Third Edition

AIRPORT ENGINEERING

NORMAN ASHFORD / PAUL H. WRIGHT

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To Joan and Joyce

PREFACE

This book has been rewritten, in its third edition, to continue to serve as a basic text for courses in airport planning and design. It will, we believe, be of valuable assistance to airport designers, planners, and administrators, as well as consultants involved in airport planning and design. This edition is a complete update of the 1984 Second Edition, taking account of major revisions to FAA, ICAO, and IATA recommendations and guidelines which have occurred in recent years. Furthermore, the revisions take account of the experiences of the two authors in teaching postgraduate short courses throughout the world.

The book begins with a concise description of the various international, national, and local organizations and agencies which affect air transportation and the manner in which airports are financed. A chapter on demand forecasting describes both traditional methods and new methods using disaggregate analysis. There is a brief coverage of material which has been found to be useful with respect to aircraft characteristics and the control, lighting, and signing facilities which are provided as an aid to air navigation.

The growing need for resource planning for air transport is covered in a new chapter on airport systems planning, and the revised chapter on airport master planning reflects the updated thinking in the latest publications in this area by ICAO and FAA. Examples of the design methods used for passenger and cargo terminals are the result of well-tested workshops which have been run in our recent courses. The fundamental principles of airport layout and design are treated, as are capacity analysis, geometric design, airport drainage, and pavement design. A completely new chapter has been added dealing with the safety aspects of design decisions.

In this new edition, we have continued in our attempt to emphasize areas of current and emerging concerns. Hence, we have included two entirely new chapters on airport systems planning and design for safety. Furthermore, significant new material has been added to the chapters dealing with demand, passenger and cargo terminals, and access. Also an important update is the revised chapter on V/STOL facilities, which has been rewritten to reflect current thinking on air side design requirements for tiltrotor aircraft.

In preparing this book, we have drawn freely from publications of the Federal Aviation Administration and the International Civil Aviation Organization. Materials published by the Air Transport Association and the International Air Transport Association were also useful sources of reference, as were publications of various aircraft manufacturers, airline companies, and other governmental agencies and industry organizations. We appreciate the use of these materials. Finally, we gratefully acknowledge the assistance of Robert Caves, Vic Hewes, Valerie Ehrendreich, and Vivien Grove who directly contributed to the preparation of the material for this book. Their help has been invaluable in producing what we hope will be a book of use to many others.

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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 less than 100 years since the first brief flight of the Wright brothers at Kitty Hawk, N.C., and Bleriot's later historic crossing of the English Channel. Before the early years of this century, except for the infrequent use of nonpowered balloons, man had been restricted to the earth's surface. Now civil aviation is a major international industry that carries over a billion passengers each year in aircraft which fly an aggregate of close to 1.5 billion km. 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 (1)

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:

> 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 1990, the original 26 ratifying states had grown to 160 member states. The modus operandi of 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 ICAO is the Assembly, in which each contracting state has one vote, the governing body of the organization is the 30 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 (Table 1.1) to the Convention on International Civil Aviation.

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, to provide a forum for industry views, and to establish industry practices.
2. *Airports Association Council International (AACI).* This organization was founded in 1991 as an association of civil airport authorities, established to serve as a forum and a focus for the views and interests of civil airport operators. The AACI 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.
3. *Institute of Air Transport (ITA).* An association of individuals and organizations with interest in civil aviation.

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.

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 of, and reporting on 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

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

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

1.4 U.S. GOVERNMENTAL ORGANIZATIONS (2)

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

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

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 Transport 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 all types of transportation in the United States are conducted safely. The Board 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.

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 varies 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 *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

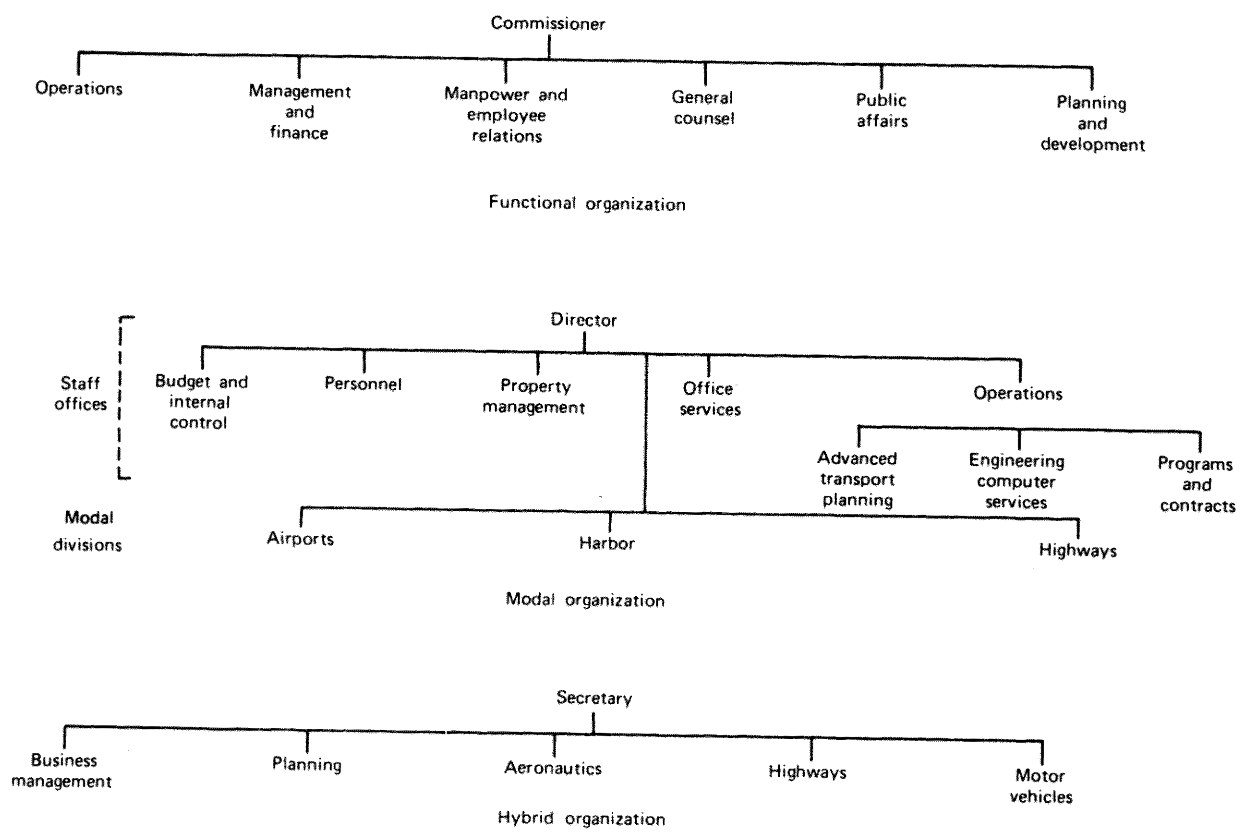

FIGURE 1.1 The aviation function within state Departments of Transportation.

capability of private finance, and the private airport operator has 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 the U.S. domestic civil aviation and progress toward de facto deregulation of the 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.

Neglecting the rather extraordinary situation in the United Kingdom, elsewhere the tendency toward public ownership has been generally international, but the form of public ownership varies from country to country. The principal forms of ownership include 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; 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. Private organizations.

An examination of international patterns of ownership indicates no special trends. France, Italy, West Germany, Holland, and the United States have the majority of their airports run by individual airport authorities. Most developing countries, as well as South Africa, Australia, Canada, Sweden, Spain, Japan, Mexico, and Belgium, own and operate their airports through centralized organizations that are part of the national government. In Brazil, where commercial aviation exhibits considerable growth potential, airport policy matters are decided by the Ministry of Aeronautics; administration of the airports is carried out by a national holding company INFRAERO (Empresa Brasiliera de Infraestrutura Aeroportuaria).

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 the 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, washrooms, 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. *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.
4. *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.
5. *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 to 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 become larger. The overwhelming source of both revenue and expenditure remains in the operating category. The low level of non-

TABLE 1.2 Income and Expense Breakdown for Airports Having Different Levels of Operational Activity

	Annual Enplanements		
Income or Expense	<500,000 (17 airports)	500,000-2,000,000 (15 airports)	>2,000,000 (11 airports)
Income			
Operating income (%)	95.7	98.5	92.2
Nonoperating income (%)	4.3	1.5	7.8
Expenses			
Operating expenses (%)	91.4	86.4	87.0
Nonoperating expenses (%)	8.6	13.6	13.0

Sources: Airport Operators Council International Uniform Airport Financial Report.

operating expense at U.S. airports reflects high levels of FAA funding for infrastructure. In fundamentally differently financed systems, nonoperating costs could rise substantially higher.

The Structure of Revenues

Operating revenues vary considerably from airport to airport, in structure and in size. Their structure depends greatly on operating volume. (Since non-operating revenues are, by their nature, not dependent on the operating characteristics of the airport, they tend to be unpredictable.) As the number of airport operations increases across the range of airport size, the busier airports attract a higher proportion of commercial air carrier operations. The larger passenger capacity of commercial carrier aircraft ensures a disproportionate

TABLE 1.3 Operating Revenue Source Distributions by Annual Enplaning Passenger Numbers at Air Carrier Airports

	Enplaned Passengers (%)				
Category	Over 2 Million	500,000– 2 Million	250,000– 500,000	125,000– 250,000	Under 125,000
Airfield area					
Air carrier landing fees	25.1	22.5	19.0	16.5	8.9
Other landing fees	0.4	0.6	1.0	1.2	2.3
Fuel and oil sales	0.9	4.6	10.0	10.6	8.4
Airline catering fees	1.1	3.3	—	—	—
Aircraft parking	0.1	1.1	1.9	1.9	2.6
Total airfield	27.6	32.1	31.9	30.2	22.2
Hangar and building area	11.4	11.6	13.6	20.2	43.9
Terminal area	12.8	13.3	18.7	14.8	10.5
Systems and services	4.3	3.1	4.0	4.0	4.0
Concessions					
Airport parking	19.7	15.5	11.5	11.0	2.1
Car rental	8.2	10.3	10.2	8.0	6.8
Restaurant and lounge	4.8	5.5	5.9	3.5	2.5
Advertising	0.6	1.2	0.9	1.5	1.2
Ground transportation	1.9	1.9	0.7	1.9	0.2
Flight insurance	2.3	2.4	0.7	0.7	0.5
Hotel/motel	1.8	1.6	0.1	1.5	0.1
Miscellaneous	4.6	1.5	1.8	2.7	6.0
Total concessions	43.9	39.9	31.8	30.8	19.4

Source: Airport World Survey.

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

TABLE 1.4 Sources of Annual Terminal Revenues at U.S. Airports

	Small Airports	Medium Airports	Large Airports
Average number of operations	172,311	146,841	338,554
Average number of enplanements	215,375	649,118	3,891,175
Revenue Category	Revenue Percentage	Revenue Percentage	Revenue Percentage
Landing Area[a]	34.3	40.2	26.5
Terminal Area			
Car rentals	8.2	8.8	7.9
Parking	10.9	15.4	16.9
Restaurant, bars	5.0	5.0	6.2
Hotel	—	0.1	0.1
Advertising	0.7	0.6	0.8
Limousines, taxis	0.6	0.7	0.4
Flight insurance	1.0	1.8	1.9
Coin-operated devices	0.5	0.8	1.6
Speciality shops, etc.	—	0.7	5.4
Parking meters	—	1.8	1.2
Personal services	—	—	0.1
Buses	—	—	1.5
Miscellaneous	0.2	0.4	0.1
	27.1	36.1	44.1
Aviation leased areas[b]	25.3	16.4	16.5
Other leased areas[c]	3.0	2.6	6.7
Other areas[d]	10.3	4.7	6.2
Total	100.0	100.0	100.0

[a]Includes leasing fees, fuel, fixed-base operations (FBO), hangar rentals, ramp tiedowns, and so on.
[b]Includes terminal and building.
[c]Includes buildings, grounds, farms, residences, parking leases, warehouses, FBOs, and facilities.
[d]Includes services, utilities, equipment rental, government reimbursements, gross business overrides, and military.
Source: Airport World Survey.

dominance of terminal income. The financial stability of the operation of large airports is strongly related to the income generated by the terminal area. More than half this income relates to surface access in the form of parking charges and leases to car rental firms (Table 1.4), 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 requirements 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.

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, 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 toward 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, by 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, several reorganizations and retitlings later, is now the Federal Aviation Administration (FAA). During the war years, the Civil Aeronautics Administration, in the interests of national defense, spent approximately $353 million for the development and construction of military airports; approximately $9.5 million went for civilian airports during the same period.

Toward the end of the war, 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, with a further $20 million for the Virgin Islands, Puerto Rico, Alaska, and Hawaii. 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, with a further $2 million for Alaska, Hawaii, Puerto Rico, and the Virgin Islands, 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 use taxes: 8% tax on airplane tickets, flat rate airport head taxes of $3 for passengers going abroad or to Hawaii and Alaska, a domestic cargo tax of 5% on tariffs, a 7¢/gal tax on noncommercial aviation fuel, and an airplane registration tax of $25 plus a levy based on the engine weight type. The act substantially increased the amount of federal funds available for airport development. Each year, $250 million was 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. Included were the purpose 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; runway and taxiway lights; touchdown lights for category II and III runways (see Section 6.7), high-intensity runway lights, obstruction lights, beacons, taxiway guidance lights, runway centerline lights; buildings associated with safety, such as the airport fire and emergency buildings; and roads, streets, and rapid transit facilities. In the original version (1970) of the act, terminals, car parking hangars, and administration buildings were absent from the list of facilities for which federal funds could be used.

Over the 10-year period of the act, planning funds were 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 from $280 million to $310 million annually, 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). These amendments increased the level of annual authorization for airport development to $500 million in 1976, climbing to $610 million in 1980. 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 nonrevenue-producing areas in the passenger terminal and for passenger transfer vehicles on both the air side and the land side.

Significant 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). Major funding over a six-year period was authorized for airport improvement, ranging from $450 million in 1982 to $1017 million in 1987. The same act authorized sums over the same period, ranging from $261 million to $1164 for facilities and equipment associated with air traffic control and navigation, and a further $800 million to $1362 million 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

TABLE 1.5 Federal Share (Percentage of Project Costs)

	Type of Airport	
Type of Project	Large Primary Airports[a]	All Other[b]
Individual airport planning[c]	75	90
Airport development[c]	75	90
Noise compatibility programs[c]	80	90
Terminal development	75	75[d]

[a] Large primary airports are primary airports that enplane 25% or more of the total annual U.S. enplanements. Approximately 70 airports qualify as large primary airports.
[b] This column includes all public-use airports not included in the first column.
[c] There may be an upward adjustment to these rates in Alaska, Arizona, California, Nevada, New Mexico, Oregon, Utah, and Washington due to the high percentage of federally owned lands in them.
[d] This rate is applicable only to commercial service airports. The remaining airports are not eligible for terminal development.

under the former program, with increases between 10% in 1984 to 30% in1987. State apportionments amount to 12% of total apportionment. In the contiguous United States, 99% of the states' apportionments are 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 were 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 (PL 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, 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.

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

For the purposes of federal administration, airports in the United States are functionally classified as shown in Figure 1.2. There are more than 16,000 airports in the United States, of which approximately 6000 are open to public use. All airports which are considered to contribute significantly to the national

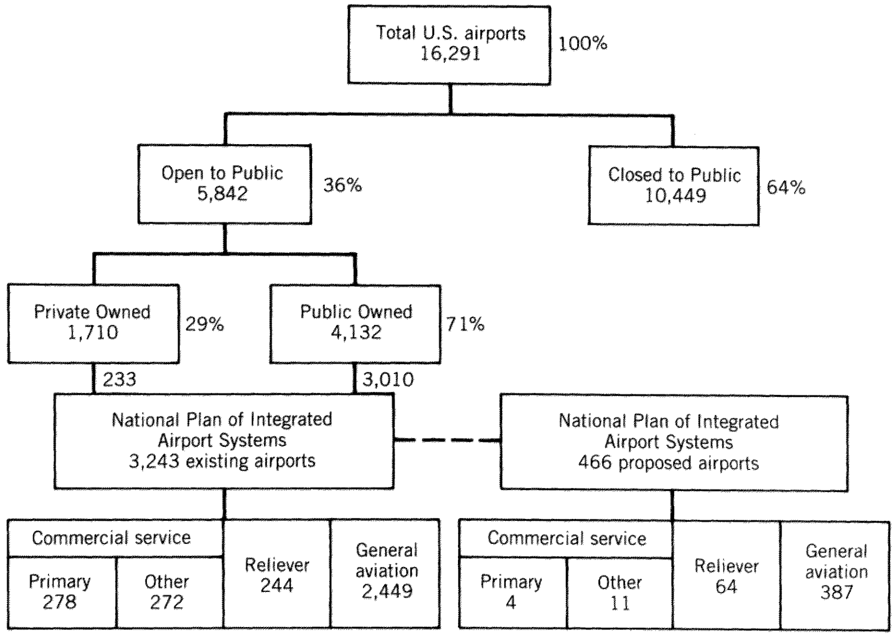

FIGURE 1.2 A classification of the U.S. airport system number of airports by ownership and public use as of March 31, 1986. (Source: FAA)

transportation system and which are open to the public are included in the National Plan of Integrated Airport Systems (NPIAS). Four categories of airport comprise the airport classification system:

Commercial Service Primary Airport. A public airport that receives scheduled service and enplanes 0.01% or more of total annual enplanements of all commercial service airports. In 1982, this lower limit of 0.01% approximated to 31,000 enplanements.

