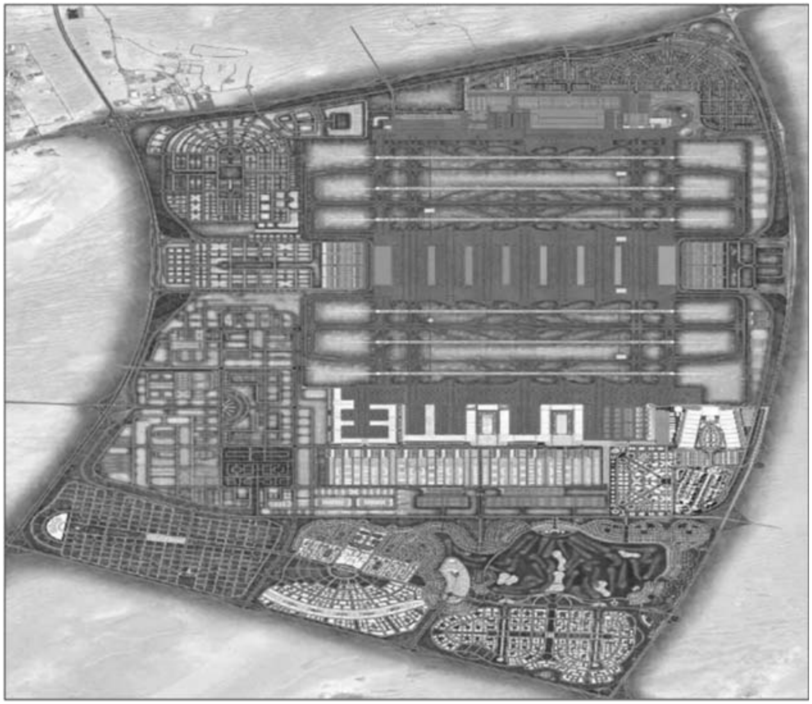

Figure 16.29 Ultimate development plan for Dubai World Central (13).

The ultimate development of JXB to accommodate the stated capacity is planned as follows:

- Five parallel runways 4.5 km in length separated by a minimum of 800 m and capable of simultaneous aircraft landing, as shown in Figure 16.30.
- Four passenger terminals accommodating 160 million passengers per annum with remote satellite concourses connected by people mover system.
- Integrated air cargo terminal complex with 16 depots with total capacity of 12 million tons per annum.

The airport will also have executive and corporate jet, VIP and general aviation terminals, with a hotel, shopping malls, and airline support and maintenance facilities. In all, DWC will have over 100,000 parking spaces. The two Dubai airports, DXB and JXB, are already linked by metro rail and will have high-speed express rail in the future.

DWC's individual precincts, schematically depicted in Figure 16.31, are (14):

- *Aviation City*: Close to the JXB airport and connected to it is Aviation City, where aviation industry and air travel businesses are housed, offices of the world's leading aviation companies and aerospace corporations are located. It also includes businesses dealing with airlines, airport and aircraft maintenance, aircraft auction and sales, spare parts banks, flight simulation, and catering and associated facilities and an aviation technology center for training and professional development.

Figure 16.30 Jebel Ali Airport master plan within Dubai World Central (13).

Figure 16.31 Dubai World Central precinct components (13).

- *Logistics City* (Figure 16.32). A global multimodal logistics hub of an integrated multimodal logistics platform of air, sea, and land transportation with air (Jebel Ali Airport), sea (JAFZA), highway (major road network of the UAE), and rail (Etihad Railways). Logistics and value-added services, including manufacturing, assembly, and high-technology light industry, are co-located in a single bonded and free-trade zone (FTZ) environment. The Logistics City office park will have more than 400,000 m^2 of commercial office space and two business hotels. The Labor Village will accommodate up to 40,000 workers in living quarters of 350,000 m^2.

Figure 16.32 DWC Logistics City and Commercial City in the back (13).

- *Commercial City (* Figure 16.32). Commercial City will be Dubai World Central's business and financial hub, with building towering from 6 to 75 stories anticipated to house the financial and business offices for leading and pioneering companies that will employ around 130,000 people. These companies call Commercial City home as they look for time savings, superb services, and first-class international access and exposure within a fast-pace environment to conduct their business. Commercial City will eventually have up to 25 hotels of different standards.
- *Residential City (* Figure 16.33). The presence of a large skilled workforce at DWC will generate a strong demand for all types of residential accommodation (from blue collar labor to executives) blended with commercial services the city population needs. The plan calls for three phases of development to ultimately accommodate up to 250,000 people living there plus a further 20,000 people working there—in essence, a small city. Residential accommodation options include a mix of 2-story villas and luxury apartments in blocks reaching up to 24 stories, plus other amenities that include three hotels, a shopping mall, and other commercial facilities within a public amenity district that provides a large shopping complex and leisure facilities such as sporting facilities, cinema complex, and other suitable entertainment and may even include a theme park in the future.
- *Science and Technology Enterprise Park*. Industrial and technology development targeting high-technology companies selecting DWC for their business, as depicted in Figure 16.34. It will also include research institutes, medical centers, pharmaceutical industries, high-technology development labs, corporate offices, conference centers, science exhibition halls, and display venues as well as science and technology academic and training institutes.
- *Golf City and Resort*. East of the DWC block lies the golf resort—one of the largest golf course complexes in the region. It is a mega golf course comprising

Figure 16.33 DWC Residential City (13).

Figure 16.34 DWC science and technology enterprise park (13).

two 18-hole courses integrated within DWC and is surrounded by a set of high-rise residential towers and villa clusters all designed as communities within a themed urban design. The resort will enhance Dubai's status on the world tourism map as an international golfing destination. Beyond the golf courses, there are also up to 2500 freehold homes ranging from 2-story villas to 24-story

Figure 16.35 DWC golf resort (13).

apartments. The golf resort will also feature a high-end boutique hotel complete with spa resort. Figure 16.35 is a rendering of the golf resort.

16.6 PLANNING OF AIRPORT CITY AND AEROTROPOLIS

For the airport to consider the Airport city concept as a strategic pillar for its long-term development, several plans, in addition to the typical airport master plan and the urban/land use plan, would be required for implementation (15). As shown in Figure 16.36, the following plans are also required: risk management plan, airport marketing plan, airport city business plan, airport resource and staffing plan, training and development plan, and risk identification study.

Based on that and after reviewing the selected examples given above of the implementation of the airport city and aerotropolis concepts in airports around the world, certain conclusions can be reached:

- The airport city concept relies mostly on integrating aeronautical and non-aeronautical functions, facilities, and services to generate revenues for the airport operator and economic benefits for the broader region.
- In order to meet future financial needs to fulfill future growth objectives, airports would support appropriate commercial development on and near their properties to reinforce growth in air passenger and air cargo traffic.
- Implementation of this concept requires airports to expand their existing planning framework, typically the airport master plan, to cover a more regional/urban

Figure 16.36 Plans required to conduct airport city strategic plan (15).

strategic planning process in collaboration with local government and in partnership with industry and businesses. This strategic planning process could be the tool for synthesizing various other airport planning efforts and serve as an umbrella for airport master plans, land use plans, business plans, and others.

- This integrated airport–urban planning process should be continuous and changeable and cover four basic steps:
  - Planning: both airport and urban
  - Analysis and evaluation
  - Implementation and execution of plans
  - Monitoring to ensure continuity and integration

Planning Process. In the planning phase, it is important to ensure that the strategic plan encompass airport city-related issues as well as engage stakeholders that represent non-aeronautical development interests (retail, hotels, office, etc.), city and regional planning and economic development bodies, and air cargo and logistics providers. Even more important is to ensure that the communication plan keeps these particular stakeholders informed about the evolution of the strategic plan.

Analysis and Evaluation. This phase requires thorough analyses to evaluate and better understand the organization and planning framework and involves articulation of the mission and vision, scanning the environment to predict developments, and analyzing critical gaps to reassess the vision, including:

- Assess any organizational constraints (governance structure, organizational structure, etc.) that make it difficult to efficiently pursue landside commercial development projects.

- Ensure commitment to the economic development of the broader region and promote use of airport facilities and aeronautical services to drive regional economic development.
- Analysis of the competitiveness of the airport in the air passenger/cargo markets to assess potential synergies between aeronautical and non-aeronautical development. This analysis should focus on opportunities for, or threats to, non-aeronautical revenue development.

Implementation and Execution. It is important in this phase to confirm the commercial development opportunities that exist in the airport, both airside and landside, to implement the plan. Also important is considering the special leasing policies that support third-party development for different zoned land uses surrounding the airport comprising the airport city. Multimodal surface accessibility (bus, metro/regional rail, and highways) to the airport and connectivity to the regional transportation network and the activity nodes of the metropolitan area to the airport are an intrinsic part of the strategic plan. IT strategies for airport connectivity to telecom and Internet are critical to support the airport city concept.

Typically, this phase should include the following:

- Develop grand implementation and execution strategies that may include:
  - Increasing non-aeronautical revenue and funding
  - Ensuring that land leasing policies encourage third-party development of facilities (e.g., cargo, maintenance, warehouses, others) that are designed to encourage airport-centered service
  - Formulating and instilling a "best-use" development plan for portions of the airport not suited for aviation and aeronautical use
  - Introducing an e-airport strategy to ensure using new technologies in the most efficient manner possible
- Prioritize key long-term goals and define short-term goals that support these strategies.
- Select key performance indicators to track implementation of short-term goals.
- Write, communicate, distribute, and execute the strategic plan.

Monitoring. In this phase feedback is received and recorded of the overall implementation and performance of the strategic plan. Monitoring will determine how frequently implementation status should be assessed, how results should be reported, and what changes should be made to the plan. Monitoring is performed through periodic checks on certain performance indicators relative to the plan mission and vision.

In parallel, a mechanism to monitor goals pertaining to airport city development is created, with a regular tracking progress report summarizing achievement of these goals. The short-term goals are then associated with the respective performance metrics and benchmark performance relative to other airport cities using comparable metrics.

Accordingly, modification and revision of parts of the strategic plan are evaluated and verified before modification.

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17

Environmental Impacts of Airports

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17.1 INTRODUCTION

Airports are unique entities that have profound economic, social, and environmental effects on a local, regional, and even national level. They provide the means for the efficient movement of passengers and goods to virtually anywhere in the world, playing a vital role in the trend toward “globalization” and the interconnections between international trade and local economies. While the economic benefits of airports and air travel are commonly recognized, there is a social and environmental cost associated with constructing and operating airports. Beginning in the late 1960s, studies that evaluated the environmental effects of airport projects became a prominent consideration during the decision-making process in the United States, followed shortly thereafter by similar studies of airport projects in Europe. These early studies were focused on identifying and attempting to quantify potential impacts on a project-by-project basis and were typically not started or even thought of until well after the planning and design process had concluded. This often resulted in costly changes to projects in order to avoid sensitive resources or features that were not considered during the planning and design process.

As environmental regulations and laws have evolved over time, so has the approach to assessing the environmental impacts of airports and airport projects. Airport owners and operators, for the most part, recognize the need to minimize the effects of airport projects and operations on the environment and surrounding community and are considering impacts much earlier in the planning process. They are also beginning to take a more holistic approach, identifying ways they can make their airports and operations more sustainable.* This chapter provides an overview of the regulatory framework in which airports operate and the environmental review process and briefly discusses the major environmental issues that airports face at the beginning of the twenty-first century.

*The concept of sustainable development is covered later in this chapter in Section 17.12.

17.2 ENVIRONMENTAL LEGISLATION

U.S. Laws

The U.S. Congress enacted the National Environmental Policy Act (NEPA) in 1969, which declared a national policy on the environment (1). The act established the President's Council on Environmental Quality (CEQ), which was charged with developing and issuing regulations implementing the NEPA and overseeing NEPA compliance. Any federal action that could potentially significantly affect the quality of the human environment must comply with the NEPA and the implementing regulations promulgated by the CEQ (2). Federal actions include decisions, approvals, and funding of projects or programs. Thus, every federal agency must consider whether the requirements of the NEPA apply prior to taking any formal actions or issuing decisions. Because each federal agency has its own separate and distinct mandate, most have issued specific guidance on how the NEPA applies to agency decision making and the steps required to ensure its compliance with the NEPA.

The NEPA provides a framework to inform decisions made by decision-makers; it requires the identification of potential environmental impacts and the consideration of alternatives that could minimize environmental impacts. However, the NEPA does not require that an alternative that has the least impact be selected; rather it is up to the federal agency to determine the action that best meets the purpose of and need for an action while avoiding or minimizing those impacts the agency deems unacceptable. Because the NEPA does not legally protect features of the natural and social environment, the U.S. Congress has enacted numerous special-purpose laws that provide varying levels of protection to specific elements of the environment. A sample of these special-purpose laws is provided in Table 17.1. It should also be noted that a number of states have enacted their own environmental policy and review laws.

European Union Laws

Environmental policy for the European Union (EU) is established by the European Commission through the Environment Action Programme, which is updated approximately every 10 years. The Sixth Environment Action Programme (3), in place through July 21, 2012, establishes four areas for priority action within the EU: (a) climate change, (b) nature and biodiversity, (c) the environment and health, and (d) management of natural resources and waste.

Relevant environmental legislation in the EU includes the Environmental Impact Assessment (EIA) Directive 85/337/EEC, which was issued in June 1985 by the Council of the European Union. The EIA directive requires an assessment be carried out for certain projects that are likely to have a physical effect on the environment; for example, construction of airports with runways exceeding 2100 m in length requires an assessment of potential impacts under this directive. Construction of airfields with runways less than 2100 m in length may or may not require an environmental impact assessment, depending on the requirements of the member state in which the facility is being constructed.

In 2001, the European Parliament and the Council of the European Union issued the Strategic Environmental Assessment (SEA) Directive 2001/42/EC. This directive supplements the EIA directive by requiring that plans and programs that may have significant effects on the environment, including transportation plans, must be subjected to an environmental assessment prior to their adoption. Each member state also has

Table 17.1 Sample of U.S. Federal Environmental Laws and Statutes

U.S. federal law or statute	Citation
Clean Air Act of 1970, as amended	PL 91-604, 42 USC 7401-7661
Aviation Safety and Noise Abatement Act of 1979	14 CFR Part 150
Endangered Species Act of 1973	PL 93-205, 16 USC 1531
Fish and Wildlife Coordination Act of 1958	16 USC 661-666c
Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended by the Community Environmental Response Facilitation Act of 1992	42 USC 6901-9675
Resource Conservation and Recovery Act of 1976, as amended by the Solid Waste Disposal Act of 1980	42 USC 6901-6992(k)
National Historic Preservation Act of 1966, as amended	16 USC 470
Archaeological and Historic Preservation Act of 1974, as amended	16 USC 469
Federal Water Pollution Control Act of 1972, as amended (commonly referred as the Clean Water Act)	33 USC 1251
Clean Water Act, Section 404	33 USC 1344
Protection of Historic and Cultural Properties	36 CFR 800
Farmland Protection Policy Act	7 USC 4201-4209
Uniform Relocation Assistance and Real Property Acquisition Policies Act of 1970	42 USC 4601
Wild and Scenic Rivers Act of 1968	16 USC 1271-1287

Note: CFR = Code of Federal Regulations; PL = Public Law; USC = U.S. Code.

laws and statutes specific to their country that cover a wide variety of environmental issues, similar to the special-purpose laws enacted in the United States.

17.3 AIRPORT ENVIRONMENTAL GUIDANCE

United States

The U.S. Federal Aviation Administration (FAA) has issued two orders related to the NEPA and environmental impact assessment. The first guidance document, Order 1050.1E, *Environmental Impacts: Policies and Procedures*, applies to all FAA actions (agencywide) (4). It provides FAA policies and procedures for compliance with the CEQ regulations implementing the NEPA and discusses the environmental process, different levels of environmental review required, and the impact categories that need to be assessed.

The second guidance document, Order 5050.4B, *National Environmental Policy Act (NEPA) Implementing Instructions for Airport Actions*, only applies to actions taken by the Airports Division of the FAA (5). It supplements Order 1050.1E by providing more detailed information on the process and steps required to adequately assess the impacts of airport development projects. The FAA also publishes *Environmental Desk Reference for Airport Actions*, which provides information on federal environmental laws other than the NEPA and the steps required to comply with those laws (6).

European Union

The European Commission has issued several communications concerning aviation and the environment. One communication [COM (1999) 640], "Air Transport and the Environment towards Meeting the Challenges of Sustainable Development," established a strategy for enacting a coherent and environmentally friendly policy for air transport. The strategy included improving the technical standards for evaluating noise and gaseous emissions, introducing economic and regulatory market incentives to reward environmentally friendly operations, establishing environmental protection measures for application at airports, and encouraging research and innovation related to the environmental performance of aircraft.

Another communication, "Reducing the Climate Change Impact of Aviation," issued in 2005 [COM (2005) 459], discusses various options for reducing the impact of the air transport sector on climate change. In 2007, "An Action Plan for Airport Capacity, Efficiency and Safety in Europe" was issued as COM (2006) 819. This communication aims, among other things, to improve the planning framework for new airport infrastructure, recognizing environmental constraints and land use implications early in the planning process, and recommending guidelines for best practices. The European Parliament and the Council of the European Union also issued Directive 2002/30/EC on management of noise at community airports. This directive provides rules and procedures that airports can take to reduce noise pollution generated by aircraft operating at their airport.

International Civil Aviation Organization

The International Civil Aviation Organization (ICAO) established the Committee on Aviation Environmental Protection (CAEP) in 1983, superseding the Committee on Aircraft Noise and the Committee on Aircraft Engine Emissions. The CAEP is primarily involved in assisting the governing body of the ICAO (the council) in formulating policies and standards on aircraft noise and engine emissions from a global perspective. Besides dealing with the technical and operations aspects of noise reduction, noise mitigation, and aircraft engine emissions, the CAEP also studies market-based measures to limit or reduce emissions, including the establishment of an emissions trading system (7).

17.4 ENVIRONMENTAL REVIEW PROCESS

The process of conducting and documenting the environmental impacts of a project has essentially remained the same since the NEPA and the EIA directives were enacted. Although the process has not changed, the level of analysis, coordination, and documentation is constantly evolving. This is due, in part, to new regulations, but it is also due to better models for predicting environmental impacts, a better understanding of the effects of airport projects and aircraft operations on the human environment, and a better informed public on environmental issues, including special interest groups. Major airport projects now typically undergo intense agency and public scrutiny, which often includes organized opposition groups.

If conducted properly, the environmental review process assists decision-makers in evaluating the need for a project while also identifying and understanding potential environmental impacts and ways that unavoidable impacts can be minimized or mitigated. Fundamentally, the environmental review process does the following:

- Initiates coordination with other agencies that have jurisdiction over potentially affected resources
- Defines the purpose and need for the proposed project

- Identifies and considers reasonable alternatives of the proposed project
- Analyzes reasonably foreseeable direct, indirect, and cumulative impacts
- Provides for public disclosure and comment
- Facilitates informed decision making
- Documents the decisions and actions to be taken by the responsible official(s) and mitigation requirements

This process is followed for all projects, but the documentation varies considerably based on the type of project and its potential impacts. The environmental process involves a number of players: the responsible agency (typically a federal agency that must make a decision regarding a proposed project), the sponsor (the airport owner or operator), resource agencies (agencies with jurisdiction over potentially affected resources), and the public, including special interest groups. Finally, it should be recognized that the ultimate goal of the environmental process is to obtain regulatory approval, including the necessary permits to allow construction and operation of the airport. Approval is often a prerequisite before obtaining federal or private funding.

Levels of Review and Documentation

In the United States, one of three levels of environmental review and associated documentation are prepared—a categorical exclusion, an environmental assessment (EA), or an environmental impact statement (EIS). The FAA has identified types of projects in FAA Order 1050.1E that are eligible for the simplest level of analysis, a categorical exclusion. These projects normally do not have a significant effect on the human environment based on previous experience with similar projects. If a project is included in the categorical exclusion list published in FAA Order 1050.1E and no extraordinary circumstances exist, then the project is exempt from environmental review under the NEPA.

Extraordinary circumstances are defined by the FAA as those actions that would have a significant effect involving one of the following (8):

- Archaeological, historical, or cultural resources protected under the National Historic Preservation Act
- Properties protected under Section 4(f) of the Department of Transportation Act (parks, wildlife refuges, wilderness areas, historical sites)
- Natural, ecological, or scenic resources of local, state, tribal, or federal significance (such as threatened or endangered species)
- Wetlands, floodplains, or coastal zones
- Unique or state or locally important farmlands
- Energy supply and natural resources
- Wild and scenic rivers
- Division or disruption of an established community or disruption of planned development
- Increase in congestion from surface transportation that would cause a decrease in level of service below an acceptable level as determined by the appropriate transportation agency

- Impact on noise levels of noise-sensitive areas
- Impact on air quality or violation of local, state, tribal, or federal air quality standards
- Impact on water quality, sole-source aquifers, a public water supply system, or water quality standards
- Effects on the quality of the human environment that are likely to be highly controversial based on environmental grounds
- Inconsistent with any local, state, tribal, or federal law relating to the environmental aspects of the proposed project
- Directly, indirectly, or cumulatively creating a significant effect on the human environment

Thus, if an action is contained on the published list of projects normally categorically excluded and no significant effect on any of the circumstances listed above would result from implementation of the action, then the action is categorically excluded from environmental review under the NEPA. A brief paper documenting that an action is eligible for categorical exclusion is normally assembled and submitted to the FAA for its concurrence prior to implementation of the action.

If an action is not contained on the published categorical exclusion list or extraordinary circumstances are involved, then preparation of either an EA or EIS is required. The difference between whether an EA or an EIS should be prepared is based on the significance of impacts. If no significant environmental impacts are anticipated or if potential significant environmental impacts can be mitigated, then an EA is normally prepared. If significant environmental impacts are anticipated and they cannot be mitigated or if the action is a major project as defined by the FAA, then an EIS must be prepared (somewhat comparable to an EIA in the EU). As an example, construction of a new airport or a new runway within a metropolitan statistical area (basically any major metropolitan areas, as defined by the U.S. Census Bureau) requires the preparation of an EIS.

Agency Coordination and Scoping

While the appropriate level of environmental documentation will be obvious for some actions, it can be less obvious for other actions. Ideally, sensitive resources within the project area would be identified during the planning phase and avoidance of those resources, where practical, would have been incorporated into the proposed project. However, it is also important to coordinate with resource agencies that have jurisdiction over potentially affected resources as early as possible in the planning process. Early coordination establishes communication between the airport sponsor(s) and resource agencies and provides an understanding of the proposed project and agency concerns early in the planning process, when they are typically more easily addressed. It is much easier to adjust project plans during the planning stage than during the design phase or after design has been completed.