Other Commercial Service Airport. A public airport receiving scheduled service and enplaning 2500 or more annual passenger enplanements, but less than the 0.01% required for the primary category.

Reliever Airport. A public airport in a metropolitan area which is intended to reduce congestion at a large air carrier airport by providing alternative general aviation facilities. In the early 1960s, Congress provided priority funding in special legislation to develop these airports. When originally set up, the classification required that the reliever airport should have an activity level of at least 50 based aircraft, 2500 itinerant operations, or 35,000 local operations. The relieved airport should be operational at 60 percent of its capacity, at least, and should either serve a standard metropolitan statistical area (SMSA) of 500,000 population or should have 250,000 annual enplanements. A general aviation airport is normally included in the NPIAS if it satisfies any one of a number of criteria: significant local, regional, or national interest; receiving U.S. mail service; significant military activity; status of a general aviation heliport with more than 400 itinerant operations by air taxi, or have more than 810 itinerant operations, or have four based aircraft.

General Aviation Airport. The FAA has established general aviation airport categories based on aircraft design. In the NPIAS, some general aviation airports may have a very small amount of scheduled commercial service—less than 2500 annual enplanements. For convenience, these are classified as general aviation and are generally suitable for lightweight aircraft with approach speeds of 120 knots or less.

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

In a mode in which demand is continuously increasing at a significant rate, an estimate of the magnitude of demand at future points in time is essential. However, the forecasting of future demand is a difficult and uncertain procedure, and, when forecasts are incorrect, an entire transportation mode is either deficient in its ability to provide for future traffic or is suffering from overinvestment and poor economic performance.

Throughout the entire postwar period, until the early 1970s, the growth rate of air transport had been consistently underestimated by most competent authorities. During this period, the unexpected growth in air transport could be associated with rapid population growth, increasing industrialization in developing countries, changes in the industrial structure in developed countries, worldwide urbanization, and, not least, rapid and marked technological changes. Forecasters of the early 1970s attempted to correct for the underestimations of previous years, developing procedures which were serious overestimates of the traffic of the 1980s—a period which provided a climate of real increases in oil prices, inflation, and a worldwide recession of unprecedented postwar depth. The uncertainties of the early 1990s have again faced the forecasters with problems.

In spite of the difficulties associated with making forecasts of air transport demand, such estimates are necessary, for the following reasons:

1. To assist manufacturers in industry to anticipate levels of aircraft orders and to develop new aircraft.
2. To aid airlines in their long-term planning for both equipment and personnel.
3. To assist central governments to facilitate the orderly development of the national and international airways system, and to aid all levels of government in the planning of infrastructure (including, e.g., terminal

facilities, access routes, runways, taxiways, aprons, and terminal air traffic control).

2.1 POSTWAR TRENDS IN AIR TRANSPORT

Accurate forecasts of air passenger and freight demand proved to be extraordinarily difficult in the past, when over an extended period rapid advances in technology continued to lower the real costs of air transport to the consumer. For example, a 1963 forecast by the FAA predicted that 100 million passengers would be transported by U.S. carriers in 1975. By the year 1971, however, the number of persons carried was already 174 million, and, by 1979, this figure was 321 million. This pattern of very buoyant expansion of demand at an exponential growth rate is typical of a demand curve of an infant industry, in which supply costs fall as demand rises. As the industry continues to mature, real air transport costs tend to stabilize at higher levels of demand, given that some input costs, such as labor, fuel, and vehicle costs, remain constant in real terms. High early growth will give way to lower, steadier rates of increase that reflect population growth, modified by the factors of socioeconomic change.

During the period 1972–1987, as shown in Figure 2.1, the overall world growth of scheduled passenger kilometers was at an average rate of 7.6% (1). Figure 2.2 and Table 2.1 show the long-term regional trends which make up the total world growth over this period, indicating that the growth rates of the individual region vary significantly from average figures (2, 3). It can be seen that European and North American growth rates have been somewhat similar

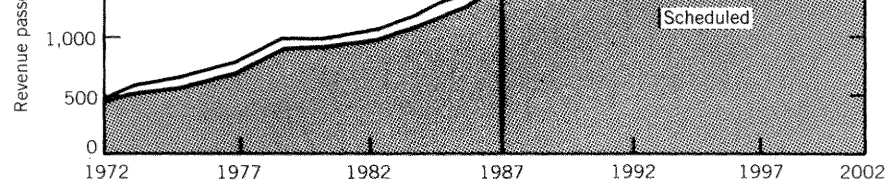


FIGURE 2.1 Total world passenger traffic. (*Source*: McDonnell Douglas, Reference 1)

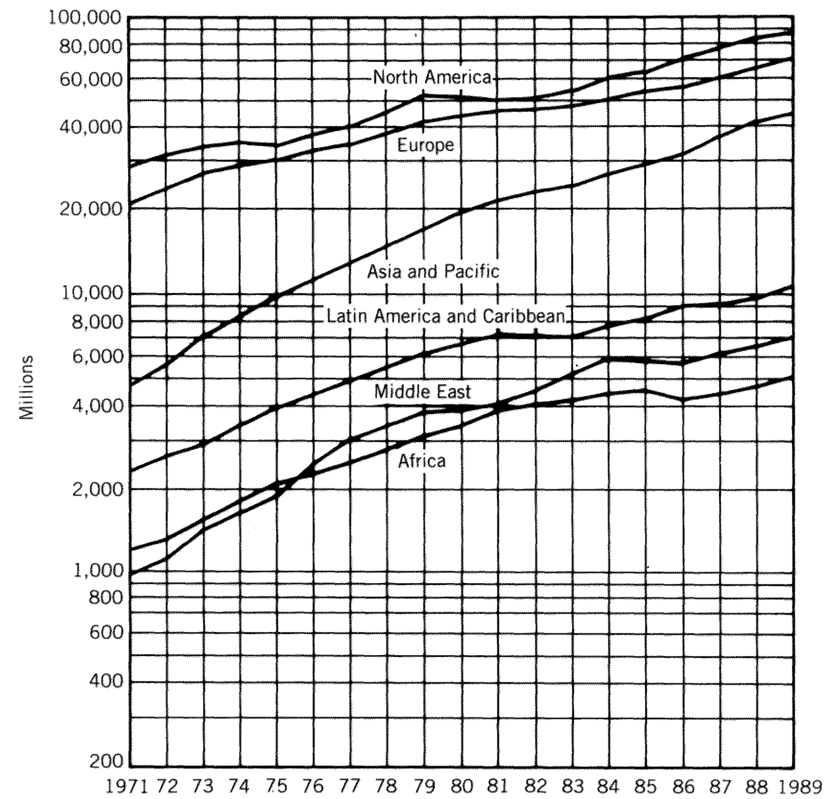


FIGURE 2.2 Long-term regional trends in air transport. (*Source*: I.C.A.O.)

to each other. Asia and the Pacific demonstrate higher than average rates, and Africa, a lower than average rate. The increased share of the Asian and the Pacific region in comparison with other regions over the period 1979–1988 is indicated in Table 2.2. The economic problems of the African region during the 1980s is reflected in depressed demand for air transport (2).

When considered in terms of overall freight movement, air freight represents a miniscule portion of ton mileage; in the United States, less than 0.4%. However, if the cost of transport is measured, this share becomes approximately 3%, since modal choice is affected by commodity value, length of haul, and commodity vulnerability. A particularly fast-growing sector of this freight market is door-to-door or express air freight. The growth of Federal Express, an initiator of the express freight concept is exemplified by its growth in turnover from 35,000 packages per night in 1978 to 1.5 million in 1991. The value of this business is entirely out of proportion to the tonnage moved in terms of general freight or even conventional air freight.

In the United States, the domestic air transport industry has matured since World War II and now represents a strong and significant mode, cater-

TABLE 2.1a World Air Passenger Traffic—Actual and Forecast 1969–2010

	Revenue Passenger Km (in billions)					
	Actual			Forecast		
Region No. and Area	1969	1980	1988	1995	2000	2010
1. North-South America	5	15	15	23	32	58
2. North-Central America	7	21	31	46	62	112
3. North Atlantic	38	110	170	234	304	489
4. Mid Atlantic	3	10	13	18	22	32
5. South Atlantic	4	11	16	23	31	51
6. & 7. Europe-Africa	8	26	33	52	73	142
8. Europe-Middle East	6	24	25	31	40	63
9. Europe-Far East	13	67	115	209	305	623
10. North & Mid Pacific	8	42	99	223	385	1065
11. South Pacific	3	9	21	32	44	87
12. Intra-North America	2	9	12	18	25	52
13. Intra-Central America	—	1	1	2	3	4
14. Intra-South America	1	4	4	7	10	22
15. Intra-Europe	21	49	78	119	159	264
16. Intra-Africa	—	1	3	4	6	13
17. Intra-Middle East	1	6	6	8	11	20
18. Intra-Far East & Pacific	5	38	89	191	312	780
19. Other Routes	1	13	24	28	34	50
20. U.S. Domestic	167	329	523	683	865	1410
21. Canada Domestic	7	20	20	24	29	42
22. Britain Domestic	2	3	4	6	8	14
23. France Domestic	2	9	17	27	39	70
24. Japan Domestic	7	29	39	63	87	162
25. Central America Domestic	1	7	7	15	21	42
26. South America Domestic	4	17	23	39	63	145
27. Europe Domestic	7	18	26	39	50	79
28. & 29. Africa Domestic	2	6	7	9	14	32
30. Middle East Domestic	1	7	8	12	15	26
31. Far East Domestic	4	14	37	80	127	298
32. Australasia Domestic	5	9	16	16	22	40
33. USSR Domestic	72	151	199	201	221	352
34. Domestic Totals	280	621	924	1215	1563	2709
35. International Totals	127	458	756	1271	1857	3928
36. Total All Regions	408	1079	1679	2487	3420	6637

Source: Douglas Aircraft Company.

ing to intercity movement of freight and passengers (3). U.S. air passenger mileage grew from 4.3 billion passenger miles in 1945 to 334 billion passenger miles in 1988, representing approximately 90% of all intercity passenger

TABLE 2.1b Passenger Traffic RPK Growth Rates—Actual and Forecast 1969–2010 (% per annum average)

	Actual	Forecast		
Region No. and Area	1969–1989	1989–1999	1999–2010	1989–2010
1. North-South America	5.92	6.42	5.99	6.19
2. North-Central America	7.59	5.47	6.33	5.92
3. North Atlantic	7.96	4.89	5.07	4.98
4. Mid Atlantic	8.17	4.04	3.84	3.94
5. South Atlantic	7.57	5.64	5.24	5.43
6. & 7. Europe-Africa	7.57	6.49	7.08	6.78
8. Europe-Middle East	7.80	3.88	4.76	4.34
9. Europe-Far East	12.04	8.21	7.56	7.87
10. North & Mid Pacific	14.35	11.51	11.04	11.26
11. South Pacific	10.31	6.78	7.16	6.98
12. Intra-North America	10.18	5.23	8.05	6.70
13. Intra-Central America	11.66	5.32	4.50	4.89
14. Intra-South America	8.76	9.01	8.30	8.64
15. Intra-Europe	7.08	5.84	5.33	5.57
16. Intra-Africa	8.89	5.83	8.45	7.19
17. Intra-Middle East	10.31	4.08	6.11	5.14
18. Intra-Far East & Pacific	16.67	10.58	9.89	10.22
19. Other Routes	16.23			
20. U.S. Domestic	5.87	4.44	5.17	4.82
21. Canada Domestic	5.77	3.08	3.85	3.48
22. Britain Domestic	5.23	5.29	5.07	5.18
23. France Domestic	10.56	6.92	6.24	6.56
24. Japan Domestic	9.17	6.71	6.47	6.58
25. Central America Domestic	10.40	7.60	6.92	7.24
26. South America Domestic	8.52	10.08	8.86	9.42
27. Europe Domestic	7.34	5.19	4.81	4.99
28. & 29. Africa Domestic	7.08	7.35	8.75	8.08
30. Middle East Domestic	14.23	4.96	5.52	5.25
31. Far East Domestic	12.18	11.04	9.10	10.02
32. Australasia Domestic	4.51	6.27	6.31	6.29
33. USSR Domestic	5.42	0.24	4.77	2.59
34. Domestic Totals	6.25	4.47	5.79	5.16
35. International Totals	9.75	7.51	7.96	7.75
36. Total All Regions	7.59	5.98	7.01	6.52

Source: Douglas Aircraft Company.

mileage (4) (see Table 2.3). During the same period, domestic air freight increased from 0.09 to 9.30 billion ton miles—an average increase of 11.3%. However, during the late 1970s and early 1980s, the growth rate in domestic cargo declined significantly. During the period of severe recession, air cargo traffic declined in absolute terms by 7% between 1978 and 1980. It is clear

TABLE 2.2 Regional Distribution of Scheduled Air Traffic; 1988 vs. 1979
(Percentage of total tonne-km performed by airlines registered in each region)

Region	All Services		International		Domestic	
	1988	1979	1988	1979	1988	1979
North America (Canada and United States only)	39.3	41.5	21.5	21.2	59.5	59.8
Europe	31.0	34.0	35.5	40.9	25.8	27.5
Asia and Pacific	19.9	14.0	28.9	21.4	9.6	7.4
Latin America and Caribbean	4.6	5.0	5.7	6.7	3.5	3.5
Middle East	3.0	3.0	5.0	5.5	0.8	0.8
Africa	2.2	2.5	3.4	4.3	0.8	1.0
ICAO World	100	100	100	100	100	100

Source: ICAO.

TABLE 2.3 U.S. Domestic Shares of Passenger and Goods Movement

Mode	Year 1945	1960	1970	1980	1988
	A. Intercity Travel: Billions of Passenger Miles (Percentages Shown in Parentheses)				
Private auto	220.3 (63.8)	706.1 (90.4)	1026.0 (86.9)	1312.1 (83.6)	1586 (80.8)
Private air	Negligible	2.3 (0.3)	9.1 (0.8)	15.0 (1.0)	12.1 (0.6)
Public air	4.3 (1.2)	31.7 (4.1)	109.5 (9.3)	203.2 (12.9)	334.2 (17.0)
Bus	27.4 (7.9)	19.3 (2.5)	25.3 (2.1)	27.7 (1.8)	23.1 (1.2)
Rail	93.5 (27.1)	21.6 (2.8)	10.9 (0.9)	11.5 (0.7)	12.8 (0.6)
Total	345.5 (100.0)	781.0 (100.0)	1180.8 (100.0)	1569.5 (100.0)	1968.2 (100.0)
	B. Intercity Freight: Billions of Ton Miles (Percentages Shown in Parentheses)				
Rail	691 (67.2)	579 (44.1)	771 (39.7)	932 (37.5)	1031 (37.0)
Truck	67 (6.5)	285 (21.8)	412 (21.3)	560 (22.5)	703 (25.2)
Oil pipeline	127 (12.4)	229 (17.4)	431 (22.3)	579 (23.3)	604 (21.9)
Great Lakes	113 (11.0)	99 (7.5)	114 (5.9)	93 (3.7)	79 (2.8)
Rivers and canals	30 (2.9)	121 (9.2)	205 (10.6)	318 (12.8)	355 (12.7)
Air	0.09 (0.01)	0.89 (0.07)	3.3 (0.17)	4.27 (0.17)	9.3 (0.32)
Total	1028 (100.0)	1314 (100.0)	1936 (100.0)	2486 (100.0)	2781 (100.0)

Source: Transportation Facts and Trends, 17th Ed.

that air cargo demand is closely related to domestic economic conditions and tends to fluctuate more than passenger traffic. It is a general rule, however, that, while the air mode accounts for only a tiny fraction of the total ton mileage of freight carried, it represents a significantly large proportion of traffic on a value basis.