A mechanism often used to initiate agency coordination, especially for large and controversial projects, is a process called scoping. This is a formal process whereby the project sponsor or the responsible agency puts together an information packet outlining the proposed project, preliminary purpose and need, preliminary alternatives, and potentially affected resources and sends that to all agencies that have jurisdiction over potentially affected resources and potentially affected communities and special interest groups. An announcement of the scoping process is also issued publicly to inform the general populace. Typically a meeting or series of meetings are held approximately 30 days after issuance of the scoping material for the purpose of presenting the information and obtaining feedback from all interested parties. The scoping process is intended to generate comments on the purpose and need for a project, identify other reasonable alternatives that may not have been considered, and identify all issues that should be examined during the environmental review process.

Scoping can also be used to determine the appropriate level of environmental documentation that should be prepared for a proposed project.

Draft Document Preparation

Once the appropriate level of documentation has been agreed upon between the responsible agency and the project sponsor(s) and a general understanding of the potential effects of the proposed project has been developed, the draft environmental document is prepared. The sections of a typical environmental document are discussed below.

Project Purpose and Need

Defining and identifying the purpose and need for a project are critically important parts of the environmental review process. The purpose and need provide the justification and reasons that a project should be undertaken and implemented and also establish the framework for identifying alternatives that satisfy the purpose and need. Typically, the need for a project is identified by the airport sponsor(s) during the planning process and is based on forecasts of new or additional aviation activity, capacity constraints at an airport, safety, or compliance issues. The purpose for a project is to solve a specific problem, such as to decrease congestion and delays. Capacity enhancement projects require a comprehensive and detailed analysis of past and future activity at an airport and most often require concurrence of the forecasts by the FAA or comparable agency before an environmental review can be initiated.

As the level of analysis required in an environmental review has evolved over the years, so too has the need for advanced substantive planning work become increasingly critical before any project can move forward through the environmental review and approval process. Advanced planning work is required to establish that projects are truly needed before undergoing extensive agency and public review (not to mention the expenditure of public funds) and that sufficient information is available to adequately assess the potential environmental impacts of the proposed project. While airport sponsors typically identify projects for implementation, without adequate justification for a project they usually cannot obtain the regulatory approvals and required funding.

Alternatives

The number of alternatives that must be examined is typically commensurate with the type of project and significance of impacts. For smaller projects or projects with no significant impacts, only two alternatives need to be considered: the “no-action” (or “do-nothing”) alternative and the proposed action. In the United States, the regulations implementing the NEPA require that the no-action alternative be examined to provide decision-makers a frame of reference when considering the potential impacts of a proposed action and the consequences of doing nothing. If an action would result in resource conflicts (significant impacts to sensitive resources), then reasonable alternatives must also be examined. Reasonable alternatives are those alternatives that are feasible and can meet the purpose and need for a project. Alternatives are typically identified by the project sponsor(s) but can also be identified by the responsible federal agency (such as the FAA) or by other resource agencies or the public. In cases where there is more than one alternative proposed action, the sponsor(s) identify their preferred alternative. The responsible agency will also select a preferred alternative after reviewing and considering the potential environmental effects of each alternative.

The alternatives section of an environmental document plays a critical role in the environmental review process. For actions with significant environmental impacts, the alternatives section must demonstrate that all reasonable alternatives, in other words those that minimize impacts and also meet the purpose and need for a project, were considered. The alternatives analysis should document reasoned decision making for identifying and selecting a proposed action. Legal challenges to airport EA and EIS documents have typically focused on the alternatives analysis because reasonable alternatives that minimize environmental impacts were not adequately considered. Thus, it is important that the purpose and need for a project be used to develop criteria for identifying the proposed action and reasonable alternatives and that this process is adequately documented during the environmental review process.

Affected Environment

A baseline to measure potential impacts of a project must be assembled prior to conducting the environmental impact analysis which compares the no-action, proposed action, and any reasonable alternatives against each other. This baseline, typically referred to as the affected environment, provides information on the existing environmental conditions throughout the geographic area potentially affected by a project. The extent of the geographic area to be studied varies depending on the type of project and its potential impacts. Some projects need to only consider the area of direct disturbance (e.g., the footprint of a structure to be constructed), while other projects will cover a large geographic extent because of potential noise, air quality, or cumulative impacts. The affected environment section of an environmental document should identify the physical characteristics of the project setting, the socioeconomic setting, sensitive resources, and how the proposed action complements or conflicts with existing and future plans for the area.

For most actions, the affected environment information is compiled from existing data sources; however, for projects with potentially significant impacts, additional study is often required to obtain recent or current data, supplement existing data, or compile data on resources where little or inadequate data exist. Generally, additional study is usually done on those resources potentially affected by a project to ensure that potential impacts are fully understood.

Environmental Consequences/Impacts

An analysis of the potential environmental impacts of the no-action alternative, the proposed action, and any reasonable alternatives to the proposed action is documented

Table 17.2 Environmental Impact Categories Considered in FAA Environmental Documents

Impact categories	
Air quality	Historical, architectural, archeological, and cultural resources
Coastal resources	Light emissions and visual impacts
Compatible land use	Natural resources and energy supply
Construction impacts	Noise
Department of Transportation Act: Section 4(f) Lands	Secondary (induced) impacts
Farmlands	Socioeconomic impacts and environmental justice
Fish, wildlife, and plants	Water quality
Floodplains	Wetlands
Hazardous materials, pollution prevention, and solid waste	Wild and scenic rivers

Source: *Environmental Impacts: Policies and Procedures,* Order 1050.1E, Change 1, Washington, DC: Federal Aviation Administration, March 20, 2006.

in the environmental consequences section of the document. The FAA requires consideration and analysis, where appropriate, of 18 separate impact categories, identified in Table 17.2. For those impact categories where the resource is not present, a simple statement noting that the resource is not present within the project study area is sufficient. For each environmental impact category, the FAA has identified a threshold of significance, that is, a level above which an impact is considered to be significant.

The extent of analysis required is commensurate with the significance of potential impacts. For example, if an airport sponsor adds a new runway, a detailed analysis of aircraft noise is typically required. However, if the airport sponsor is developing an aircraft rescue and fire fighting facility, a detailed aircraft noise analysis is usually not required. A more detailed discussion of specific environmental issues is provided in subsequent sections of this chapter.

The environmental consequences section also identifies ways to minimize a project's effect on the environment, commonly referred to as mitigation. Some mitigation is required as part of permit conditions to allow construction to occur, while other mitigation is negotiated between the responsible agency, airport sponsor(s), and applicable resource agencies to address unavoidable impacts to sensitive or protected resources. Mitigation requirements are highly dependent on the nature and extent of impacts as well as the regulatory and legal protections afforded to the affected resources. Oftentimes resources are protected at both a federal and state level; thus, the same project with similar impacts at two different airports can have vastly different mitigation requirements.

Public Review and Participation

The environmental review process in both the United States and the EU requires meaningful public participation. In the United States, the CEQ regulations implementing the NEPA require that agencies provide notice of public hearings, public meetings, and the availability of environmental documents for public review. The Council of the European Union issued a decision in February 2005 (2005/370/EC) approving the Århus Convention, which ensures public access to environmental information held by public authorities, fosters public participation in decision making that affects the environment, and extends the conditions of access to justice in environmental matters.

Public participation programs for environmental documents can range from a minimum of publishing notices and making documents publicly available for review to comprehensive programs involving public information meetings, stakeholder meetings, project websites, newsletters, and public hearings. Typically, projects involving greater public controversy require a more comprehensive public involvement program. Although airport sponsor(s) have not always had good relations with surrounding communities (and some still do not), most have found that open communication and ongoing dialogue with the public and community groups improve relations and foster an environment whereby airport and community concerns can be addressed and sometimes mitigated.

Public participation is usually initiated at the beginning of the environmental process through scoping, if held, or through public notice that a sponsor or agency is initiating an environmental study. For some projects, public participation continues throughout the development of the draft document in the form of newsletters, stakeholder meetings, and public information meetings. For other projects, limited public participation may occur until publication of the draft document for public review. In the United States, a public hearing is required for a draft EIS, but one is not required for a draft EA. However, the draft EA must be released and made available for public review and for certain types of projects, an opportunity for a public hearing provided. If the opportunity for a public hearing is provided and an agency or member of the public requests a public hearing on a draft EA, then the responsible agency must hold one.

A minimum of 30–45 days (in the United States) must be provided for public review of draft environmental documents to ensure that adequate time is provided for comment and review. After close of the comment period on a draft environmental document, all comments received are compiled and summarized and then analyzed to determine what changes, if any, are required to the draft document.

Final Document Preparation

The final environmental document contains all agency and public comments received throughout the environmental study and includes a summary of how those comments were addressed or considered. Any necessary changes to the draft document are incorporated based on the review comments or any additional information provided to the responsible agency. If a preferred alternative was not identified in the draft document, the final document identifies the sponsor's and responsible agency's preferred alternative. The sponsor's preferred alternative may not be the same as the responsible agency's preferred alternative. A final document is then issued and circulated, including being made available to the public.

Prepare Decision Document

After the final environmental document has been issued, the responsible agency reviews the document and prepares a decision document. In the United States, there are two types of decision documents—a finding of no significant impact (FONSI) and a record of decision (ROD). A FONSI is issued for EA documents when no significant impacts would result from the proposed action, while a ROD is issued for all EIS documents. A hybrid decision document called a FONSI–ROD is issued for EA documents when no significant impacts would result with implementation of mitigation.

The decision document summarizes the purpose and need for a project, alternatives considered, the sponsor's preferred alternative, the responsible agency's preferred alternative, potential effects of the proposed action, and any mitigation required to reduce negative effects of the proposed action. The decision document also details the actions that the responsible official is approving or disapproving. In some cases, if an EA finds that the proposed action would result in unavoidable impacts that could not be reduced below a level of significance, a decision will be made that an EIS is required and must be prepared prior to project approval. Decision documents must also be circulated and made available for public review.

17.5 AIR EMISSIONS/QUALITY

Effects of Aviation

The effects of airports and aircraft on air quality are complex and controversial—effects not only occur in areas immediately surrounding airports but also occur on a regional and global level. Not only do emissions from airports and aircraft affect air quality in areas immediately surrounding airports, but aircraft exhaust is also emitted in the upper atmosphere during flight. Emission sources at airports typically include the following:

- *Aircraft emissions* are a function of the number of annual aircraft operations, the aircraft fleet mix (types of aircraft and engines serving an airport), and the length of time aircraft spend in various modes of the landing and takeoff cycle. Six aircraft operating modes comprise a landing and takeoff (LTO) cycle: approach to the airport, landing roll on the runway, taxi in from the runway to the gate or apron, taxi out from the gate or apron to the runway, takeoff on the runway, and climbout from the airport.
- *An auxiliary power unit* (*APU*) is a small turbine engine that generates electricity and compressed air to operate aircraft instruments, lights, and ventilation when aircraft are parked at the gate, and the APU can also be used to provide power to start the main aircraft engines. Because jet fuel is used as the power source for APUs, they emit exhaust.
- *Ground support equipment* such as tugs that haul baggage carts, fuel trucks, and catering trucks also create exhaust. Additionally, passengers, employees, hotel and rental car shuttles, parking shuttles, and suppliers all generate motor vehicle traffic on airport roadways and in parking lots that can be a significant source of pollutant emissions at an airport.
- *Construction emission sources* can include construction vehicles and equipment, land development activities, asphalt paving activities, asphalt batch plants, and painting activities.
- *Stationary sources* can include heating and cooling plants, emergency generators, and other industrial facilities located on airport property.

An assessment of air quality effects at an airport needs to consider all of these factors. The vast number and types of activities that can affect air quality make understanding and properly characterizing these effects a complex and challenging process.

Air Quality Standards

The Clean Air Act enacted in 1970 by the U.S. Congress required that the U.S. Environmental Protection Agency (EPA) set national ambient air quality standards (NAAQSs) for criteria pollutants and required states to identify nonattainment areas (areas where the NAAQSs for one or more pollutants are not met). Subsequently in 1990, the U.S. Congress passed the Clean Air Act Amendments (CAAA), which established nonattainment classifications in terms of severity and required the preparation and submittal of state implementation plans (SIPs) demonstrating how each nonattainment area would achieve the NAAQSs (9).

The EPA, under mandates of the CAAA, has established primary and secondary NAAQSs for seven air contaminants or criteria pollutants. These contaminants include carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), lead (Pb), sulfur dioxide (SO_2), particulate matter (PM_{10}), and fine particulates ($PM_{2.5}$). The primary standards were established at levels sufficient to protect public health with a satisfactory margin of safety. The secondary standards were established to protect public welfare from other adverse effects of air pollution.

Directive 2008/50/EC on ambient air quality and cleaner air for Europe was issued by the European Parliament and the Council on May 21, 2008, to replace several previous directives and establish common methodologies and limits for air pollutants. The directive includes specified limits for the same criteria pollutants identified by the EPA but also includes limits for benzene. The European Aviation Safety Agency utilizes the engine certification standards adopted by the Council of the ICAO contained in *Annex 16—Environmental Protection,* Volume II, *Aircraft Engine Emissions* to the Convention on International Civil Aviation (10). The ICAO engine certification standards establish limits for emissions of NO_x, carbon monoxide, and unburned hydrocarbons for an LTO below 915 m (3000 ft) of altitude.

A brief description of the criteria pollutants is provided below:

- *Benzene* (C_6H_6) is a colorless or light yellow liquid at room temperature and has a sweet odor and low vapor point and is extremely flammable. Benzene occurs naturally in volcanoes and as byproducts of forest fires. Sources of benzene in the air include tobacco smoke, gas stations, motor vehicle exhaust, industrial emissions, glues, paints, furniture wax, and detergents. Long-term exposure to benzene can affect the bone marrow, causing a decrease in red blood cells leading to anemia, leukemia, or cancer.
- *Carbon monoxide* (*CO*) is an odorless, colorless gas that is highly toxic. It is formed by the incomplete combustion of fuels. The primary sources of this pollutant are automobiles and other ground-based vehicles. The health effects associated with exposure to CO are related to its affinity for hemoglobin in the blood. At high concentrations, CO reduces the amount of oxygen in the blood, causing heart difficulties in people with chronic diseases, reduced lung capacity, and impaired mental abilities.

- *Nitrogen dioxide* (NO_2) is a poisonous, reddish-brown to dark brown gas with an irritating odor. NO_2 forms when nitric oxide (NO) reacts with atmospheric oxygen (O_2). Most sources of NO_2 are man made, the primary being high-temperature combustion. Significant sources of NO_2 at airports are boilers, aircraft operations, and vehicle movements. NO_2 emissions from these sources are highest during high-temperature combustion, such as aircraft takeoff mode. NO_2 may produce adverse health effects such as nose and throat irritations, coughing, choking, headaches, nausea, stomach or chest pains, and lung inflammations (e.g., bronchitis, pneumonia).
- *Ozone* (O_3), commonly referred to as smog, is formed in the atmosphere rather than being directly emitted from pollutant sources. Ozone forms as a result of volatile organic compounds (VOCs) and oxides of nitrogen (NO_x) reacting in the presence of sunlight in the atmosphere. VOCs and NO_x are termed "ozone precursors," and their emissions are regulated to control the creation of ozone. High ozone levels occur in warm-weather months and are known to damage lung tissue and reduce lung function. Scientific evidence indicates that ambient levels of ozone not only affect people with impaired respiratory systems (e.g., asthmatics) but also healthy children and adults. Ozone can cause health effects such as chest discomfort, coughing, nausea, respiratory tract and eye irritation, and decreased pulmonary functions.
- *Lead* (*Pb*) is a heavy metal solid that is bluish white to silvery gray in color. Lead occurs in the atmosphere as lead oxide aerosol or lead dust. Historically, ground access vehicles operating on leaded gasoline were a significant source of lead in the air at airports. The amount of lead emissions from vehicles has decreased, however, due to the significant federal controls on leaded gasoline and the resultant increase in the use of unleaded gasoline in catalyst-equipped cars. Another source of this pollutant at an airport is the combustion of leaded aviation gasoline in piston-engine aircraft.
- *Sulfur dioxide* (SO_2) is formed when fuel containing sulfur (typically coal and oil) is burned, during the metal smelting process, and during other industrial processes. Large SO_2 concentrations are found in the vicinity of large industrial facilities. The physical effects of SO_2 include temporary breathing impairment, respiratory illness, and aggravation of existing cardiovascular disease. Children and the elderly are most susceptible to the negative effects of exposure to SO_2.
- *Particulate matter* (PM_{10}) and *fine particulates* ($PM_{2.5}$) consist of solid and liquid particles of dust, soot, aerosols, and other matter small enough to remain suspended in the air for a long period of time. PM_{10} consists of particulate matter with an aerodynamic diameter less than or equal to 10 μm and $PM_{2.5}$ consists of particulate matter with an aerodynamic diameter less than or equal to 2.5 μm. Particulates smaller than 10 μm (i.e., PM_{10} and $PM_{2.5}$) represent that portion of particulate matter thought to represent the greatest hazard to public health. PM_{10} and $PM_{2.5}$ can accumulate in the respiratory system and are associated with a variety of negative health effects. Exposure to particulates can aggravate existing respiratory conditions, increase respiratory symptoms and disease, decrease long-term lung function, and possibly cause premature death. The segments of the population that are most sensitive to the negative effects of particulate

matter in the air are the elderly, individuals with cardiopulmonary disease, and children. Aside from physical negative effects, particulate matter in the air causes a reduction of visibility and damage to paints and building materials.

A portion of the particulate matter in the air comes from natural sources such as windblown dust and pollen. Man-made sources of particulate matter include combustion of materials, automobiles, field burning, factories, vehicle movement or other man-made disturbances of unpaved areas, and photochemical reactions in the atmosphere. Secondary formation of particulate matter may occur in some cases where gases such as sulfur oxides (SO_x) and nitrogen oxides (NO_x) interact with other compounds in the air to form particulate matter. Fugitive dust generated by construction activities is a major source of particulate matter.

The secondary creators of particulate matter, SO_x and NO_x are also major precursors to acidic deposition (acid rain). While SO_x are a major precursor to particulate matter formation, NO_x have other environmental effects. NO_x have the potential to change the composition of some species of vegetation in wetland and terrestrial systems, create the acidification of freshwater bodies, impair aquatic visibility, create eutrophication of estuarine and coastal waters, and increase the levels of toxins harmful to aquatic life.

Aircraft engine emissions consist of approximately 70% carbon dioxide (CO_2), a little less than 30% water vapor (H_2O), and less than 1% each of nitrogen oxides (NO_x), carbon monoxide (CO), oxides of sulfur (SO_x), unburned or partially combusted hydrocarbons (also known as volatile organic compounds), particulates, and other trace compounds. A small portion of the volatile organic compounds (VOCs) and particulates are considered hazardous air pollutants (HAPs). Approximately 10% of all aircraft emissions, except for hydrocarbons and CO, are produced during taxiing operations, landing, and takeoff; the bulk of all aircraft emissions occur during flight at higher altitudes (11).

Climate Change and Greenhouse Gas Emissions

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988 to assess available information on the science, impacts, and economics of climate change and to provide advice to the United Nations Framework Convention on Climate Change. Specifically, the IPCC has been examining the effect of greenhouse gases, which are atmospheric gases that can trap heat and potentially increase the temperature of the earth's surface leading to climate change. The ICAO requested that the IPCC, in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, prepare a special report, *Aviation and the Global Atmosphere*. This report documented that (12):

- Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere which alter the atmospheric concentration of greenhouse gases, trigger the formation of condensation trails or contrails, and may increase cirrus cloudiness, all of which contribute to climate change
- Aircraft are estimated to contribute about 3.5% of the total radiative forcing (a measure of change in climate) by all human activities and that this percentage,

which excludes the effects of possible changes in cirrus clouds, was projected to grow

Subsequent findings in the Fourth Assessment Report published in 2007 include the following (13):

- Total radiative forcing contributed by aircraft is about 3.0% of the total of anthropogenic radiative forcing by all human activities.
- Total CO_2 aviation emissions is approximately 2% of global greenhouse emissions.
- The amount of CO_2 emissions from aviation is expected to grow around 3–4% per year.

Similarly, the EPA estimated in 1997 that U.S. aviation accounted for about 3% of the total U.S. greenhouse gas emissions from human sources (14).

The EU has taken a leading role in attempting to reduce the impact of aviation on climate change. In 2005, the European Commission issued a communication “Reducing the Climate Change Impact of Aviation” [COM (2005) 459]. This communication outlines the commission’s proposal to continue and extend research on analyzing the impact the air transport sector has on climate change and reducing aircraft CO_2 and NO_x emissions. This communication also established the intent of the commission to include the air transport sector in the greenhouse gas emissions trading scheme established by the EU in 2003. A directive to include aviation within the Emissions Trading System (ETS) was published on January 13, 2009 (Directive 2008/101/EC). Beginning in 2012, airlines will be required to surrender one allowance for each ton of CO_2 they emit during a reporting year; if the airline operator does not have enough allowances to cover their annual CO_2 emissions, then they will be required to purchase more allowances or face civil penalties.

Greenhouse gas emissions from U.S. aircraft are not regulated (as of mid-2010); however, the EPA determined in an endangerment finding issued on December 7, 2009, that the current and projected concentrations of the six key well-mixed greenhouse gases in the atmosphere—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—threaten the public health and welfare of current and future generations (15).

Air Toxics

Air toxics, also known as hazardous air pollutants, or HAPs, related to aircraft operations have also become a cause for public concern. According to the EPA, toxic air pollutants are those pollutants known or suspected to cause cancer or other serious adverse health effects (16). The combustion of aviation fuels is the primary source of air toxics related to aircraft operations; the air toxics of concern include benzene and other hydrocarbons such as 1,3-butadiene, formaldehyle, acetaldehyde, acrolein, and naphthalene (17). In 2010, neither the United States nor the EU regulated air toxics specifically from aircraft operations, although disclosure of hazardous air pollutant emissions from airport operations are sometimes included in FAA NEPA documents. The need for health risk assessments to identify potential source/receptor relationships for specific air pollutants associated with airport and aircraft emissions was being considered by the ICAO in 2010 (18).