2.2 CONVENTIONAL METHODS OF FORECASTING

Conventionally, forecasting of future air traffic demand has been carried out at the macroscopic scale, viewing demand as a response to the overall levels of change of one or more variables. These very simple methods have been applied with reasonable success at the local, national, and international levels, in cases where rates of growth of traffic have been remarkably constant over time. Methods that have been used include judgment, surveys of expectation, trend forecasting, and base forecasting, which we now consider in turn.

Judgment

Under conditions of very limited growth, a crude but effective method of forecasting is the judgment estimate by a forecaster who is close to the problem and is able to integrate and balance the factors involved in the specific situation. The chances of success diminish as the complexity of the situation increases and the need for long-term forecasts predominates. Use of judgment can easily result in forecasting by hunches, a procedure that is abhorrent to analytical planners.

Surveys of Expectation

A technique not very widely used is the survey of expectation, directed to individuals in the air transport industry who might be said to be in a position to judge future trends. By selection of a broad range of interests in the selection of those surveyed, the forecaster hopes for a balanced view.

A refined procedure, which has become more widely used in general transportation planning, is *delphi analysis*—approaching the estimate of the future by applying an iterative procedure to a survey of expectation. In this procedure, experts make forecasts and then receive a feedback of results from the entire group of forecasters. After each iteration, the range of responses tends to narrow, and consensus is ultimately reached. In general, however, surveys of expectation are more suitable to aggregate forecasts at the regional or national levels than to disaggregate estimates at the airport level.

Trend Forecasting

Extensive use has been made of trend forecasting, in which the planner simply extrapolates, basing judgment on past growth figures. In short term, this

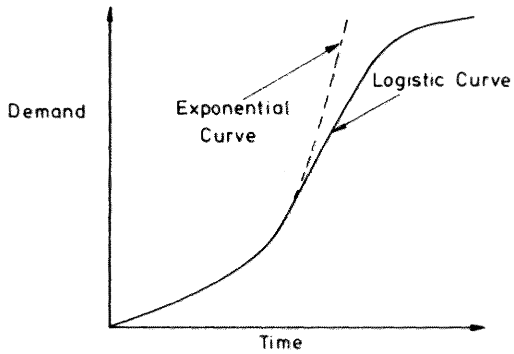


FIGURE 2.3 The logistic curve of growth.

technique is reasonably reliable, especially when the extrapolation procedure is carried out with modified growth rates to account for short-term disturbances in secular trends. In the long term, this type of extrapolation is likely to be most unreliable and is theoretically difficult to substantiate. Past experience with long-term trend forecasting has been less than satisfactory. Early trend forecasts were straight-line extrapolations that were almost always too low in the rapid growth years of the 1950s and the early 1960s. Forecasts over the next 10 years, that is, 1960–1970, were of an exponential nature, but opinion is now more conservative, reflecting an industry consensus that the curve of growth is more likely to be logistic (see Figure 2.3).

Base Forecasts on Ratios of National Forecasts

In the United States, a technique for air traffic forecasting widely used at the local level is the *base forecast* method, which assumes that a city's percentage of the annual national passenger volumes remains relatively constant over time. Airport forecasts are obtained by step-down percentages of national forecasts. The method suffers, however, from two serious limitations.

1. A percentage of national figures does *not* necessarily remain constant; rapidly growing areas attract more traffic demand in more static areas with primary sector economic bases may not change significantly. Extremely large errors will occur at airports which develop a hubbing function where previously no such function was carried out. Section 2.17 deals with route choice demand analysis, which can be used to estimate this effect.
2. National forecasts have been historically incorrect, as noted earlier.

Certainly, the method presents severe limitations in its application to Western Europe, where charter traffic is an important segment of total air passenger traffic; this traffic is particularly vulnerable to changes in fares.

Typically, two techniques have been used in the United States:

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 volumes 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 following ratio:

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

4. Obtain the national forecast of air passenger volumes per 1000 population for the design year.
5. From the ratio computed in step 3 and the national forecast of step 4, calculate the local passenger volumes per 1000 population.

The step-down method is useful when the market area of an airport can be reasonably well defined (e.g., the United States and Canada). In smaller countries, such as those of Western Europe, the market areas of many airports overlap and there is competition for passengers. In such conditions, the method is less useful. A typical example of a model of the step-down type was used in a Washington State study:

$$E_i = M_{i/j} \cdot M_{j/s} \cdot M_{s/us} \cdot E_{us} \tag{2.1}$$

where

E_i = domestic enplanement at i
$M_{i/j}$ = percent market share for airport i of scheduled domestic total enplanement in region j
$M_{j/s}$ = percent market share for region j of total state market s
$M_{s/us}$ = percent market share of state s of total U.S. market
E_{us} = total scheduled domestic enplanements in the United States.

2.3 ANALYTICAL METHODS OF AIR TRAVEL DEMAND FORECASTING

Trend forecasting is simplistic in that the technique looks at experience over time and attempts to continue the curve of historical demand in the light of general prognostications of overall conditions. Upturns or downturns in the general state of the economy are applied to past trends and are used to modify this macroscopic model.

In the past, in most nations, air transport appeared at one time to exhibit an exponential growth, with air passenger traffic figures compounding at a growth rate of approximately 10% per year during the 1950s and 1960s. Clearly, exponential growth can continue for a limited period, but in the long term it is more reasonable to expect that growth in the industry will adhere more to the logistic curve, which is the conventional historical curve of demand for a new technology.

The exponential curve leads fairly rapidly to unattainable levels of demand, but the logistic curve more realistically reflects the very rapid growth rates of demand at the point of introduction of the technology, where marginal production costs fall rapidly to an eventual saturation of the market at fairly constant marginal production costs. Thus, when trend forecasting is applied to the early part of the curve, it tends to give absurdly high long-term forecasts for demand functions that, in fact, follow the logistic form.

Analytical methods endeavor to overcome the grosser errors of trend analysis in trip generation by attempting to relate the level of traffic to changes in the level of a variety of causal or closely associated factors (5, 6). In the case of air traffic demand, it has been found that the number of trips made by the individual traveler depends not only on a number of socioeconomic variables outside the air transport system, such as income, employment type, and family structure, but also on system-based variables, including frequency and level of service (including speed and even comfort). As changes occur in these variables across the area being investigated, changes in demand levels can be predicted; these predictive procedures are capable of reflecting realistic changes over time in a manner that cannot be hoped for in trend forecasting.

Conventional analysis of traffic demand divides the modeling procedure into four distinct consecutive steps: generation, distribution, modal split, and assignment, as shown below:

Generation ⟶ Distribution ⟶ Modal choice ⟶ Assignment

Generation models indicate how many trips originate or terminate in a specific area; these models are often based on the socioeconomic characteristics of the area and the nature of the transport system. In the *distribution* phase, the trips are modeled as trip interchanges between specific pairs of origins and destinations, usually using some form of equilibrium model, with time or distance as the parametric impedance to travel.

Modal choice models split the interchanges into those specific to individual modes; choice normally is a function of the structure and nature of the transport system and the socioeconomic status of the trip market. *Assignment* models indicate which route is taken by the individual traveler from a choice of all available routes. Until deregulation came about, the assignment phase of the modeling chain had little relevance. Direct flights have increasingly given way to routings through hubs. A form of assignment model particular to the air transport mode, called *route choice modeling*, has been developed. This is discussed further in Section 2.17. The reader is referred to standard references on transport modeling for a more complete description of the model chain (7).

In the case of air transport, the model chain has frequently been simplified to a mode-specific chain of the following form:

Air trip generation ⟶ Air trip distribution

This simplified chain is inadequate insofar as it assumes that air traffic generations are peculiar to the mode itself and are not subject to modal choice dependent on the nature of the competing modes. Sections 2.5 to 2.8 give a more complete description of the various analytical models.

2.4 THE VARIABLES FOR PASSENGER DEMAND MODELING

Travel can be recognized as the product of four basic factors that must be accounted for in any realistic analysis that is attempting to predict demand over time. These basic factors are as follows:

A supply of people.
A motivation to travel.
Resources available for expenditure on travel in terms of time and money.
A transport infrastructure capable of supporting travel demand.

Over the long term, it is necessary to consider the nature of the factors underlying demand when attempting to make forecasts. Where a complete demand analysis is to be carried out, the procedure should consist of the following steps:

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. A base survey collecting the socioeconomic data that describe the status

of the population, the nature of the area, and the technological status of the system.
4. Establishment of relationships between the predictive variables and both levels and changes in levels of air transport demand.
5. Prediction of the anticipated level of the exogenous variables in the design year.
6. Prediction from the design year levels of the exogenous variables and predictive relationships of future demand levels.

Simplistic methods of prediction, such as trend forecasting, take explicit account of the first step only, and steps 2 to 6 are mixed with subjective judgment, with varying degrees of success.

In attempting to make more sophisticated predictions, the analyst must enumerate and quantify the variables that are likely to affect the level of demand. In the past, variables in the following areas have been used (8):

1. Demographic variables, including city size and population density.
2. Proximity to other large cities.
3. Economic character of the city.
4. Governmental activity, including promotional and regulatory policies, subsidy of competing modes, and energy conservation and balance-of-payments policies.
5. Fare levels.
6. Developments in competing transport modes.
7. Technological developments in the aircraft industry.
8. Adequacy of infrastructure provision of the air mode and competing modes.
9. Urban and regional development character.
10. Various other imponderables, such as sociocultural changes in leisure and work patterns, changes in communication technology, and secular changes in life patterns.

2.5 AIR TRIP GENERATION MODELS

In the process of generation, the analyst models directly the number of trip ends (or trip origins and destinations). The scale of the generation model can vary. At one end of the range it is possible to produce macromodels to describe and forecast aggregate levels of trip making at the national level, or disaggregated models related to individual airports and different trip purposes. Two principal techniques of analysis have been used: market analysis and regression.

Market Analysis

The market analysis approach normally assumes that an area's share of the total air transport market remains constant over time. National demand totals are estimated for the design date, usually by using straightforward trend forecasting or cross-classification (category analysis). In the short term, the assumption of constant total market share is likely to be reasonably valid, but, clearly, under changing economic and demographic conditions, the analyst can be less sanguine with respect to the accuracy of the premise.

Trend analysis for national demand totals can be carried out in a manner similar to that described in Section 2.2. Alternatively, the cross-classification analysis technique can be used: here it is assumed that individuals with different social, economic, and demographic characteristics demonstrate different and predictable air travel behavior that is constant over time. Based on a surveyed information base, travel demand is categorized for the different elements that comprise the total population; the variables used include income, age, employment type, family structure, and education. Demand rates are computed at each level of the predictive variables from base year survey data. Next, these trip rates are applied to the forecast national population disaggregated into its component parts by level of predictive variable. The aggregation of the component demand levels then gives total projected demand for the future population. A model of this type is often called a *propensity to fly* model. A somewhat modified form of the preceding procedure was used in conjunction with an inquiry into the siting of a new airport for London. In this case, the variables used for classification were *trip purpose, family income,* and *family structure.* The computed demand level was modified by a factor reflecting the *surface accessibility* of the trip origin to the site in question.

Regression Analysis

It is also possible to forecast air passenger transport demand with regression techniques. Statistical models for demand analysis have been widely used for many years in the prediction of urban passenger transport (8). When applied to air transport, a statistical relationship is established between rate of air trip generation (the dependent variable) and a number of predictive variables (the independent variables). The analysis is usually carried out by observing air trip generations from survey data and recording associated levels and changes of levels of socioeconomic data of the area and the physical characteristics of the overall origin-to-destination air-ground transport system. By the use of correlation analysis, factor analysis, or other multivariate statistical methods, suitable predictive variables are chosen that seem to be best capable of modeling air trip generation. Then regression models can be constructed to describe existing relationships, and these are used to forecast future air trip generations.

Typically, the air trip generation regression model would be of the following form:

$$T = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n \tag{2.2}$$

where

T = the number of air trips generated
$x_1, \dots x_n$ = the independent or predictive variables
$a_0, \dots a_n$ = regression constants

Models of this form are suitable for both national and local demand analysis. Variables most commonly used for the projection of travel generated in an area are population, income, type of employment, and accessibility of catchment population to the airport. For national aggregate levels of demand, gross domestic product has been found to be a most useful variable.

It is essential that in the relationships modeled there be not only statistical correlation but also a logical or implied causal relationship between the predicted and predictive variables. It is also most important that the predictive variables be largely independent of each other (8).

An example of a regression model used to predict the total air trip generation at an airport is that developed in Virginia (9):

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

where

E_i = predicted enplanements
P_i = population of hinterland
F = U.S. average airfare/mile
Y_i = per capita income of hinterland

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 air trip ends at the individual airports 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 the 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, the use of gravity model was advocated for predicting the air trip interchange between cities. The model took the following form:

$$T_{ij} = \frac{kP_iP_j}{d_{ij}^x} \tag{2.4}$$

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:

$$T_{ij} = \frac{kT_iT_j}{C_{ij}^x} \tag{2.5}$$

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 interstation 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

$$T_{ij} = k(T_iT_j)^p \tag{2.6}$$

where p is a calibrated parameter.

A modified form of gravity model was used in Canada:

$$T_{ij} = K \cdot \frac{P_i^{0.62}\ P_j^{0.35}}{D_{ij}^{0.56}} \cdot R_i^{4.88} \cdot A_j^{0.83} \cdot S_{ij}^{1.25}\ F_{ij}^{0.38}\ \ C_{h_i}^{-0.38}\ C_{h_j}^{-1.4} \qquad (2.7)$$

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_{h_i} = percent of manufacturing and retail employment of total employment at i

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

$$Y_{it} = a_i(F_{it})^{\alpha i}\ (I_{it})^{\beta i}\ (1 + \gamma_i)^{t-1} \qquad (2.8)$$

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 atutonomous 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 nonmode-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 found 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. Though 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:

$$\frac{T_{ijk}}{T_{ij}} = \frac{\exp(-\alpha C_{ijk})}{\sum_{r=1}^{n} \exp(-\alpha C_{ijk})} \qquad (2.9)$$

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

$$\log\left[\frac{T_{ijp}}{T_{ijq}}\right] = -\alpha\left[(M_{ijp} - M_{ijq}) + \lambda(t_{ijp} - t_{ijq})\right] \qquad (2.10)$$

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 model has been successfully used to analyze 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:

$$T_{ij} = r P_i^s P_j^t d_{ij}^u l_i^v l_j^w \tag{2.11}$$

where

T_{ij} = the volume of air passenger traffic between city i and city j
P_i, P_j = the populations of cities i and j
d_{ij} = the distance between i and j
l_i, l_j = the 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 2.11 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:

$$\frac{F_{ij}}{P_i P_j} = \alpha + \beta t + Q_{ij} \tag{2.12}$$

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:

$$T_{ij} = a(\alpha_i \text{GNP}_i)^b \ (\alpha_j \text{GNP}_j)^c \ \beta_{ij}^d \left(F_{ij} + A + \frac{B}{F_{ij} - C}\right) \tag{2.13}$$

where

T_{ij} = air traffic between stations i and j
α = station share of gross national product (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

$$\left(\frac{\Pi}{P}\right)_B = A + Mf_{y_B}\left[R_1(Z_0, Z_D)_{y-l}^P + \frac{R_2}{1 + [K(\overline{F}/I)^q]}\right] \tag{2.14}$$

Leisure

$$\left(\frac{\Pi}{P}\right)_L = A + Mf_{yL}\left[\frac{1}{1 + [K(\overline{F}/I)^q]}\right] \tag{2.15}$$

where

Π = 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
$\bar{F}$ = 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 (7) 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 mode by a set of variables that completely describe the pertinent attributes of a transport mode for the type of travel being considered (11). 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:

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

where

$\alpha_0, \alpha_1 \ldots, \alpha_7$ = regression constants
P_i, P_i = the populations of the two nodes
Y_i, Y_j = the median incomes at the two nodes
M_i, M_j = the institutional (industrial) indices of the two nodes
H_{ij} = the least required travel time
H_{kij} = the travel time by the kth mode
N_{ij} = the number of modes between i and j
C_{ij} = the least cost of travel between i and j
C_{kij} = the travel cost by the kth mode
D_{ij} = the best departure frequency from i to j
D_{kij} = the 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 (12). This model was applied to absolute levels of demand derived from the following regression models:

Business

$$\ln(T_{ij}) = -7.32 + 0.29\ln(P_i) + 0.37\ln(P_j) + 0.89\ln(Y_{ij}) - 0.33\ln(t_{ij}) \qquad (2.17)$$

Leisure

$$\ln(T_{ij}) = -15.65 + 0.31\ln(P_i) + 0.42\ln(P_j) + 1.40\ln(Y_{ij}) \qquad (2.18)$$

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 THE FAA FORECASTING SYSTEM (13)

The United States is unique in having a national system of air transport demand forecasting which is comprehensive of the whole system at various levels of disaggregation. These forecasts are carried out by the FAA providing information at three levels: national, hub, and terminal area. The structure of the total model is of the step-down type. Aggregate models of the regression type are developed at the *national* level. Where appropriate, these forecasts are stepped down to forecasts at the medium and large *hubs*. The 25 large hubs handle more than 65% of all passenger enplanements. A further step-down procedure is used to develop facility or *terminal area* forecasts.