Air Quality Assessment

Most air quality assessments, both in the United States and in Europe, rely on the development of detailed emission inventories followed by dispersion modeling. Emission inventories quantify the type, frequency, and duration of various emission sources from aircraft, ground vehicles, ground support equipment, stationary sources, and other activities on an annual basis. Dispersion modeling is then conducted to determine the extent and severity of air quality effects related to those operations and activities. In environmental analysis documents, modeling is conducted for a base year and then for future years to assess potential effects of proposed projects on the airport and surrounding environment.

Several models have been developed to identify and analyze the potential effects of human activity on air quality. The FAA has issued guidance for analyzing air quality effects of aviation in a document titled *Air Quality Procedures for Civilian Airports and Air Force Bases* (19). The FAA requires that the latest version of the Emissions Dispersion Modeling System (EDMS) be used to quantify air quality impacts from aviation sources. Typically, other EPA-approved models are used to evaluate the impacts of nonaviation sources (e.g., “hot-spot” analysis of on-road vehicles, emissions from construction equipment). The FAA also developed a model to evaluate the effect of aviation emissions globally, called the System for Assessing Aviation’s Global Emissions (SAGE). This model is an in-house tool that is being incorporated into the next-generation air quality model, called the Aviation Environmental Design Tool (AEDT). The AEDT model will combine EDMS with the FAA’s integrated noise model, which will allow users to understand the effects that changes in flight procedures have on both air quality and noise (discussed in more detail later in this chapter). This model is scheduled for public release at the end of 2011 (20).

The Atmospheric Dispersion Modelling System (ADMS-Airport) is intended to assess compliance with the air quality limits contained in the EU air quality directive and other European air quality standards. EUROCONTROL developed the Airport Local Air Quality Studies (ALAQS-AV) model as an airport air quality inventory tool for aircraft, ground support equipment, stationary, and ground vehicle sources. The advanced emission model (AEM) was also developed by EUROCONTROL to estimate aviation emissions and fuel burn (21).

Minimization of Effects

Research and policies aimed at minimizing the effects of aviation on air quality and climate change continues to evolve at a rapid pace. Airlines, government agencies, and research institutions in both Europe and the United States are actively researching and testing alternative fuels and operating procedures to reduce the greenhouse gas emissions and fuel consumption of aircraft. These initiatives include the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), the Commercial Aviation Alternative Fuels Initiative, the ICAO’s Global Framework for Aviation Alternative Fuels, and the International Air Transport Association (IATA) Carbon Offset Program, among others.

Airports and airlines have also instituted a variety of measures to reduce air quality impacts, including use of cleaner burning fuels (such as compressed natural gas) and alternative fuels (such as biodiesel) for airport vehicles and ground support equipment, use of electric and hybrid-electric vehicles, implementation of anti-idling campaigns, use of one-engine taxi procedures, provision of electricity and air for parked aircraft at gates (in lieu of APUs), reduction of ground delays by improving airfield infrastructure (aprons, taxiways, etc.), and other measures. Aircraft and aircraft engine manufacturers are also developing lighter and more efficient aircraft, which decrease fuel consumption and emissions of air pollutants. The FAA and EUROCONTROL are also working on ways to reduce air quality impacts, including initiatives such as optimization of the airspace system within their respective jurisdictions to improve the airlines' ability to fly direct and shorter routes using global positioning system (GPS) technology and development of continuous descent approach/arrival (CDA) procedures at airports that decrease noise and emissions for aircraft landings.

17.6 BIODIVERSITY AND NATURAL RESOURCES

Airport development has a physical, direct effect on the environment through the construction of airfield, landside, and support facilities. While airport development may occur on previously disturbed land, some development also occurs on undisturbed, natural lands, particularly at airports located outside of urban areas. Biodiversity and natural resource impacts (effects to flora, fauna, endangered species, ecosystems, and natural habitats) can occur if sensitive species or habitats occur adjacent to or on airport property or if they exist underneath flight paths and are sensitive to aircraft noise. Some airports may also contain sensitive species or habitat within their property boundaries. This can occur because airports contain relatively large land areas and because past actions by others may have led to habitat destruction or fragmentation in areas surrounding the airport. Thus, the best habitat for a species may exist on airport property and can result in airports containing isolated populations of sensitive species or habitat. In these instances, almost any airport development may affect biodiversity and natural resources, requiring extensive coordination with the responsible natural resource agencies.

Relevant statutes in the United States include the Fish and Wildlife Coordination Act of 1958, the Marine Mammal Protection Act of 1972, the Endangered Species Act of 1973, and the Migratory Bird Treaty Act of 1980. The European Commission issued a communication in 2006, entitled "Halting the loss of biodiversity by 2010—and Beyond—Sustaining Ecosystem Services for Human Well-Being" [COM (2006) 216], which introduced an action plan for biodiversity. The Sixth Environment Action Programme also contains objectives to protect and restore natural systems and halt the loss of biodiversity (22). Airports can minimize their effects on biodiversity and natural resources by, to the extent possible, avoiding disturbance of habitat utilized by sensitive species and restricting development to previously disturbed areas. Mitigation in the form of habitat protection or restoration may be necessary in cases where impacts to sensitive habitats are unavoidable.

Another issue of importance to airports related to biodiversity is the presence of wildlife that may pose a hazard to aircraft operations. The FAA has issued guidance on hazardous wildlife attractants (23) that requires airport owners and operators to minimize habitat features and activities that may attract wildlife that could interfere with aircraft operations. Some examples include discouraging or preventing the location of municipal waste landfills within 5 mi of commercial service airports and the location of stormwater detention basins or other bodies of water that store water for longer than a 48-hr period within 5000 ft of a runway that serves piston-powered aircraft and within 10,000 ft of a runway that services turbine-powered aircraft. The FAA also requires that airports conduct a wildlife hazard assessment if a wildlife–aircraft strike meeting certain conditions occurs and in some cases requires a wildlife management plan as part of the airport certification requirements.

17.7 HISTORIC, ARCHAEOLOGICAL, ARCHITECTURAL, AND CULTURAL RESOURCES

Historic resources are places where events of local, regional, or national historic significance occurred, places associated with figures of historic importance, or structures that are representative of particular periods of history and are maintained in a setting that replicates that time period. Archaeological resources are artifacts, remnants, or fossils that provide information about habitats, settlements, cultures, or flora and fauna that existed in the distant past. Architectural resources are structures that are identified as being architecturally significant because they are unique or are good examples of specific architectural styles or of structures designed and built by noted architects. Cultural resources are places, artifacts, or remnants that hold cultural significance to specific tribes, ethnic groups, or religious groups.

Airport development and operation can affect historic, archaeological, architectural, or cultural resources in a number of ways. Direct impacts occur when airport development physically disturbs, displaces, or destroys these resources. Indirect impacts can occur from aircraft noise or visual impacts, which can disturb the enjoyment or experience of historic or cultural resources. A number of statutes protecting these resources have been enacted in the United States, including the Antiquities Act of 1906, the National Historic Preservation Act of 1966, the Archaeological and Historic Preservation Act of 1974, the American Indian Religious Freedom Act of 1978, the Archaeological Resources Protection Act of 1979, and the Native American Graves Protection and Repatriation Act of 1990.

Effects to these resources from airport development and aircraft operation can be minimized by identifying, avoiding, and protecting historic, archaeological, architectural, and cultural resources, where possible. If impacts are unavoidable, then it may be possible to mitigate effects by relocating historic or architectural resources if the integrity of the resource would not be compromised (features that make a resource historically important) or through data recovery and recordation of all relevant information and artifacts by a professional archaeologist or architectural historian.

17.8 NOISE AND LAND USE

Sound, when transmitted through the air and upon reaching the ear, may be perceived as desirable or unwanted (24). People normally refer to noise as unwanted sound. Because sound can be subjective, individuals have different perceptions, sensitivities, and reactions to noise. Loud sounds may bother some people, while certain rhythms or frequencies of sound may bother others. Sounds that occur during sleeping hours are usually considered to be more objectionable than similar sounds that occur during daytime hours.

Effects of Aviation

Aircraft noise originates from both the engines and the airframe of an aircraft, but the engines are by far the more significant source of noise. Meteorological conditions affect the propagation (or transmission) of sound through the air. Wind speed and direction and the temperature immediately above ground level cause diffraction and displacement of sound waves. Humidity and temperature materially affect propagation of air-to-ground sound through absorption associated with the instability and viscosity of the air.

Effects of noise exposure can include sleep disturbance, interruption or interference with speech and communication, adverse academic performance, induced stress and stress-related illnesses, and annoyance. Because noise effects can be intrusive and the reaction to and perception of noise varies from person to person, it remains challenging for airports and airlines to develop and implement techniques that mitigate all noise effects.

The ICAO states that aircraft manufactured in 2007 are about 75% quieter than ones manufactured 40 years ago and that the number of people exposed to significant levels of aircraft noise has fallen by approximately 30% in 2006, when compared to 2000 levels (25). However, a recent ICAO/CAEP analysis indicates that the global population exposed to significant aircraft noise levels will increase by 78% from 2005 to 2025 due to the projected increase in number of aircraft operations (26). Significant levels of aircraft noise in both cases are defined as people exposed to day–night average sound level (DNL) of 65 dB or higher; this metric is discussed in detail in the next section.

Thresholds and Standards

Noise levels are measured using a variety of scientific metrics. As a result of extensive research into the characteristics of aircraft noise and human response to that noise, standard noise descriptors have been developed for aircraft noise exposure analyses. Some of these descriptors are described below.

A-Weighted Sound Pressure Level, dBA or AL. The decibel is a unit for describing sound pressure level. When expressed in dBA (in the United States) or AL (in Europe), the sound has been filtered to reduce the effect of very low and very high frequency sounds, much like the human ear does. Without this filtering, calculated and measured sound levels would include events that the human ear cannot hear (e.g., dog whistles and low-frequency sounds such as the groaning sounds made from large buildings with changes in temperature and wind). With the A-weighting, calculations and sound monitoring equipment approximate the sensitivity of the human ear to sounds of different frequencies. Some common sounds on the dBA scale are listed in Table 17.3. As shown in the table, the relative perceived loudness of a sound doubles for each increase of 10 dBA, even though a 10-dBA change corresponds to a change of relative sound energy by a factor of 10. Generally, sounds with differences of 2 dBA or less are not perceived to be noticeably different by most listeners.

Maximum Noise Level, L_{max}. L_{max} is the maximum or peak sound level during a noise event. This metric only accounts for the instantaneous peak intensity of the sound, and not for the duration of the event. As an aircraft passes by an observer, the sound level increases to a maximum level and then decreases. Some sound-level meters measure and record the maximum, or L_{max}, level.

Table 17.3 Common Sounds on the A-Weighted Decibel Scale

Sound	Sound level (dBA)	Relative loudness (Approximate)	Relative sound energy
Rock music, with amplifier	120	64	1,000,000
Thunder, snowmobile (operator)	110	32	100,000
Power mower	100	16	10,000
Orchestral crescendo at 25 ft, noisy kitchen	90	8	1,000
Busy street	80	4	100
Interior of department store	70	2	10
Ordinary conversation, 3 ft away	60	1	1
Quiet automobiles at low speed	50	1/2	.1
Average office	40	1/4	.01
City residence	30	1/8	.001
Quiet country residence	20	1/16	.0001
Rustle of leaves	10	1/32	.00001
Threshold of hearing	0	1/64	.000001

Source: *Aircraft Noise Impact—Planning Guidelines for Local Agencies*, Washington, DC: U.S. Department of Housing and Urban Development, 1972.