Air carrier models are developed in five different areas:

1. Yield.
2. Route passenger miles.

3. Enplanements.
4. Operations.
5. Fleet structure.

Additionally, general aviation forecasts are developed in three areas: fleet structure, hours flown, and number of operations. These are discussed briefly in Section 2.16.

The U.S. national air carrier forecasts are modeled in a number of stages:

1. Yield, in terms of dollars per passenger mile, is predicted by a regression equation of the form

$$Y = a_0 + a_1 \cdot JF + a_2 \cdot W + a_3 \cdot ATM \quad \ldots \quad (2.19)$$

where

JF = jet fuel cost
W = wages
ATM = air transport movement per aircraft

2. Revenue passenger miles are then forecast from the equation

$$RPM = b_0 + b_1 \cdot \text{GNP} + b_2 \cdot Y \quad \ldots \quad (2.20)$$

where

GNP = real gross national product
Y = real yield

3. Using subjective and trend analysis, the following forecasts are made, based on historic trends and anticipated technology changes: *load factors, average number of seats per aircraft,* and *average passenger trip length*.
4. Forecast enplanements are calculated from

$$\text{Enplanements} = \frac{RPM}{\text{Average trip length}} \quad \ldots \quad (2.21)$$

The FAA method is a highly interactive procedure involving the FAA at headquarters and regional levels, the states, local governments, airport facility operators, air carriers, general aviation bodies, and aircraft manufacturers. This consultation is achieved via conferences, seminars, and published reports.

2.10 AIRPORT CHOICE MODELS (14)

It is not at all unusual for airport operators to speak of their passenger markets as coming from some undefined "catchment area," as though all travelers within this area are bound to use some particular airport. A little thought, however, leads one to the conclusion that this concept is untenable where an individual has a choice of airports to use, even if that choice is not immediately obvious. In 1976, de Neufville was one of the first to identify that the patterns of passenger usage were determined by both the passenger and the airlines. Drawing on available data, he argued that access distance largely determined airport attractiveness in terms of demand for short-haul flights but also that a high provision of flight frequency could overcome the disadvantage of poor access. Kanafani had earlier, in 1975, modeled competition among airports in the Los Angeles-San Francisco corridor using flight frequency, access time, and fare in an aggregate zonal model.

Since then, others have successfully built and calibrated airport choice models in a number of countries, using more robust disaggregate models. These can be used to predict the level of future airport usage under different provisions of service. Equally, the choice model can predict the effect of changes of service provision at competing airports and, importantly, the effect of introducing a new airport into the system.

A number of investigations have used the logit model of the form

$$P_{gk} = \frac{e^{V_{gk}}}{\sum_{r=1}^{e} e^{V_{rk}}} \quad \ldots (2.22)$$

where

P_{gk} = probability that alternative g will be chosen by individual k

$$V_{gk} = a_1 X_1 + a_2 X_2 + \ldots + a_n X_n \ldots \quad (2.23)$$

= representative function of the utility where

$a_1, a_2, \ldots a_n$ = parameters to be estimated
$X_1, X_2, \ldots X_n$ = explanatory variables

Based on data gathered in Central England, Benchemam and Ashford calibrated four models (15):

P_r (selecting airport)$_{\text{business}}$ = f(access time, flight frequency)

P_r (selecting airport)$_{\text{leisure}}$ = f(access time, flight fare, flight frequency)

P_r (selecting airport)$_{\text{inclusive tour}}$ = f(access time, flight flight frequency)

P_r (selecting airport)$_{\text{domestic}}$ = f(access time, flight fare, flight frequency)

Work by Harvey produced similar findings in the San Francisco Bay area (16):

P_r (selecting airport)$_{\text{business}}$ = f(access time, relative flight frequency, absolute flight frequency)

P_r (selecting airport)$_{\text{non-business}}$ = f(access time, flight frequency).

Similar success has been achieved in calibrating this model in developing countries (17).

The interesting conclusion which can be drawn from these models is that airport management can best attract passenger traffic to its airport by encouraging airlines to increase flight frequency at competitive fare levels.

2.11 LOAD FACTORS AND AIRCRAFT MIX

Any analysis of air transport demand must take into account the relationships between air passenger movements and aircraft movements. This relationship hinges on two factors: the load factor and aircraft mix.

The *load factor* is the ratio of passenger miles carried to seat miles operated. Operators naturally wish to maintain high load factors which make operation of the aircraft equipment profitable. Since average load factors cover both peak and off-peak operation, high load factors may indicate that some traffic is being turned away at peak times. This condition may be less profitable than accepting a lower overall load factor. Figure 2.4 shows international trends in load factors from 1971 to 1988. Since the oil crisis of 1973, airlines have attempted to increase their efficiency by increasing load factors. This has frequently been achieved by lowering the net yield per passenger kilometer by the introduction of low fares with restrictions on availability and by accepting standby passengers at very low fares. Because of the requirements of positioning aircraft and scheduling to avoid airport operational restrictions, load factors of over 80% are impossible on a system-wide basis. Forecasts of future load factors are made by using time series or trend analysis, recognizing the constraints of maximum feasible levels of this factor and the likely structure of future aircraft fleets.

In computing the number of aircraft operations that a facility can anticipate handling, a planner must keep abreast of expected changes in aircraft fleet mix which will affect the operations under consideration. Figure 2.5 shows projected aircraft fleet mix changes across the industry. Clearly, it is essential in designing an individual facility for the airport planner to confer with airlines to ensure that assumed fleet mix changes are in conformity with

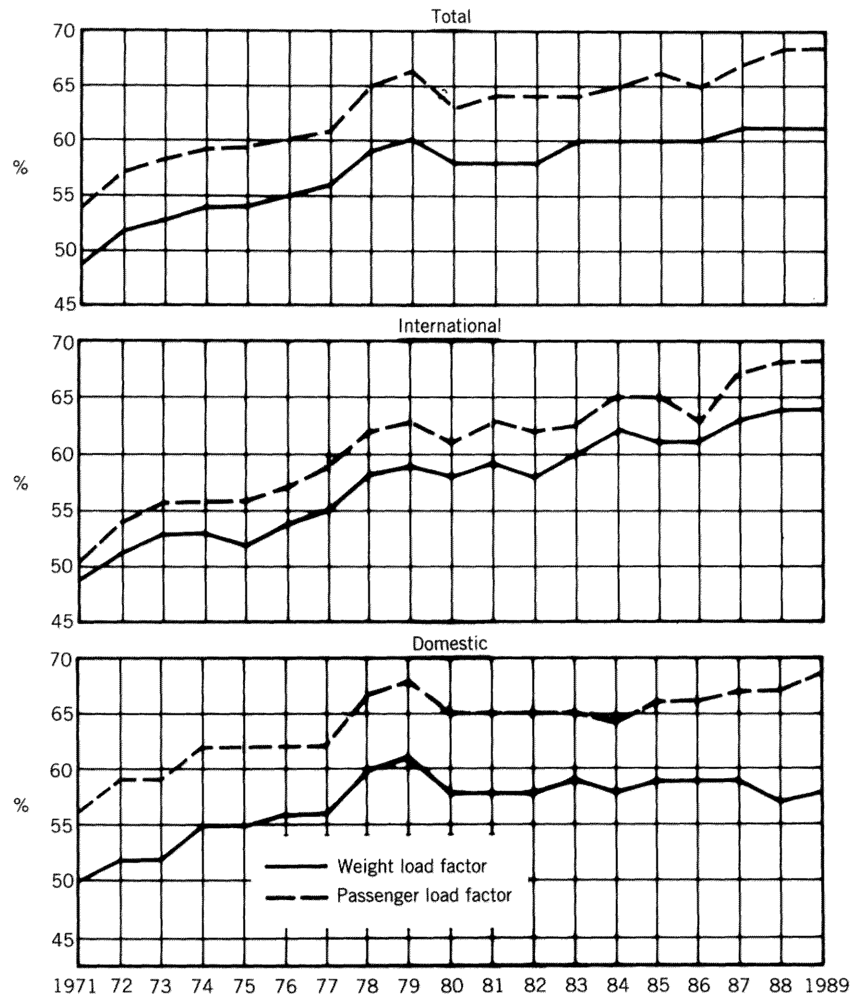


FIGURE 2.4 Trends in load factors on scheduled services—world averages (ICAO states), 1971–1988. (*Source*: Reference 2)

airline plans and that these plans correspond to the long-term expectations of the industry. Trends observable from Figure 2.5 appear to indicate the long-term phasing out of most propeller and turboprop aircraft and the increased use of wide-bodied jets. Judging what aircraft will be available and the timing of their introduction is extremely important and is perhaps the most difficult element of demand forecasting. The methodology used is shown in Figure 2.6 (18).

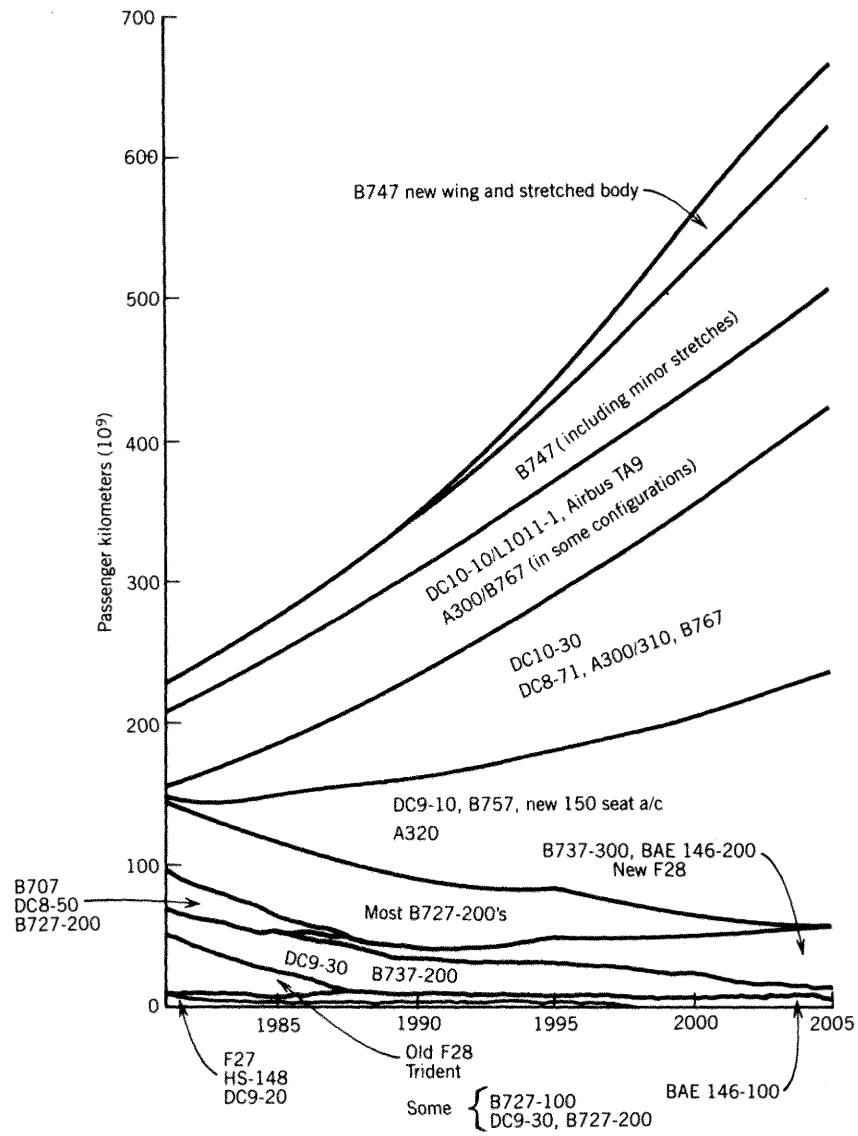
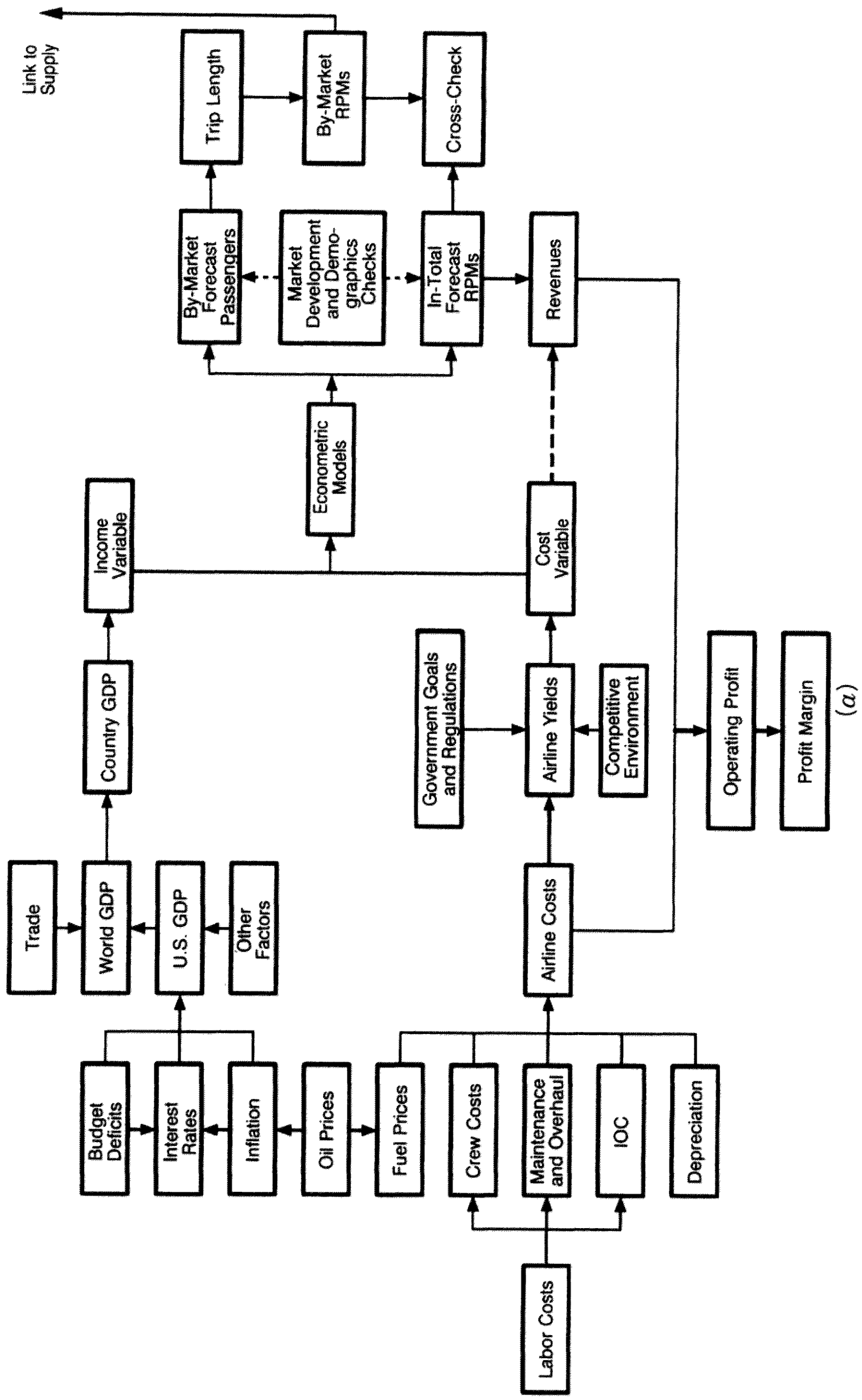
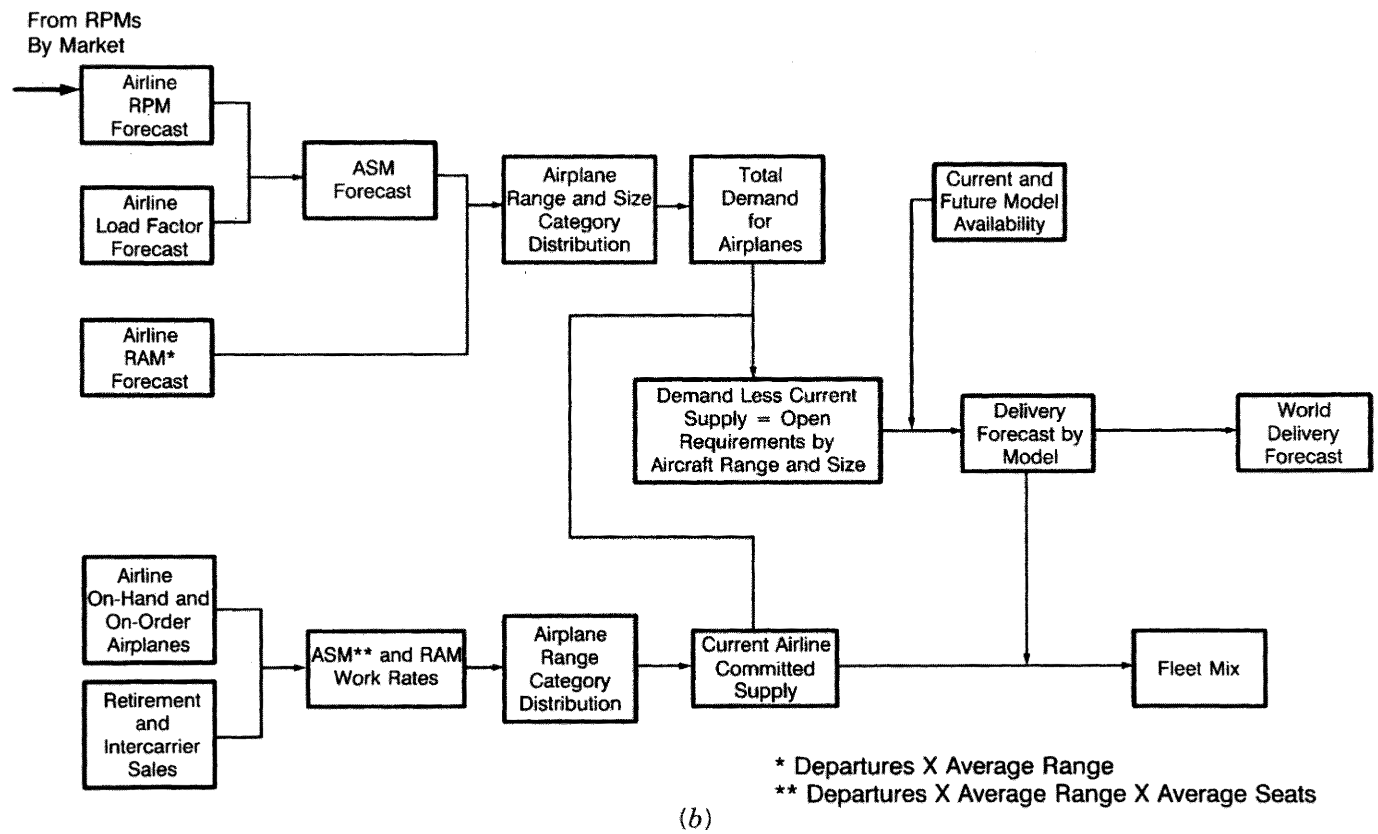


FIGURE 2.5 Historic and forecast fleet mix for U.S. domestic scheduled traffic.


Budget Deficits
Interest Rates
Inflation
Oil Prices
Fuel Prices
Crew Costs
Maintenance and Overhaul
IOC
Depreciation
Labor Costs
Trade
World GDP
U.S. GDP
Other Factors
Airline Costs
Country GDP
Government Goals and Regulations
Airline Yields
Competitive Environment
Operating Profit
Profit Margin
Income Variable
Cost Variable
Econometric Models
By-Market Forecast Passengers
Market Development and Demo-graphics Checks
In-Total Forecast RPMs
Revenues
Trip Length
By-Market RPMs
Cross-Check
Link to Supply
(a)



(*b*)

FIGURE 2.6 Manufacturers' models for forecasting future fleet structure. (*Source*: Boeing Airplane Company)

2.12 ESTIMATES OF AIR CARRIER MOVEMENTS

Estimates of aircraft movements can be obtained by simple trend analysis, projecting growth rates of movements from past experience. This approach is likely to be satisfactory only for short-term forecasting, since it takes no account of changes in technology and equipment, nor does it allow for possible market saturation-all factors that can have significant effects in the long run. Whereas simple extrapolation methods can give reasonable estimates of general aviation activity, air carrier movements are better predicted using refined analysis of estimates of air passenger volumes gained from the modeling procedures discussed previously.

To convert annual estimates of air passenger movements to peak air carrier movements, it is necessary to understand the temporal variations of demand as they relate to the design facilities. Figure 2.7 shows that pattern of variation of passenger and aircraft movements throughout the year depends greatly on the function of the airport. Heathrow, the principal airport for London, shows typical variations of demand, with a peak during the summer and lowest flows during February. The peak/average ratio for this airport, which serves large volumes of business traffic and to a lesser degree leisure traffic is the relatively low figure of 1.31. This is a similar ratio to that observed at New York JFK, which is somewhat similar in function. By comparison, Luton, another airport in the London area, serving principally holiday and charter traffic, has a very large variation in monthly flow

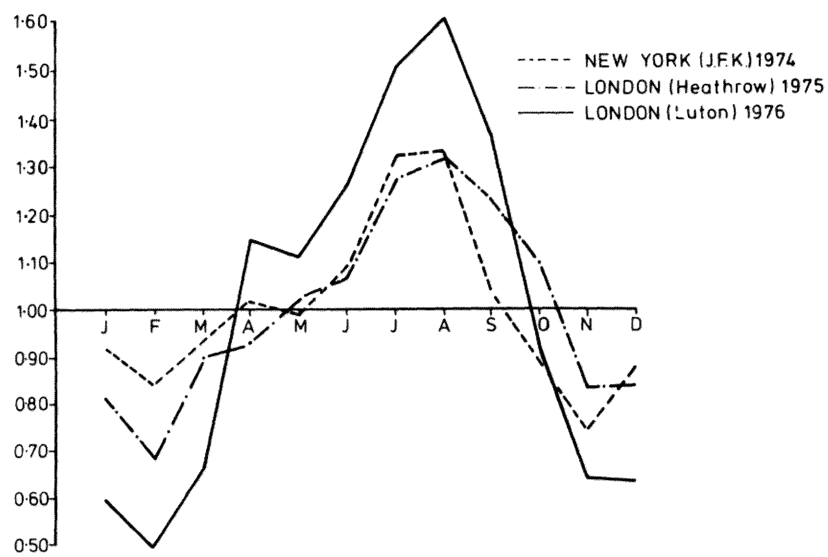


FIGURE 2.7 Monthly variations in passenger traffic in three airports. (*Source*: FAA Airport Activity Statistics, CAA Monthly Statistics)

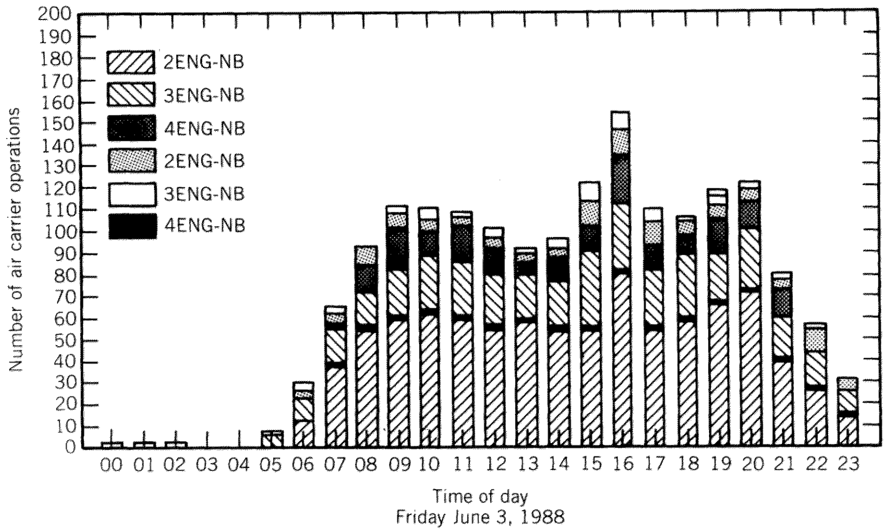


FIGURE 2.8 Hourly profile of air carrier operations by equipment type, Atlanta Hartsfield International Airport. (*Source*: Official Airline Guide, June 1988)

throughout the year, as indicated by the ratios of 1.54 for commercial air transport movements and 1.61 for passenger flow.

As important as the large variation of traffic throughout the year is fluctuation of volume during the day. Figure 2.8 gives the hourly variation of flow at Atlanta International Airport (19). Airport peak hours (0800–1000, 1500–1800) tend to coincide closely with the peak condition of urban transport; this unfortunately complicates the surface access problem, since major reliance is often on road-based modes (see Chapter 13).

Figure 2.9 outlines a procedure for computing the peak hour passenger and aircraft movement figures necessary for facility design. Using factors gained from past experience at the airport in question, annual passenger volumes can be factored to provide peak month, peak day, and peak hour passenger volumes. These are converted at each stage to aircraft movements from an estimate to aircraft mix, using historical data and trend analysis of fleet replacement. The following alternative approach to the peak hour design figure has been used by the Port Authority of New York (20).

$$\begin{aligned} \text{Average monthly passengers} &= 0.08417 \times \text{annual passenger flow} \\ \text{Average daily passengers} &= 0.03226 \times \text{average monthly flow} \\ \text{Peak day flow} &= 1.26 \times \text{average daily flow} \\ \text{Peak hour flow} &= 0.0917 \times \text{peak daily flow} \end{aligned}$$

Peak hour passenger flows were converted into peak aircraft flows using estimates of average passenger load per aircraft computed from projected load factors and projected seatings per aircraft movement.

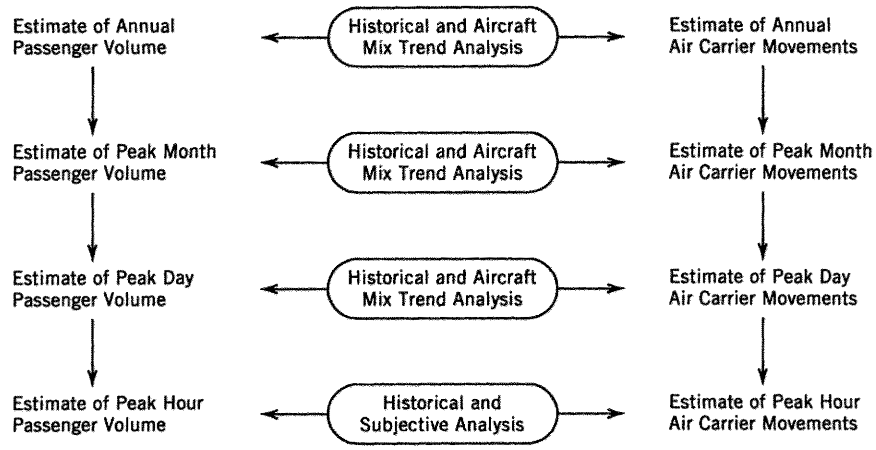


FIGURE 2.9 Procedure for computing monthly, daily, and hourly peak air carrier movements and passenger volumes. (*Source*: FAA)

In Section 10.9, the FAA relationship between peak hour flows and annual volumes is given in conjunction with other estimates used for peak planning.

Figures 2.10 and 2.11 show graphs recommended for planning purposes which relate peak hour passenger flows and peak hour aircraft operations to annual passenger throughput in terms of enplanements.

Throughout the rest of the world, the concept of the 30th highest hour or

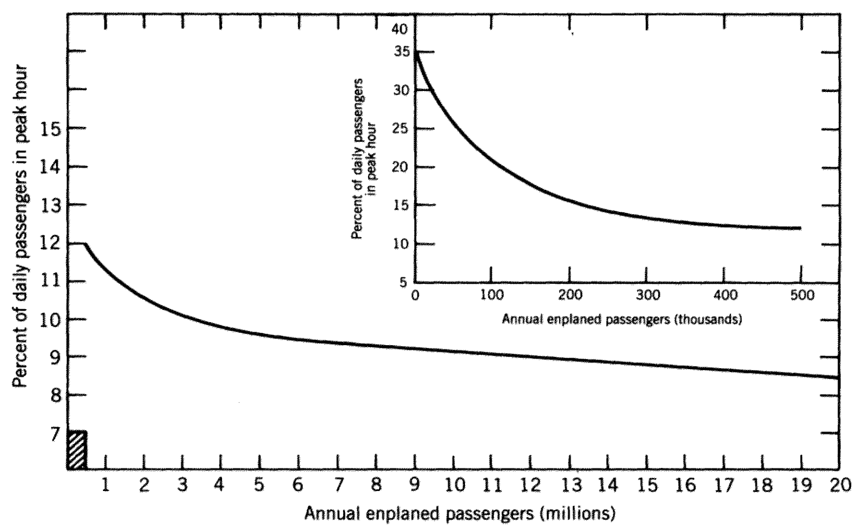


FIGURE 2.10 Percent of daily passengers in peak hour versus annual enplaned passengers. (*Source*: FAA)

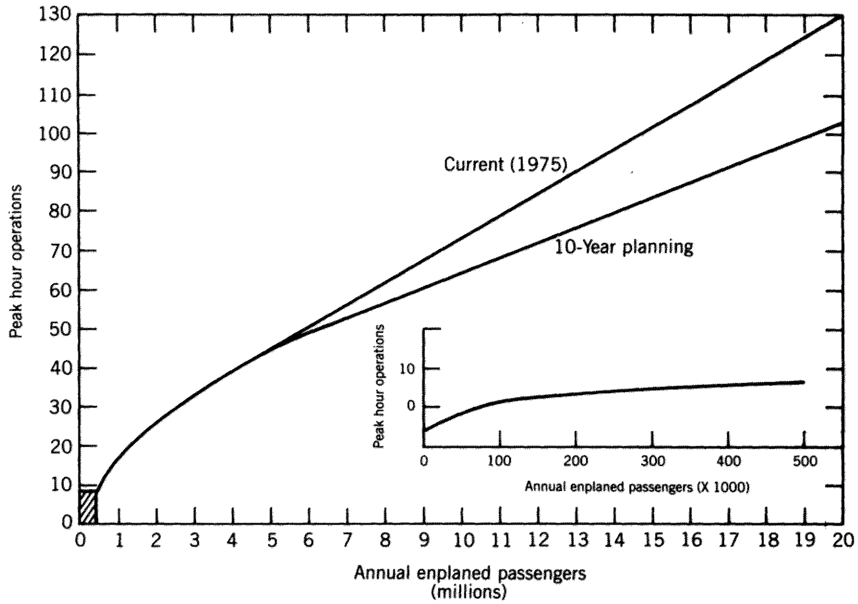


FIGURE 2.11 Estimated peak hour operations versus annual enplaned passengers. (*Source*: FAA)

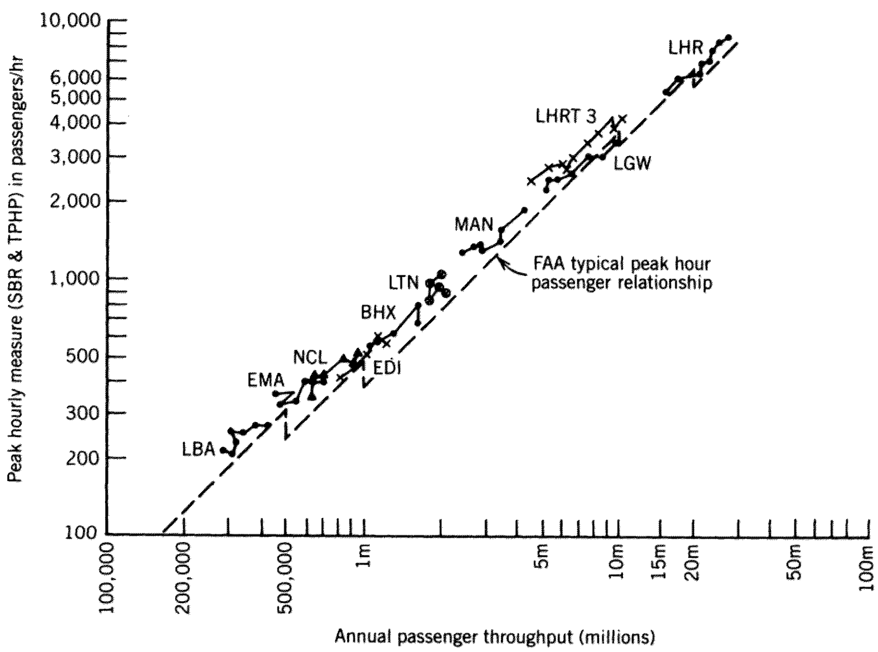


FIGURE 2.12 Relationship between Standard Busy Rate (SBR) and FAA Typical Peak Hour Passengers (TPHP) and annual passenger throughput. (*Source*: Civil Aviation Authority and Federal Aviation Administration)

Standard Busy Rate (SBR) is often used. This is the passenger traffic flow which is exceeded by only 29 other hours of operation. Figure 2.12 show the log-log relationship between the SBR and total annual passenger flows that has been observed over an eight-year period for a range of British airports (21). For comparative purposes, the Typical Peak Passenger Flow (FAA) relationship has been plotted on the same graph (see Table 10.1).