Sound Exposure Level, SEL or L_{AE}. Sound exposure level (SEL in the United States or L_{AE} in Europe) is a time-integrated measure, expressed in decibels, of the sound energy of a single noise event to a reference duration of 1 sec. The sound level of a noise event (for the duration that the sound level exceeds a specified threshold) is integrated over the 1-sec period to account for both the magnitude of the sound level and the duration of the sound. The standardization of discrete noise events into a 1-sec duration allows the calculation of the cumulative noise exposure of a series of noise events that occur over a period of time. Because of this compression of sound energy, the SEL of an aircraft noise event is typically 7–12 dBA greater than the L_{max} of the event. SEL values for aircraft noise events depend on the location of the aircraft relative to the noise receptor, the type of operation (landing, takeoff, or overflight), and the type of aircraft and engine.

A-Weighted Day-Night Average Sound Level, DNL. DNL, also denoted as L_{dn}, is expressed in dBA and represents the noise level over a 24-hr period. DNL includes the cumulative effects of a number of sound events rather than a single event. It also accounts for increased sensitivity to noise during nighttime hours. The DNL values are used to estimate the effects of specific noise levels on land uses. The calculation of DNL applies a 10-dB-weighting penalty (equivalent to a 10-fold increase in aircraft operations) for each hour during the nighttime period (10:00 p.m.–7:00 a.m.) before the 24-hr value is computed. The weighting penalty accounts for the more intrusive nature of noise during the nighttime hours.

The EPA introduced the DNL metric in 1976 as a single-number measurement of community noise exposure. The FAA adopted DNL as the noise metric for measuring cumulative aircraft noise under FAR Part 150, *Airport Noise Compatibility Planning*. DNL is expressed as an average noise level based on the average daily aircraft operations for a calendar year and the average annual operational conditions at the airport; it does not represent average noise levels associated with different aircraft operations.

To calculate the DNL at a specific location, SEL values at that location associated with each individual aircraft operation (landing, takeoff, or overflight) are determined. Using the SEL for each noise event and applying the 10-dB penalty for nighttime operations as appropriate, a partial DNL value is then calculated for each aircraft operation. The partial DNL values for each aircraft operation are added logarithmically to determine the total DNL.

The logarithmic addition process, whereby the partial DNL values are combined, can be approximated by the following guidelines:

When two DNLs Differ By	Add the Following Amount to the Higher Value
0 or 1 dBA	3 dBA
2 or 3 dBA	2 dBA
4 to 9 dBA	1 dBA
10 dBA or more	0 dBA

For example:

$$70 \text{ dBA} + 70 \text{ dBA (difference : 0 dBA)} = 73 \text{ dBA}$$

$$60 \text{ dBA} + 70 \text{ dBA (difference : 10 dBA)} = 70 \text{ dBA}$$

Adding the noise from a relatively quiet event (60 dBA) to a relatively noisy event (70 dBA) results in a value of 70 dBA because the quieter event has only 1/10 of the sound energy of the noisier event. As a result, the quieter noise event is "drowned out" by the noisier one, and there is no increase in the overall noise level as perceived by the human ear.

Day–Evening–Night Average Sound Level (Lden). The European Parliament and Council issued an environmental noise directive (2002/49/EC) that stipulates the use of Lden to assess aircraft noise. Lden is an indicator of the overall noise level during the day, evening, and night, which is used to describe the annoyance caused by exposure to noise. In addition to assigning a 10-dB penalty for nighttime noise, Lden assigns a 5-dB penalty for the 4-hr evening period (6:00–10:00 p.m.).

DNL (in the United States) and Lden (in the European Union) are used to describe existing and predicted noise exposure in communities in an airport environs based on the average daily operations over the year and the average annual operational conditions at an airport. Therefore, at a specific location near an airport, the noise exposure on a particular day is likely to be higher or lower than the annual average exposure, depending on the specific operations at the airport on that day.

Noise Modeling

In 1978, the FAA released the first version of a computer simulation model designed to assess aircraft noise exposure. Known as the integrated noise model (INM), it has become the standard tool in the United States for modeling airport noise. The INM generates noise exposure contours and noise levels at individual locations and provides a graphical image of aircraft noise levels for a selected geographic area. While the EU has not adopted a single noise model for the calculation of Lden, the European Civil Aviation Conference (ECAC) has issued guidance on computing noise contours around civil airports (27). The ICAO has also developed guidance promoting a uniform method of assessing noise around airports (28). Version 7.0 of the INM is compliant with the ECAC guidance and is also based on the ICAO guidance (29).

The INM computes DNL using an internal database that includes performance characteristics and noise data for a wide variety of civilian and military aircraft. Noise exposure levels are calculated from airport-specific data that are input into the model. The input includes runway coordinates, flight tracks, fleet mix, activity levels, runway and flight track utilization, average local temperatures, time of day, and departure trip length data. The INM correlates these data with the internal aircraft database using a series of algorithms that calculate noise exposure. The INM database incorporates detailed information about each aircraft type, including departure profiles for different trip lengths, approach profiles, and SEL noise curves based on distances and various thrust settings. The outputs of these calculations include plots of points that connect to form noise contours, or points of equivalent sound level. The INM is typically used to model average annual aircraft noise exposure, that is, the average sound level over an average 24-hr period of both busy and quiet times for the airport.

Other output from the INM include the area within each contour, noise measurements at locations (referred to as grid points), and SEL curves or values for specific aircraft types. The SEL curves can be used to estimate SEL for a specific aircraft type depending on how far the aircraft is from a listening point or observer and the estimated thrust setting. The validity and accuracy of DNL and Lden calculations depend on the basic information used in the calculations.

A model based on the INM computational core, the Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA), was developed by the FAA and the ICAO CAEP to assess the number of people exposed to significant levels of aircraft noise worldwide. This model has evolved over time with the FAA and CAEP utilizing different methodologies to develop aviation forecasts as input into the model. Another FAA program, the Noise Integrated Routing System (NIRS), is the FAA's standard regional noise model, used to assess noise effects over large regions (e.g., multistate regions).

As mentioned previously, the FAA is in the process of developing the AEDT, a software tool to integrate combined noise and air quality modeling on the flight, airport, regional, and global scales. The AEDT is planned for release in 2011 and will replace the INM, EDMS, MAGENTA, and SAGE and will also include the functionality of the NIRS model for regional airspace analysis (30).

Assessment of Effects

Inextricably linked with aircraft noise is land use—the effects of aircraft noise are typically evaluated by identifying the noise-sensitive land uses and population exposed to specific levels of aircraft-generated noise. Noise-sensitive land uses include residences, schools, parks, hospitals, churches, wildlife refuges, and other settings where quiet or the expectation of quiet is an intrinsic feature. The noise contours of aircraft-generated noise define the geographic extent of land uses and population that are exposed to a specific noise level; the edge of the noise contour demarks the limits of noise exposure to that specific noise level. In other words, everything within the noise contour is exposed to an average annual noise level of that specified amount or higher.

Typically noise contours for airport projects are generated for existing conditions and then for future no-action and future-action (proposed action and any reasonable alternatives to the proposed action) contours. For future airport activities, the reliability of DNL and Lden calculations is affected by a number of uncertainties:

- Future aviation activity levels—the forecast number of aircraft operations, the types of aircraft serving the airport, the times of operation (daytime, evening, and nighttime), and aircraft flight tracks—are estimates. Achievement of the estimated levels of activity cannot be assured.
- Acoustical and performance characteristics of future aircraft are also estimates. When new aircraft designs are involved, aircraft noise data and flight characteristics must be estimated.
- Single flight tracks used in computer modeling represent a wider band of actual flight tracks.

These uncertainties aside, noise contour mapping was developed as a tool to assist in land use planning around airports. The mapping is best used for comparative purposes rather than for providing absolute values. That is, DNL and Lden calculations provide valid comparisons between different projected conditions as long as consistent assumptions and basic data are used for all calculations.

Thus, sets of DNL and Lden calculations can show anticipated changes in aircraft noise exposure over time or differences in noise exposure associated with different airport development alternatives or operational procedures. However, a line drawn on a map does not imply that a particular noise condition exists on one side of that line and not on the other. DNL and Lden calculations provide a means for comparing noise exposure under different scenarios.

Nevertheless, DNL and Lden contours can be used to (a) highlight an existing or potential aircraft noise problem that requires attention, (b) assist in the preparation of noise compatibility programs, and (c) provide guidance in the development of land use controls, such as zoning ordinances, subdivision regulations, and building codes. DNL and Lden are still considered to be the best noise metrics available for expressing aircraft noise exposure (31).

The evaluation of noise effects is determined by comparing the no-action and future-action contours for the same timeframe. According to FAA Order 1050.1E, a significant noise impact is considered to occur if analysis shows that the future action would increase noise by DNL 1.5 dB or more at noise-sensitive areas exposed to aircraft noise of DNL 65 dB and higher when compared to the no-action alternative for the same timeframe. Figure 17.1 provides an example of aircraft noise contours overlaid on land use.

Table 17.4 shows suggested land use compatibility guidelines promulgated by the FAA in Federal Aviation Regulation (FAR) Part 150. These guidelines are based upon the statistical variability of the responses of large groups of people to noise. However, as individual responses to any given noise environment may vary, these guidelines may not accurately reflect individual perception of or reaction to an actual noise environment. For purposes of determining compatible or incompatible land uses, predicted or measured DNL levels and applicable land uses are compared to the guidelines. Estimates of total noise exposure resulting from aircraft operations, as expressed in DNL, can be interpreted in terms of the probable effect on land uses.

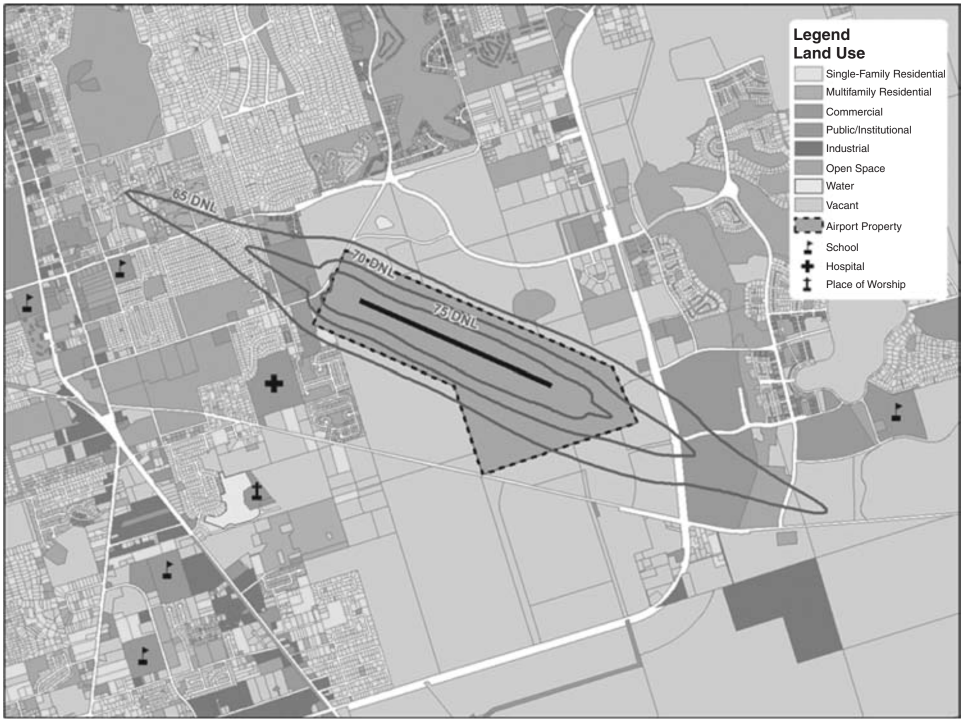

Figure 17.1 Aircraft noise contours over land use example.