2.13 AIR FREIGHT DEMAND

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. Figure 2.13 presents a forecast for world air cargo traffic made by one major aircraft manufacturer.

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

$$F = f(\mathrm{GNP}, \mathrm{P_A}) \tag{2.24}$$

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:

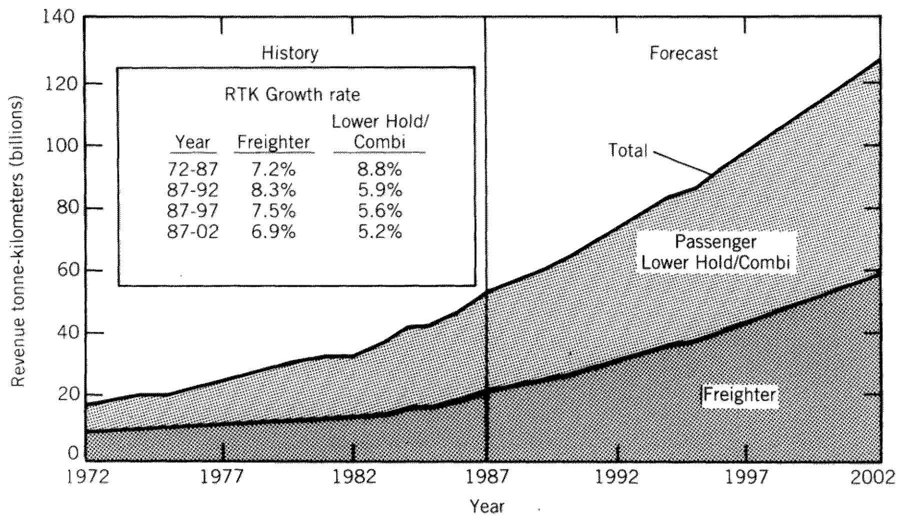


FIGURE 2.13 World air cargo traffic forecast. (*Source*: McDonnell Douglas)

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.

2.14 AIR FREIGHT GENERATION MODELS

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 (see Section 2.5). 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 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.

2.15 AIR CARGO DISTRIBUTION AND MODAL SPLIT MODELING

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.

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 other airports to the freight terminals at 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.

2.16 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, (2) number of aircraft operations, and (3) passenger forecasts.

The number of based aircraft forecast calls for an inventory of presently based aircraft, 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:

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

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

$$S^B_{t+1} = f_1\left(\frac{AP_{t+1}}{P_{t+1}}, r_{t+1}, W_{t+1}\right) \cdots \qquad (2.26)$$

$$S^P_{t+1} = f_2\left(\frac{AP_{t+1}}{P_{t+1}}, r_{t+1}, Y_{t+1}\right) \cdots \qquad (2.27)$$

where

AP = aircraft price index
P = implicit Gross National Product 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. The FAA has given data on the average number of passengers per plane.

	Average Number of Passengers per Plane	
Airports	1975	1980
Air carrier	3.26	3.36
Other	2.20	2.50

A brief treatment of modeling general aviation activity is contained in *Manual on Air Traffic Forecasting* (6).

2.17 ROUTE CHOICE MODELING

An area of increasing importance in the subject of demand modeling is predicting 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, because 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 complex, and only recently have they begun to be understood (22). A model calibrated in the United Kingdom on CAA data was of the form:

$$p(a,r) = p(r/a),\ p(a)$$

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

$$p(a) = \frac{\exp\,[\delta^R\,\Phi^R\,(a)]}{\sum_{a^*EA} \exp\,[\delta^R\,\Phi^R\,(a*)]}$$

where

A = the 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)

The manner in which route choice models are integrated into airport demand analysis and airport system planning is shown in Figures 4.10 and 4.13 and in Sections 4.9 and 4.11.

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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, the route structuring, and the 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 km 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. In addition, 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

*The original author of this entire chapter in the first and second editions was Robert Caves, Department of Transport Technology, Loughborough University. The material in the current edition is still largely his work.

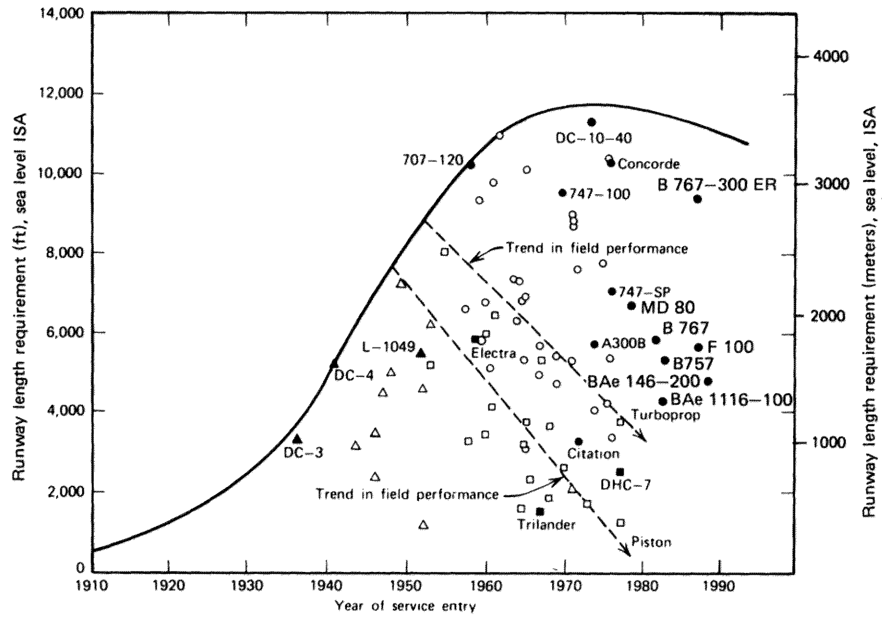

FIGURE 3.1 Trends in runway length.

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, in 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. Much speculation has taken place about the design of future aircraft carrying 800–1000 passengers. There has been considerable resistance from airport operators to the introduction of aircraft with double decked access or greatly increased wingspans. Rising 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 makes it unreasonable for aircraft designers to call for increases of runway length on a massive scale. Figure 3.2 charts the variation in the ratio of airport costs to total system operating costs with route throughput and stage length in an assumed air transport system.

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 the aircraft 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

*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.

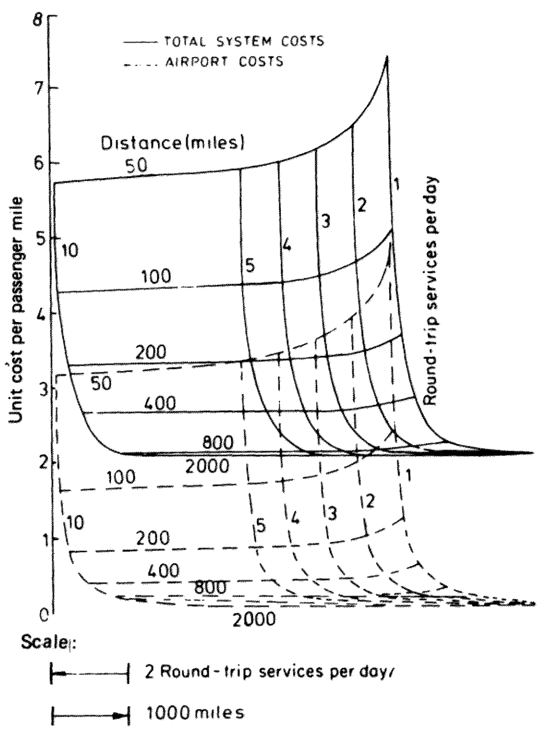

FIGURE 3.2 Airport and total aviation system operating costs.

because the operating costs for this type of flight are acceptably low. This double trend of both increasing and decreasing runway length 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 3.3) 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 3.4). The combination of improvements in speed and absolute size has resulted in the upward trend in seat mile per hour productivity shown in Figure 3.5. With the exception of the early pure jets, a similar upward trend also occurred in seat miles per gallon because of advances in engine fuel

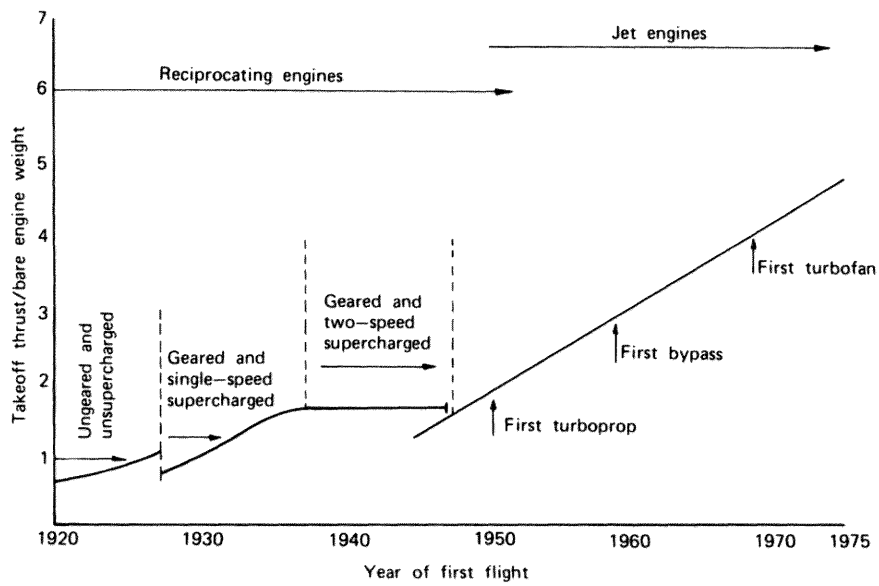

FIGURE 3.3 Trends in ratios of takeoff thrust to bare engine weight.

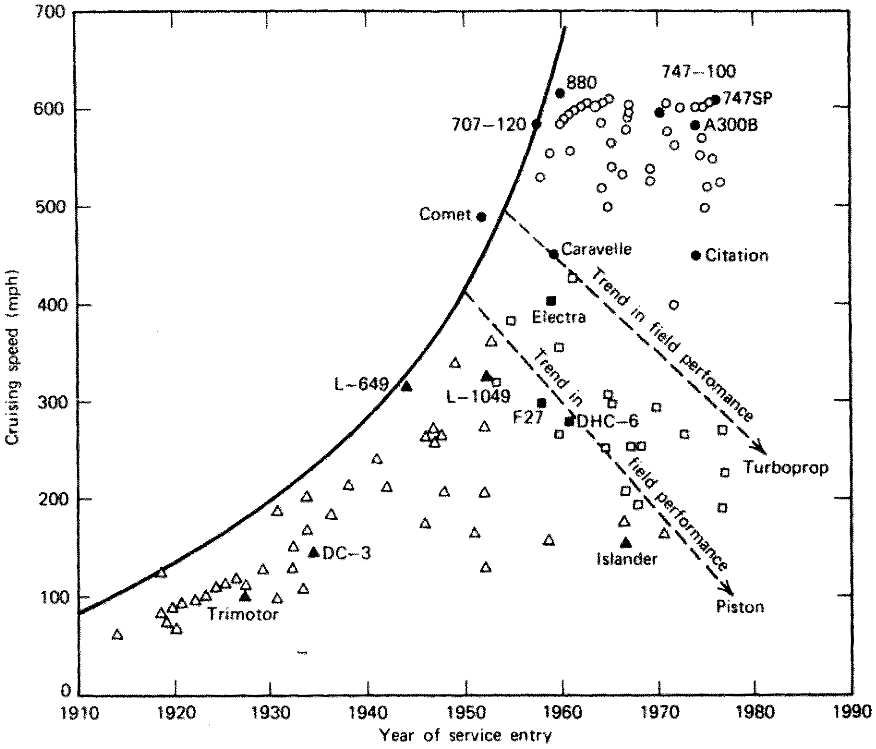

FIGURE 3.4 Trends in cruising speeds of subsonic passenger transport aircraft.

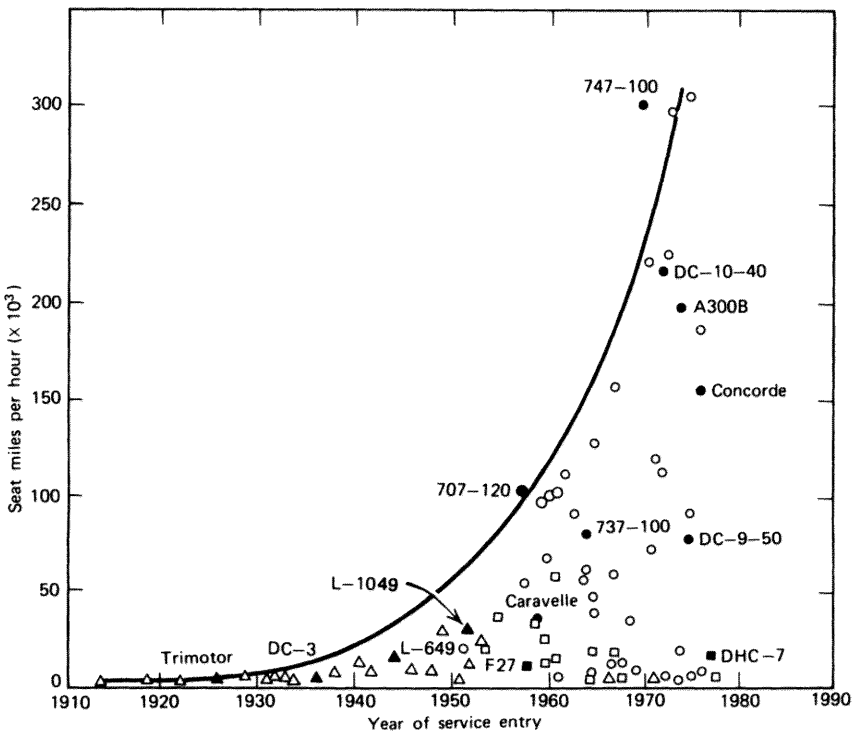

FIGURE 3.5 Trends in productivity in terms of passenger seat miles per hour.

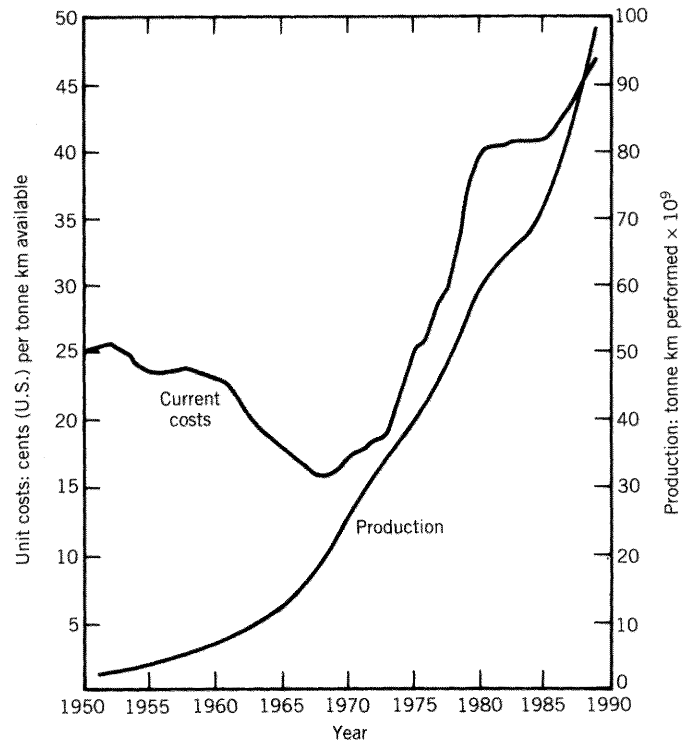

FIGURE 3.6 Air transport passenger traffic in relation to air transport costs.

efficiency. All these effects, combined with economies of scale, generated the reduction in real costs per tonne kilometer plotted in Figure 3.6.

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.

For level flight,

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

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, hence a 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.

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 3.7 and 3.8 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.

*In this case, "productivity" is defined as seat 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.

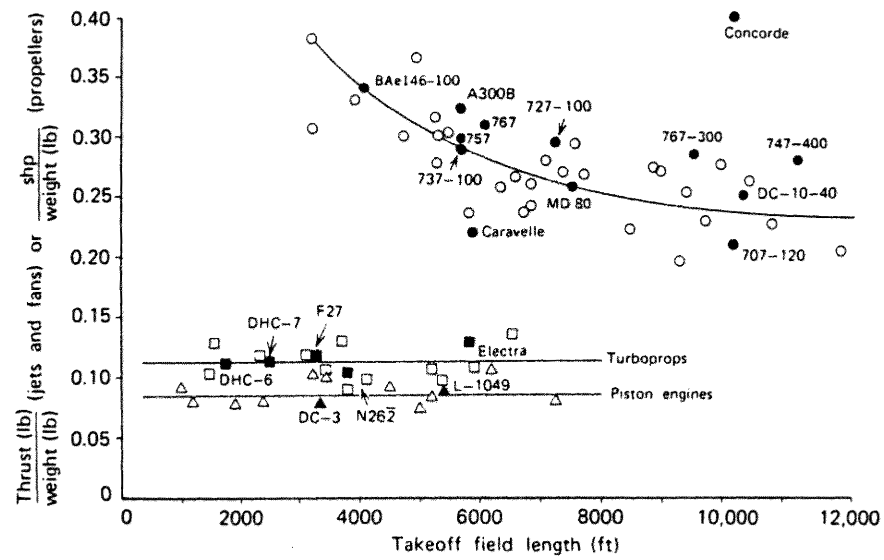

FIGURE 3.7 Effect of power-to-weight ratio on field length.

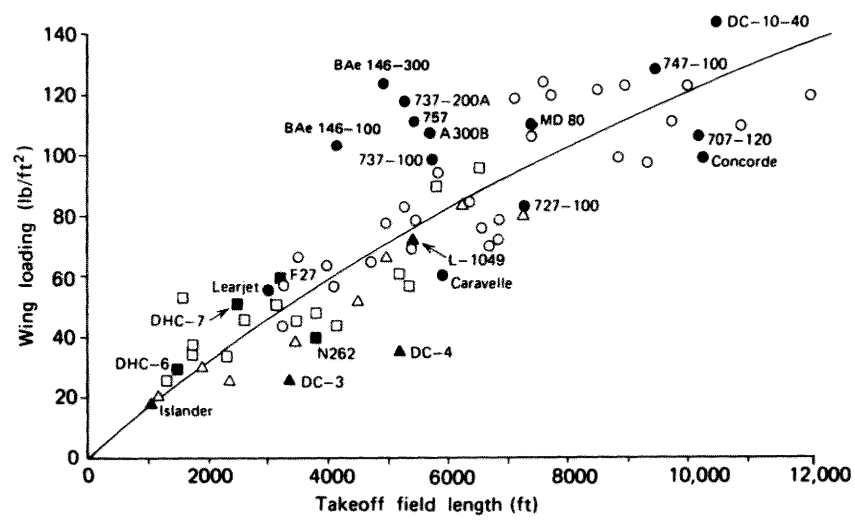

FIGURE 3.8 Effect of wing loading on field length.

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 ICAO. In the Unites 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. In essence, an aircraft type is required to demonstrate the field length required for the following cases: (1) to complete a takeoff to 35 ft (11 m) altitude with all engines operating, (2) to complete a takeoff to 35 ft (11 m) altitude with an engine failure at a critical point, (3) to stop after aborting a takeoff with an engine failure at the same critical point, and (4) 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

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

Aircraft Type	Powerplant	Dimensions (ft)						Number of Passengers (max)
		Span	Length	Height	Turning Radius	Wheel Base	Track	
Intercontinental								
747-400	4 × 58,000 lb	211.0	231.9	63.5	151.0	84.0	36.1	660
DC-10	3 × 50,000 lb	165.3	182.2	58.1	123.9	72.3	35.0	380
Concorde	4 × 30,850 lb	83.8	203.8	37.9	127.0	59.7	25.3	128
707-320B	4 × 19,000 lb	145.8	152.8	42.5	—	59.0	22.1	219
Transcontinental								
L-1011 Tristar	3 × 42,000 lb	155.3	178.6	55.3	141.3	70.0	36.0	400
A300 B4	2 × 51,000 lb	147.1	175.8	54.3	111.5	61.1	31.5	345
727-200[a]	3 × 16,000 lb	108.0	133.2	34.0	82.0	63.3	18.8	189
A 310-200	2 × 48,000 lb	144.0	153.1	51.9	103.3	40.9	31.5	265
767-200	2 × 48,000 lb	156.3	159.2	52.0	110.5	64.6	30.5	255
Short haul								
757-200	2 × 37,400 lb	124.5	155.3	44.5	92.0	60.0	24.0	233
1 11-475	2 × 12,550 lb	93.5	93.5	24.5	51.5	33.1	14.3	119
737-500	2 × 20,000 lb	94.8	101.8	36.5	56.4	37.4	17.2	132
Trident 3B	3 × 11,960 lb[b]	98.0	131.2	28.3	80.0	52.4	19.1	180
DC-9-50	2 × 16,000 lb	93.3	125.6	28.0	68.0	56.1	16.4	139
F28-2000	2 × 9,850 lb	77.3	97.2	27.8	58.0	33.9	16.5	79
BAe146-200	4 × 6,700 lb	86.4	93.7	28.3	41.2	36.8	15.5	106
Commuters								
Brasilia	2 × 1,500 eshp	64.9	64.7	20.7	58.4	22.3	19.9	30
HS-748-2A	2 × 2,280 eshp	98.5	67.0	24.8	74.0	20.7	24.8	60
F27-500	2 × 2,140 eshp	95.2	82.3	28.6	65.9	31.6	23.7	56
DHC-7	4 × 1,174 eshp	93.0	80.3	26.2	62.0	27.5	23.5	54
Nord 262C	2 × 1,145 eshp	74.1	63.3	20.3	57.0	23.8	10.3	29
SD 3-30	2 × 1,120 eshp	74.7	58.1	15.7	53.8	20.2	13.9	30

[a] One RB 162 booster.

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 (ft)		Cruise	Payload Range: ISA, Still Air, No Reserves			
							Range at Max Payload		Max Range Payload	
	Takeoff (max)	Landing (max)	Empty, Operating	Takeoff	Landing	Speed (knots)	(nautical mi)	lb × 1000	(nautical mi)	lb × 1000
Intercontinental										
747-400	800	574	391.0	11,100	7,000	495	6,067	144.0	7,670	40.0
DC-10-30	555	403	267.3	10,490	5,960	499	4,390	104.5	6,660	47.8
Concorde	400	245	174.8	10,280	8,000	1,176	4,430	28	4,480	23.5
707-320B	333.6	247	147.8	10,000	6,250	478	5,175	53.9	6,500	33.3
Transcontinental										
L-1011 Tristar	430	358	239.4	7,750	5,700	495	2,885	85.6	4,845	32.0
A300 B4	330.7	293.2	191.3	8,740	5,950	481	1,820	77.6	3,400	39.8
727-200[a]	207.5	160	103	10,080	4,800	495	2,615	41	3,190	33.9
A310-200	291	261	169.5	6,050	5,460	488	2,210	69.7	4,430	27.1
767-200	300	270	178.3	5,650	4,700	506	2,220	67.7	4,900	15.9
Short haul										
757-200	220	198	129.8	6,180	4,820	494	1,200	64.0	4,660	11.8
1 11-475	99.7	87	54.8	7,470	4,770	457	1,303	26.2	2,026	20.2
737-500	115.5	114	69.4	6,650	5,260	482	1,565	44	2,500	21.1
Trident 3B	158	130	82.4	8,595	5,680	480	1,990	35.4	2,375	28.3
DC-9-50	120	110	65	7,880	4,680	465	1,275	33	2,420	21.4
F28-200	65	59.6	37	5,490	3,540	457	920	17.5	2,620	5.1
BAe146-200	88.3	77	47.2	4,950	3,480	419	1,535	22.1	1,646	20.9
Commuters										
Brasilia	21.7	21.7	12.3	3,540	4,000	287	575	6.0	1,570	3.2
HS-748-2A	46.5	43	26	5,380	3,370	242	1,160	12.5	1,740	9.0
F27-500	45	42	26.3	5,470	3,290	248	825	13.2	2,180	5.66
DHC-D7	41	39	24.4	1,800	1,900	238	637	11.1	1,740	6.44
Nord 262C	23.8	23	15.9	3,510	1,720	211	270	6.78	1,280	4.53
SD3-30	22	21.7	14.2	3,900	3,400	197	395	5.85	910	4.00

Source: References 5, 6, manufacturers' brochures.

TABLE 3.1c Characteristics of General Aviation Aircraft

Aircraft	Powerplant	Dimensions (ft)			Number of Passengers (max)	Weight (lb × 1000)			FAR Field Length (ft)[a]		Cruise Speed (knots)[b]
		Span	Length	Height		Takeoff (max)	Landing (max)	Empty, Operating	Takeoff	Landing	
Gulfstream 2	2 × 11,400 lb	68.9	79.9	24.5	19[c]	62.0	58.5	35.6	5000	3190	480
BAe 125-700	2 × 3,750 lb	47.0	50.7	17.6	14[c]	25.5	22.0	14.0	5800	2550	441
Learjet 36	2 × 3,500 lb	38.1	48.7	12.3	8[c]	17.0	13.3	8.76	3500	3690	460
Citation	2 × 2,200 lb	43.8	43.5	14.4	6[c]	11.7	11.0	6.35	3275	2300	351
Beech 99	2 × 715 eshp	45.8	44.6	14.4	15[c]	10.9	10.9	6.00	3100	2220	248
Twin Otter	2 × 715 eshp	65.0	51.7	18.6	20[c]	12.5	12.5	6.70	1200[d]	1050[d]	165
Merlin 3	2 × 904 eshp	46.3	42.2	16.8	7[c]	12.5	11.5	6.99	3080	2860	275
MU 2K	2 × 724 eshp	39.2	33.3	12.9	6[c]	9.92	9.44	5.92	1700	1490	318
BNZA-21	2 × 300 hp	53.0	39.5	13.9	8[c]	6.60	6.60	3.74	1090	960	157
Cessna 421	2 × 375 hp	41.9	36.1	11.6	8[e]	7.45	7.45	4.43	2507	2178	235[e]
Piper PA-31P	2 × 425 hp	40.8	34.6	13.1	8[e]	7.80	7.80	4.90	2200	2700	244[e]
Cessna 337	2 × 225 hp	38.0	29.9	9.1	6[e]	4.63	4.63	2.71	1675	1650	170[e]
Aztec E	2 × 250 hp	37.2	31.2	10.3	6[e]	5.20	5.20	3.04	1250	1620	183[e]
Cessna 210	1 × 285 hp	36.9	28.3	9.7	6[e]	3.80	3.80	2.12	1900	1500	164[e]
Cherokee 180	1 × 180 hp	32.0	23.3	7.3	4[e]	2.15	2.15	1.27	1700	1075	115[e]
Cessna 150	1 × 100 hp	32.7	23.8	8.10	2[e]	1.60	1.60	1.00	1385	1075	102[e]

Source: Manufacturers' data.

[a] Figures refer to sea level, 59°F (international standard atmosphere), dry runway, and zero wind for the worst applicable FAR regulations.

[b] Cost-economic true air speed (TAS).

[c] Plus two crew, but may need only one.

[d] Short takeoff and landing (STOL) regulations.

[e] Includes crew, maximum speed.

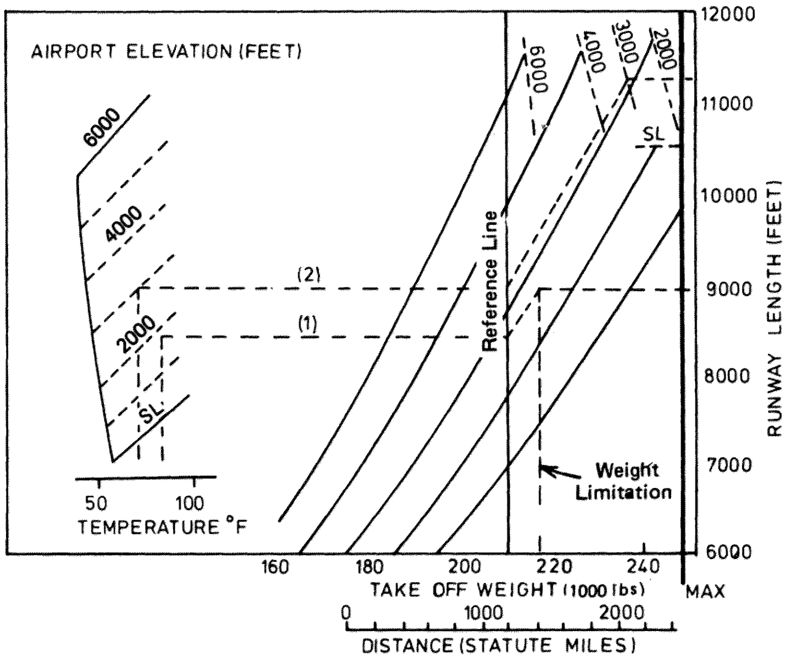

FIGURE 3.9 Aircraft performance on takeoff: example ICAO requirements for large aircraft. (*Source*: Reference ICAO)

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). Figure 3.9 is an example taken from the ICAO *Aerodrome Design Manual* (3). The dotted lines on the figure show the method of reading the chart, the runway length required at a given airfield altitude, and temperature being determined either by the aircraft's takeoff weight (line 1; 220,000 lb) or by its ability to maintain climb capability after takeoff (line 2; for airfield altitude of 3000 ft). Allowance is also made for wind strength and direction, runway slope, runway surface conditions, and the need to retain some minimum climb capability on the takeoff flight path with one engine inoperative.*

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

Checking the ability of an aircraft to take a specified payload from, or to land at, a specified airfield in specified environmental conditions.

*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.

Calculating the allowable maximum payload that may be moved under those specific conditions when the payload is limited by available field length.

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, 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 3.10; the speeds to be controlled during the demonstration are symbolized as follows:

V_1 = takeoff decision speed chosen by the aircraft manufacturers: $> 1.10\ V_{mc}$, $<$ 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} = lift-off speed: $\geq 1.1\ V_{mu}$ ($\geq 1.05\ V_{mu}$ 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) $\geq 1.2\ V_s$, $\geq 1.1\ V_{mc}$
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 ocurs 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.