Each generalized land use listed in Table 17.4 describes a wide range of human activity with various sensitivities to noise. The DNL values included in the table are only applicable to potential aircraft noise effects on people located in areas surrounding airports. The noise analysis produces specific DNL values; however, the noise descriptors used as the basis for calculating DNL represent typical human response (and reaction) to aircraft noise. Because people vary in their responses to noise and because the physical measure of noise accounts for only a portion of an individual's reaction to that noise, DNL can be used only to obtain an average response to aircraft noise that might be expected from a community. The ultimate determination of what constitutes acceptable land use within specific noise contours is the responsibility of local authorities.

Minimization of Effects

The mitigation of aircraft noise effects takes a variety of forms. Aircraft manufacturers are continuing research in lighter aircraft, different airframe construction, and different engine technologies to find ways to minimize aircraft noise at the source. The FAA and EUROCONTROL are instituting and developing flight procedures to minimize aircraft noise as well, such as continuous descent approach (CDA) and area navigation (RNAV) procedures, which allow aircraft to fly precisely defined arrival and departure routes. RNAV routes are typically established to ensure that aircraft overfly less noise-sensitive areas, avoiding populated areas. Airport sponsors in the United States initiate FAR Part

Table 17.4 Suggested Land Use Compatibility Guidelines in Aircraft Noise Exposure Areas

Land use	DNL 65–70	DNL 70–75	DNL 75+
Residential			
Residential other than mobile homes and transient lodgings	NLR required[a]	NLR required[a]	Incompatible
Mobile homes	Incompatible	Incompatible	Incompatible
Transient lodgings	NLR required[a]	NLR required[a]	Incompatible
Public use			
Schools, hospitals, and nursing homes	NLR required[a]	NLR required[a]	Incompatible
Churches, auditoriums, and concert halls	NLR required[a]	NLR required[a]	Incompatible
Governmental services	Compatible	NLR required	NLR required
Transportation	Compatible	Compatible[b]	Compatible[b]
Parking	Compatible	Compatible[b]	Compatible[b]
Commercial use			
Offices, business, and professional	NLR required	NLR required	NLR required[b]
Wholesale and retail—building materials, hardware, and farm equipment	Compatible	Compatible[b]	Compatible[b]
Retail trade—general	NLR required	NLR required	NLR required
Utilities	Compatible	Compatible[b]	Compatible[b]
Communication	NLR required	NLR required	NLR required
Manufacturing and production			
Manufacturing—general	Compatible	Compatible[b]	Compatible[b]
Photographic and optical	Compatible	NLR required	NLR required
Agriculture (except livestock) and forestry	Compatible	Compatible	Compatible
Livestock farming and breeding	Compatible	Compatible	Incompatible
Mining and fishing resources production and extraction	Compatible	Compatible	Compatible
Recreational			
Outdoor sports arenas and spectator sports	Compatible[c]	Compatible[c]	Incompatible
Outdoor music shells, amphitheaters	Incompatible	Incompatible	Incompatible
Nature exhibits and zoos	Compatible	Incompatible	Incompatible
Amusements, parks, resorts, and camps	Compatible	Compatible	Incompatible
Golf courses, riding stables, and water recreation	Compatible	Compatible	Incompatible

DNL = Day-night average sound level in A-weighted decibels.

Compatible = Generally, no special noise attenuating materials are required to achieve an interior noise level of DNL 45 in habitable spaces, or the activity (whether indoors or outdoors) would not be subject to a significant adverse effect by the outdoor noise level.

Incompatible = Generally, the land use, whether in a structure or an outdoor activity, is considered to be incompatible with the outdoor noise level even if special attenuating materials were to be used in the construction of the building.

NLR = Noise level reduction. NLR is used to denote the total amount of noise transmission loss in decibels required to reduce an exterior noise level in habitable interior spaces to DNL 45. In most places, typical building construction automatically provides an NLR of 20 dB. Therefore, if a structure is located in an area exposed to aircraft noise of DNL 65, the interior noise level would be about DNL 45. If the structure is located in an area exposed to aircraft noise of DNL 70, the interior noise level would be about DNL 50, so an additional NLR of 5 dB would be required if not afforded by the normal construction. This NLR can be achieved through the use of noise attenuating materials in the construction of the structure.

[a] The land use is generally incompatible with aircraft noise and should only be permitted in areas of infill in existing neighborhoods or where the community determines that the use must be allowed.

[b] NLR required in offices or other areas with noise-sensitive activities.

[c] Provided special sound reinforcement systems are installed.

Source: Ricondo & Associates, Inc., as derived from the U.S. Department of Transportation, Federal Aviation Administration, Federal Aviation Regulations Part 150, *Airport Noise Compatibility Planning*, Code of Federal Regulations, Title 14, Chapter I, Subchapter I, Part 150, Table 1, January 18, 1985, as amended.

150 studies specifically to identify and implement noise abatement procedures, including "fly quiet" programs and other voluntary measures. As a last resort, noise mitigation measures such as sound insulation or purchase of homes affected by significant noise may be considered to mitigate aircraft noise effects.

The ICAO Assembly adopted a policy to address aircraft noise in September 2001 which is referred to as the "balanced approach" (Appendix C of Assembly Resolution A36-22). The balanced approach consists of identifying a noise problem at an airport and then analyzing measures to reduce the noise using four approaches: (a) reduction of noise at the source, (b) land use planning and management, (c) noise abatement operational procedures, and (d) operating restrictions* Only where such action is supported by a prior assessment of anticipated benefits and of possible adverse impacts. (32). The FAA's Part 150 program generally utilizes this same approach with the exception of operating restrictions. In the United States, airport operators cannot implement operating restrictions at an airport unless an FAR Part 161 study is completed and approved by the FAA. An FAR Part 161 study examines the consequences of implementing operating restrictions and must meet six statutory conditions:

1. Is reasonable, nonarbitrary, and nondiscriminatory
2. Does not create an undue burden on interstate and foreign commerce
3. Maintains safe and efficient use of the navigable airspace
4. Does not conflict with federal law
5. Was developed through a process that afforded adequate opportunity for public comment
6. Does not create an undue burden on the national aviation system

In the 20 years since FAR Part 161 was enacted, no airport operator has yet received FAA approval to implement operating restrictions.

17.9 SOCIAL AND SOCIOECONOMIC RESOURCES

The effects of airports on social and socioeconomic resources can be both positive and negative. Large commercial airports provide employment for a large number of people, including airport management and maintenance staff, airline staff, firefighting personnel, security personnel, air traffic controllers, passenger and baggage screening personnel, and baggage handlers. In addition to direct employment generated by airports, indirect employment results from providing services to passengers, including car rentals, food vendors, taxi-cab drivers, hotel staff, restaurant staff, and gift and news shop vendors. When combined together, airports can have a significant economic impact on the surrounding region through the expenditures and tax revenue generated by employees and passengers. Some of the negative social and socioeconomic effects of airports can include displacement of homes and businesses, community disruption including effects on planned development, increased traffic congestion, risks to human health, and environmental justice concerns.

The displacement of homes and businesses can occur with construction of new airports, expansion of existing airports, or efforts to mitigate significant noise impacts. Airports require a considerable amount of land to accommodate safely and efficiently runways and other infrastructure. Because airports represent significant investments by both the community and the government and these investments are closely tied to the economic well-being of a community or region, airport development or expansion needed to maintain the economic health of the airport may require the acquisition and relocation of nearby properties, including homes or businesses. Although property owners have rights and may not wish to relocate, if implementing the airport project is deemed to provide greater benefits to society than not implementing it, local governments typically exercise the right of eminent domain. In the United States, the FAA and/or airport owner must follow the requirements of the Uniform Relocation Assistance and Real Property Acquisition Policies Act of 1970 (42 U.S.C. 4601), which requires that fair market value be given to the property owner(s) along with assistance to identify and relocate to a comparable property.

When airport development includes land acquisition and relocation, the overall effect on the community must be considered. Airport development can disrupt a community if a significant portion of a neighborhood or community would be relocated or if the neighborhood or community would be bisected by airport development. In these cases, an airport may be required to provide additional assistance to the homes and businesses that may not be directly affected by the project but would experience loss of community or may not be able to continue operating as a business due to the severity of impact. Airport development can also affect planned development if it prevents development from occurring as planned by the local planning agency. Other common negative effects of land acquisition programs are landlocked parcels (cutting off access to property), severed parcels (acquiring a portion of property that cuts it off from adjacent property owned by the same landowner), and uneconomical remnants (acquiring only the portion of property needed for development and leaving a piece that has no economic value to the landowner).

Airports also generate considerable amounts of vehicular traffic. Access trips by airline passengers, employees, suppliers, and cargo operators all can contribute to surface traffic volumes that may cause congestion on area intersections and roadways. Projects that increase airport capacity can increase roadway congestion, interfere with existing traffic patterns, reduce the level of service of area intersections and roadways, route construction traffic through residential areas, or have other negative effects on surface transportation. Consideration must be given to providing sufficient roadway capacity to accommodate increased airport traffic, reduce congestion, maintain the level of service on area intersections and roadways, and minimize construction traffic effects when planning and implementing airport projects.

The Sixth Environment Action Programme of the EU emphasizes the need to achieve a quality of the environment that does not give rise to significant impacts on or risks to human health. Specifically, it proposed to identify the risks to human health, including that of children and the elderly, and setting standards based on those identified risks. In the United States, Executive Order 13045, *Protection of Children from Environmental Health Risks and Safety Risks*, requires federal agencies to identify and assess environmental health risks and safety risks that may disproportionately affect children. In general, health risks associated with the construction and operation of airports include noise; air quality; water quality; and the transport, storage, and/or generation of hazardous waste. Typically the potential effects to health associated with these resources are assessed during the specific assessment of the resource categories, but the specific health risk should also be evaluated as a potential social impact.

The concept of environmental justice arose in the United States in the 1980s when a number of studies found that a disproportionate share of hazardous and polluting industries were located in communities composed primarily of minority and/or low-income populations. Executive Order 12898, *Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations*, was issued by the president in 1994. The order requires all federal agencies to consider whether a disproportionate share of a federal action would affect minority or low-income populations. This analysis usually requires the use of census data to identify minority and low-income populations in the vicinity of an airport and then determine whether a project would adversely affect those populations disproportionate to other populations in the area.

17.10 WASTE MANAGEMENT

Waste management at airports includes consideration of both solid and hazardous waste. Solid waste is generated at airports during construction (demolition and construction debris), operation (passengers in the terminal and on airplanes), and maintenance activities (landscape debris, light bulbs, etc.). Hazardous waste can be present at airports due to aircraft fueling, aircraft maintenance (if present), rental car maintenance (waste oil), emergency generators, and other activities. Hazardous waste may also be present at an airport due to past activities that may have contaminated soil or water or because hazardous waste is being transported by plane or vehicle onto airport property.

Environmental concerns related to solid waste include the volume of waste generated requiring disposal in area landfills and the location of landfills in relation to runways and flight paths. Many airports have active recycling and reuse programs aimed at reducing the amount of solid waste generated and transported to landfills. Because municipal waste landfills can attract seagulls and other scavengers, the FAA has issued guidance recommending that these types of landfills be located at least 5 mi from runways serving turbine-powered aircraft to minimize risks associated with aircraft–wildlife strikes (33).

Several laws have been enacted in the United States governing the handling and disposal of hazardous materials, including the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA or Superfund) and the Community Environmental Response Act of 1992. For airport projects, the FAA must consider whether an action would generate, disturb, transport or treat, store, or dispose any hazardous materials. If so, then a remediation or treatment plan must be developed as well as containment measures in the event of a spill or release.

The Sixth Environment Action Programme includes objectives to develop a system for the evaluation and risk management of chemicals as well as banning the use of the most hazardous pesticides. European Union policy concerning waste is aimed at reducing the amount of waste generated, maximizing the recycling and reuse of waste, and improving final disposal and monitoring. The EU encourages the safe disposal of waste that cannot be recycled or reused by incineration and discourages waste disposal into landfills. The landfill directive, issued in 1999, establishes strict standards for landfill management, banning certain types of wastes from landfills, and sets targets for reducing the amount of biodegradable waste in landfills. Biodegradable waste is a significant producer of carbon dioxide (CO_2) and methane (CH_4), both of which are greenhouse gases.

17.11 WATER RESOURCES

Airport construction and operation can directly and indirectly affect water resources through physical impacts to surface waters (such as streams, rivers, and lakes) or wetlands, through impacts to the quality of surface waters and groundwater, and through increases in storm water quantity.

Direct, physical impacts to surface waters and wetlands occur when airport facilities are located such that they disrupt water movement through the placement of fill in a water body or through dredging. During planning, consideration to avoiding the impact to a surface water or wetland should be considered, and if avoidance is not possible, consideration of minimizing the impact should be given. If development does directly affect a water resource, mitigation of the impact, such as improvements to wetland resources elsewhere, may be required.

Impact to water quality is the most common water resource issue facing airports during construction and operation. Water quality effects typically result from impairing the quality of storm water runoff by increasing its load of contaminants.

During construction, removal of natural ground cover and other airport construction practices can result in soil erosion and sedimentation entering the storm water runoff and receiving water bodies. An increase in the sediment load in storm water runoff not only can lead to clogged drainage structures and flooding but also is detrimental to biological activity, because it filters out light and covers the bottom of lakes and streams, which affects habitats supporting fish and plant species.

Storm water runoff can be affected by airport operations such as the use of chemicals for snow and ice removal, accidental fuel and oil spills on the aprons, and the discharge of firefighting foam used for aircraft emergencies. Wastes associated with the fueling, operation, and cleaning of aircraft may also be carried to nearby lakes and streams through the storm drainage system. Fuel spills and leaks, oil and grease deposits, and harsh cleaning detergents can be serious sources of water pollution unless such wastes are collected and treated. Other operational activities at an airport can affect water quality through contaminants in storm water runoff such as major aircraft overhaul activities that use toxic chemicals to remove paint and clean and rechrome engine parts and other light-industrial-type activities.

To minimize effects to storm water runoff, airport operators implement storm water pollution control practices for construction activities (measures such as use of siltation control to minimize soil erosion and sedimentation) and operations (measures such as spill control plans to ensure infrastructure controls and a plan of action are in place to quickly respond to spills).

Airport development typically involves the construction of vast expanses of runways, taxiways, buildings, aprons, and other impermeable surfaces. These impermeable surfaces decrease the infiltration of rainwater into the ground and increase the quantity of runoff and the likelihood of flooding. Coordinated and cooperative regional planning may be required to ensure that the capacity of the streams to absorb waste is not exceeded and that their usefulness to downstream communities is not jeopardized.

Other water resource considerations during construction and operation of an airport include quantities of sanitary wastewater generated by the airport and effects to coastal lands.

Sanitary wastewater is generated by passengers, employees, and visitors during activities such as toilet use, washing, and food preparation. This wastewater must be treated to remove inorganic solids and dissolved impurities and to destroy disease-causing organisms. Sanitary treatment capacity must be sufficient to meet the demands of an airport, so coordination with municipal sanitary treatment plants may be required.

Airports are frequently constructed along coastal lands where subsurface materials may be weak and unstable. In these circumstances, it may be necessary to relocate channels and drain and fill swampy areas. Proposed earthwork changes of this nature should be undertaken only after the hydrologic impact has been carefully evaluated and considered. When airports are located in coastal areas, the decreased infiltration of rainwater may lower the groundwater table. The lowered groundwater table may allow seawater to intrude into aquifers, which serve as a source of fresh water for nearby residents. Hydrologic studies should be made to measure the impact of decreased infiltration, and in extreme cases it may be necessary to recharge the groundwater artificially to prevent salinity intrusion.

The United States has enacted several laws to protect water quality and water resources, including the Federal Water Pollution Control Act (Clean Water Act), the Safe Drinking Water Act, the Fish and Wildlife Coordination Act of 1980, the Coastal Zone Management Act, and the Coastal Barrier Resources Act. The Clean Water Act provides the federal government the authority to set water quality standards, control discharges into water bodies, protect wetlands, and protect aquifers. Before approving an action that may affect wetlands or floodplains, federal agencies in the United States are required to demonstrate that they have avoided or minimized any impacts to wetlands and floodplains to the extent practicable.

Water quality standards in Europe were adopted in the mid- to late 1970s and updated by the drinking water directive adopted in 1998. The water framework directive was adopted in 2000, which sets protections for all surface and groundwater and established that these waters should be managed by the river basin instead of geopolitical boundaries. Not only does the water framework directive concern itself with water quality standards, it also provides protections for groundwater quantities, limiting annual withdrawals to the annual recharge rates.

Water supply (or source of potable water) for airport uses, is also an issue at a number of U.S. airports, especially in arid regions of the country. Innovative uses of rainwater and “grey” water (water collected from sinks and other nonsanitary uses) are being explored and implemented to reduce water consumption.

17.12 SUSTAINABLE DEVELOPMENT

The concept of sustainable development and increasing the sustainability of airport operations has become an important consideration for many airport sponsors and airlines. In 1983, the United Nations assembled the Brundtland Commission (or the World Commission on Environment and Development) to address an escalating concern over “the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development" (34). With the exponential growth of the human population, the commission explained, improved global management was essential to prevent the exhaustion of the earth's finite resources for future generations. Thus, the Brundtland Commission introduced the term "sustainable development," defining it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The term "sustainability" has evolved as it has become increasingly incorporated into many different businesses, processes, and industries, including the aviation industry, especially since the late 1990s. Despite this evolution, the concept of sustainability still draws on the original definition established by the Brundtland Commission, although various organizations and individuals have interpreted it differently. As of mid-2010, various initiatives and high-level policy, in the case of the EU, have been enacted, but neither the United States nor the European Union have a unified set of guidelines or interpretation yet of how to guide sustainable airport development and operation. Thus far, the incorporation of sustainability concepts has been primarily driven at the local level, with various trade, industry, and governmental groups developing and providing guidance to airport sponsors.

An example of this is a research project sponsored by the Airport Cooperative Research Program (ACRP), part of the Transportation Research Board of the National Academy of Sciences in the United States. The ACRP project defined an airport sustainability practice as "a broad term that encompasses a wide variety of practices applicable to the management of airports" (35). The ACRP report documented practices that ensure (a) protection of the environment, (b) social progress, and (c) the maintenance of high and stable levels of economic growth and employment. These three aspects of sustainability (environmental, social, and economic) encompass what is commonly referred to as the "triple bottom line" approach to sustainability.

Another example is the Sustainability Working Group of the Environmental Affairs Committee, Airports Council International-North America (ACI-NA), which defined airport sustainability as "a holistic approach to managing an airport so as to ensure the integrity of the economic viability, operational efficiency, natural resource conservation and social responsibility (EONS) of the airport" (36). The ACI-NA definition has taken the triple bottom line one step further to include the operational aspects of airports.

The FAA, as of mid-2010, did not have an official policy relating to sustainability, beyond encouraging airport sponsors to include sustainable considerations when planning and designing airport projects. However, the FAA has been involved in initiatives such as the Sustainable Aviation Guidance Alliance (SAGA). SAGA consists of a diverse range of airport associations and aviation interests, including representatives from the Airport Consultants Council (ACC), the American Association of Airport Executives (AAAE), the Air Transport Association of America (ATA), the FAA, and other airport representatives and consultants. SAGA released a resource guide (37) and database (38) in 2009 to assist airports in developing and implementing sustainability programs.

The European Commission issued a communication on sustainability in 2001, titled "A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development" [COM (2001) 264]. The communication outlined a strategy for sustainable development that relied on economic, social, environmental, and global governance pillars or aspects. Three specific objectives of the EU strategy are to limit climate change, limit the adverse effects of transport, and develop transport that is environmentally friendly and conducive to health. A 2009 review of the strategy found that, for transportation sources, consumption of nonrenewable energy sources and greenhouse gas emissions continues to rise, although the EU has committed to having 10% of all transport energy be derived from renewable energy sources by 2020 (39).

The Global Reporting Initiative (GRI) was established in 1998 to develop a mechanism for reporting and measuring the sustainability performance of organizations; the United Nations Environment Programme (UNEP) joined GRI as a partner in 1999. In 2000, GRI released its first sustainability reporting guidelines. Since that time, GRI has developed guidelines for specific economic/business sectors such as logistics and transportation; draft guidelines for the airport operators sector were available in 2010 (40). However, the GRI guidelines are focused on how to report sustainability performance, not how to improve performance and operations in terms of sustainability.

The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED®) has developed a green building certification system to measure the design, construction, operation, and maintenance of buildings. The LEED® certification system focuses on energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources. While the LEED® certification system is focused on buildings, concepts from the system have been utilized to develop sustainability programs at airports. Two examples of these types of programs are the *Sustainable Airport Manual* (41) and the *Sustainable Airport Planning, Design and Construction Guidelines* (42), implemented at Chicago O'Hare International Airport and Los Angeles International Airport, respectively.

The *Sustainable Airport Manual* contains guidance on sustainable practices that cover administrative procedures, sustainable site management, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, construction practices, and innovation in the design/construction process. The purpose of the manual is to identify airport-specific sustainable planning techniques and practices that can be implemented early in the design process. Other airports and airport sponsors that have established sustainability programs include Frankfurt International Airport, Greater Toronto Airports Authority, Halifax Stanfield International Airport, Montreal Airports, Schiphol Airport Group, Stansted Airport, and Vienna International Airport. Airlines such as Virgin Atlantic are also taking leading industry roles in integrating sustainability concepts into their operations.

Because sustainability is essentially defined within and by organizations, each of these efforts is somewhat unique, reflecting the values and site-specific conditions at each airport or within each organization. In other words, although some sustainability practices may be common among a number of airports or organizations, no two sustainability programs are going to be exactly alike. Partly this reflects local geography, local environment, and the demographics of the surrounding community, but it also reflects the priorities and values of the airport sponsor/organization and community. As airports and the airline industry evolve, it is anticipated that sustainability practices and concepts will become fully integrated into the organization and that the industry will continually evaluate ways to ensure that airport and aircraft operations are sustainable for future generations.

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