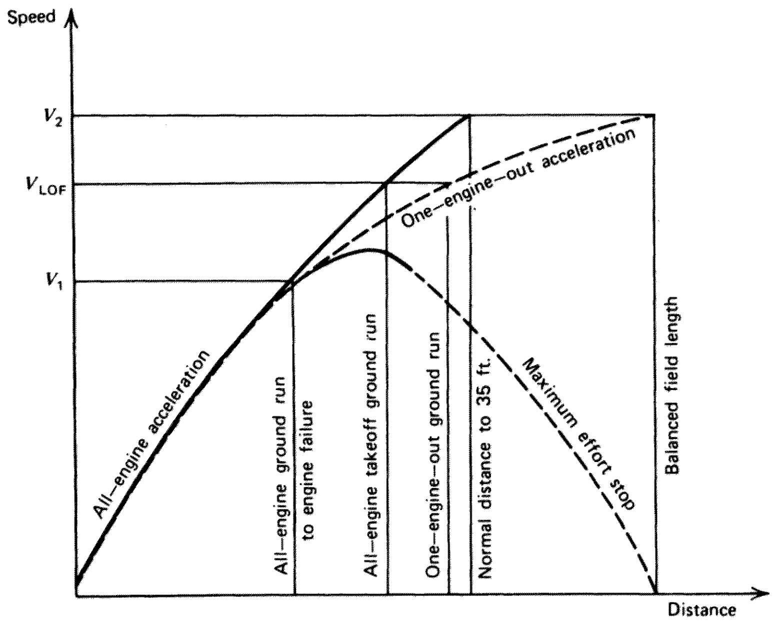

FIGURE 3.10 Takeoff field length demonstration requirements for transport category aircraft. (*Source*: References 3 and 4)

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 (5, 6). 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 (7). A clearway may not be longer than half the difference between 115% of the distance between the lift-off 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 lift-off 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 3.11. 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 3.1 b 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, rela-

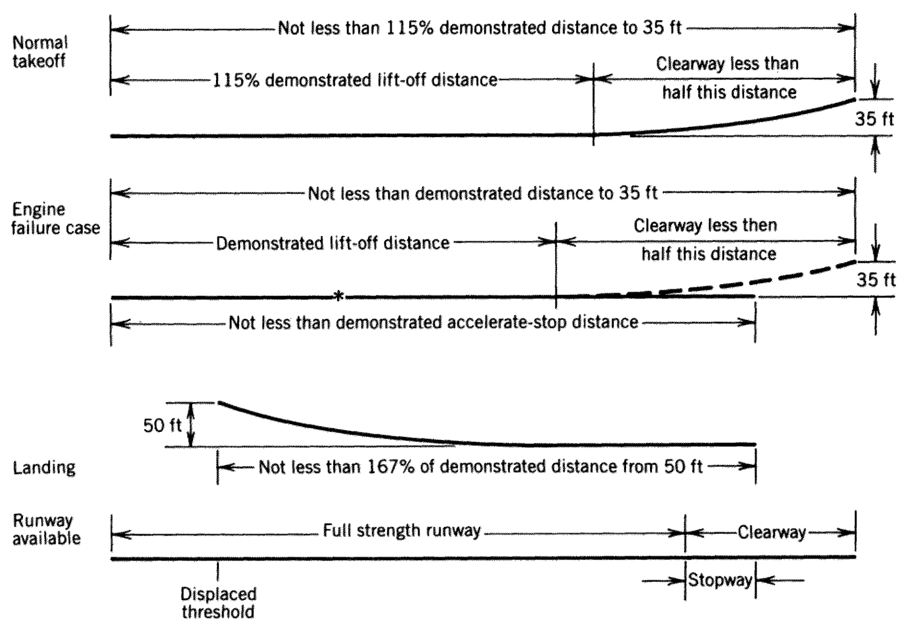

FIGURE 3.11 Field length definitions (* indicates engine failure at speed V_1).

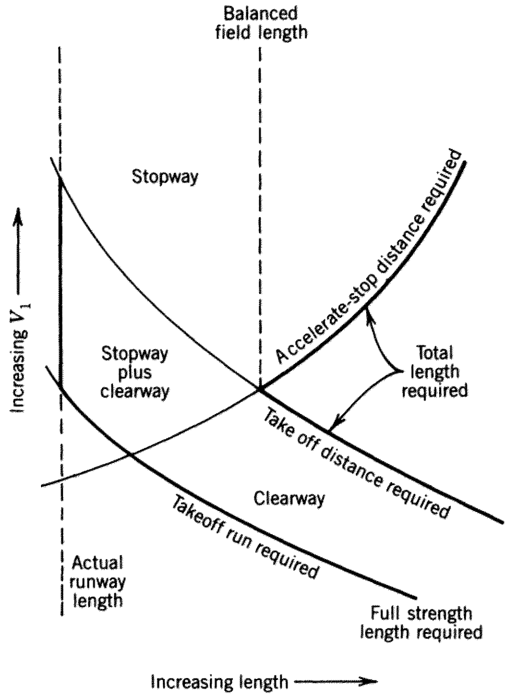

FIGURE 3.12 Use of unbalanced field performance.

tive to the emergency 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 on 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 3.12. 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 certificated in the United States under Federal Avia-

*It is the responsibility of individual countries to certificate aircraft appearing on their own register. Developed countries, such as the United States, the United Kingdom, France, Germany, and tion Regulations, Part 25, and so must meet the same field length requirements as those applicable to aircraft greater than 12,500 lb all-up-weight (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 6,000 and 12,500 lb. No specific demonstration is required for aircraft below 6,000 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 certificated 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 Learjets, Sabreliners, Cessna Citations, and Fan Jet 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 6 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 takeoff 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 3.9 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 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

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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.

TABLE 3.2 Increases in Field Length (ft × 1000) Due to Changes in Altitude and Temperature

	Takeoff				Landing			
	Sea Level		5000 ft		Sea Level		5000 ft	
Aircraft	ISA	ISA + 20°C	ISA	ISA + 20°C	ISA	ISA + 20°C	ISA	ISA + 20°C
Concorde	10.28	12.35	12.50	13.08	8.00	8.00	9.28	9.28
707-320B	10.00	11.40	12.65[a]	12.84[a]	6.25	6.25	6.94	6.94
L-1011	7.75	9.25	12.95[a]	13.30[a]	5.70	5.70	6.40	6.40
767-200	5.65	6.10	7.70	8.60	4.75	4.75	5.35	5.35
727-200	10.08	13.19	13.81[a]	14.12[a]	4.80	4.80	5.31	5.31
737-200	6.55	7.73	8.80[a]	10.20[a]	4.29	4.29	5.14	5.14
DC-9-50	7.88	9.80	10.85[a]	12.15[a]	4.68	4.68	5.30[b]	5.10[b]
HS-748-2A	5.38	5.70[a]	5.50[a]	5.90[a]	3.37	3.36[b]	4.76[b]	4.67[b]
Nord 262C	3.51	3.68[a]	3.84[a]	3.94[a]	1.72[b]	1.72[b]	1.94[b]	1.88[b]

[a] Weight limited by climb gradient requirement on takeoff.

[b] Weight limited by climb gradient requirement on overshoot.

Source: Manufacturers' data.

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 3.13, 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.
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 per-

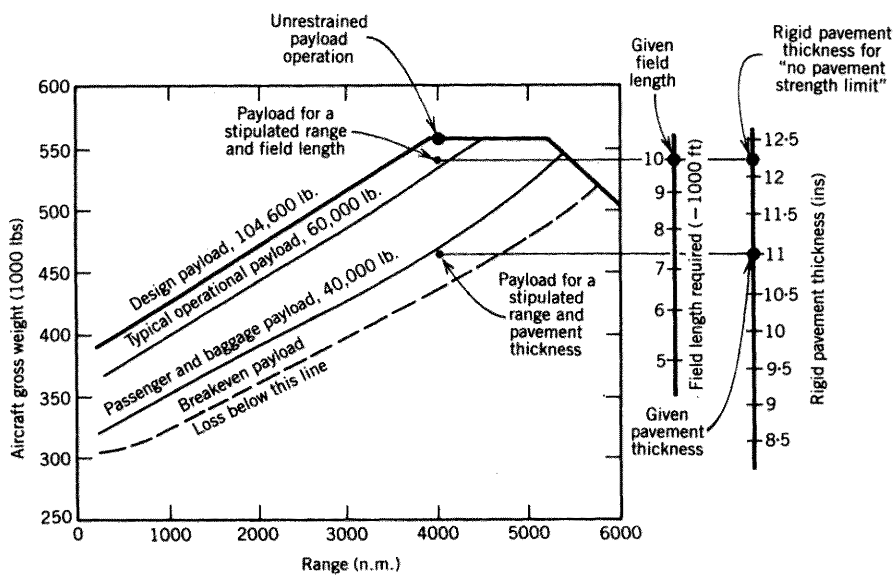

FIGURE 3.13 Aircraft gross weight versus payload-range capability. (*Source*: Reference 9)

formance 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 3.14). 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.

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 3.14). 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

*These terms are defined in Section 6.2.

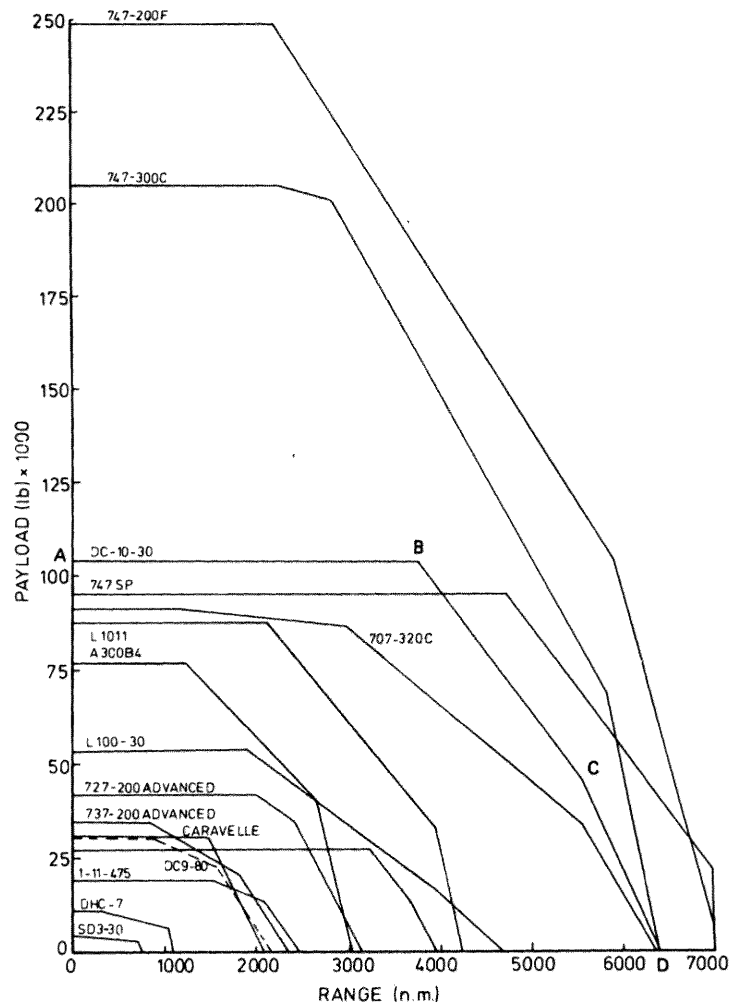

FIGURE 3.14 Payload ranges of various commercial aircraft. (*Source*: Manufacturers' data)

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% (16).

Following the air crash at Munich in the late 1950s, the FAA carried out test 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 (¾ in.) of slush effected a drag more than equivalent to the loss of one engine. It was further found that 3.5 cm (1⅜ in.) of slush was almost equivalent to the loss of two engines and 4.5 cm (1⅞ 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. The more difficult it is to compensate for a given crosswind without 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 theUnited 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 (7, 10), 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

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 (kts)	20	13	10

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

*1 knot = 1 nautical mi/hr = 1.5 statute mi/hr = 1.85 km/hr.

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 the 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 (11).

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 airport, 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 the 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 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, etc.: 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, spac-

*As an example, the MBB VFW-614 has its engines placed over the wing primarily to avoid ground ingestion problems.

ing 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 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 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.

The air cargo industry has always looked forward to the day when it would be able to commission its own dedicated freighter aircraft design. Such aircraft do not yet exist in quantity, because it is so much cheaper to utilize surplus carrying capacity in the holds of scheduled passenger services—normally available because the average passenger load factor seldom exceeds 65% and hence the aircraft is seldom operated at its maximum takeoff weight unless cargo is carried. As aircraft have increased in size, the volumetric capacity available for underfloor cargo has increased in greater proportion. Hence, although air cargo is growing at a faster annual rate than passenger traffic, it is likely that the majority of cargo will continue into the foreseeable future, that is to 2010, to be handled in belly holds of scheduled passenger service aircraft. The siting of cargo terminals and the associated taxiways and service roads should reflect careful consideration of this trend.

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 the 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 (12).

Much research is being 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 3.15. The spoiler reduces the rolling moment required

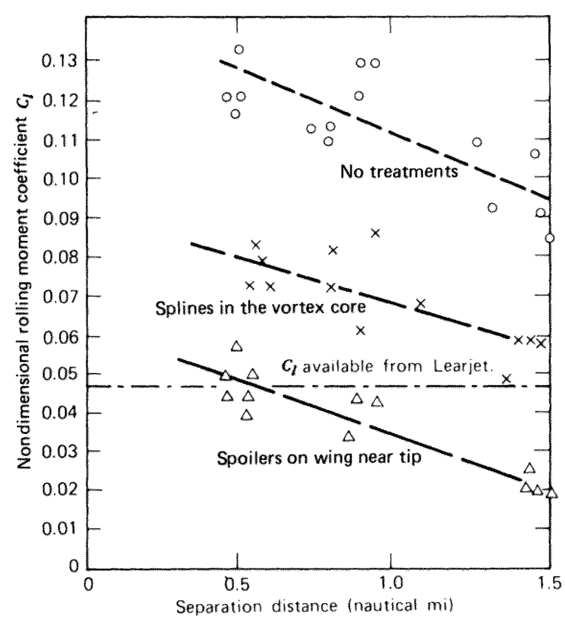

FIGURE 3.15 Effect of the wake of a Boeing 747 on a Learjet. (*Source*: Reference 12)

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.

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, and so forth.
3. Access to upper decks of 747s.
4. Baggage handling.
5. Handling large batches inside the terminal.

These matters are discussed in Chapter 10.

3.5 NOISE

The noise generated by aircraft creates problems in making decisions regarding 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 jet-powered aircraft with bypass ratios greater than 2. In 1973, they were modified to apply to all aircraft manufactured after that date. The regulations with respect to noise on the sideline and below the approach path is indicated by a solid line in Figure 3.16; the broken line shows regulations for take-off. The Stage 2 regulations are shown because they do not vary with the number of engines. The Stage 3 regulations, applicable to aircraft certified after 1977, are approximately 8–12dB lower than Stage 2 levels, representing a substantial improvement in noise emission. 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 Chapter 2 corresponding to FAA Stage 2 and Chapter 3 corresponding to Stage 3.

The first generation of 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, many airports have already also excluded all Stage 2 aircraft, e.g., John Wayne Airport, Orange County CA.

Because the permitted noise level in EPNdb is weight related, on the basis that aircraft carrying fewer passengers should be required to generate less noise, there is not a great deal of difference between Stage 2 and Stage 3 aircraft at the upper end of the weight range, perhaps only 3 or 4dB. The upper end of the Stage 2 curve was dictated by advanced technology aircraft whereas the

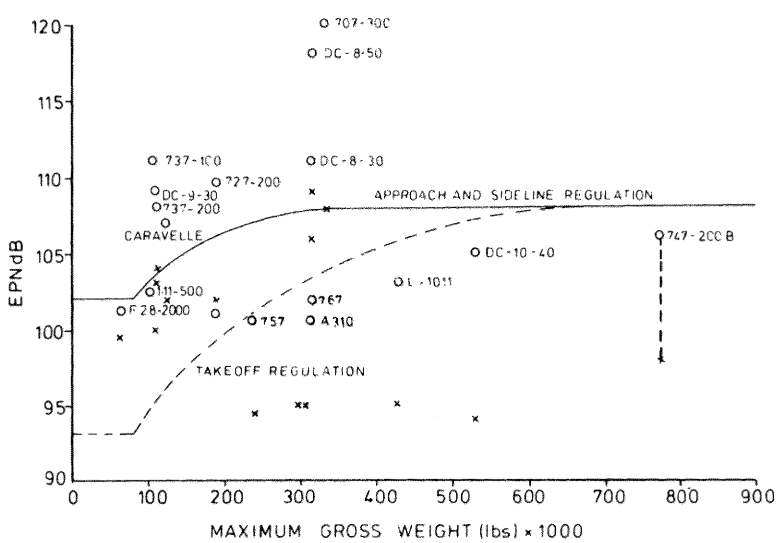

FIGURE 3.16 Aircraft noise measured with reference to CFR 14, Part 36. (*Source*: Reference U.S. Code of Federal Regulations, Part 36)

lower end related to earlier and noisier engines. At the lower aircraft gross weight range, therefore, the difference is substantial.

At the beginning of the 90s, there are international (ICAO, ECAC*) and national (FAA) programs which legislate the phasing out of all Chapter 2 aircraft over a ten 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 market "hush kits" for Stage 2 aircraft such as Boeing 727s, 737-200s and DC9s which are just capable of meeting Stage 3 requirements, making full use of allowable trade-offs among approach, take-off and sideline noise constraints. Hush kitting, because of its marginality with respect to requirements, is not as effective as reengining as a solution to non-compliant aircraft. For example, BAC1-11s and Boeing 727s reengined with Rolls Royce Tay engines easily comply with Stage 3 regulations. Furthermore, ICAO has for some time considered implementing more stringent Chapter 3 regulations which would have the effect of lowering the permissible EPNdB by 3 or 4dB. Hush kitted Stage 2 aircraft would be unable to comply with these more stringent regulations. Table 3.4 shows a guideline classification of aircraft with respect to compliance with the Stage 2/Stage 3 requirements.

It can be seen from Figure 3.17 that 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 take-off and climb out power with one engine non-functional, the climb rate under normal operation is very high. This is allowed for in the noise certification limits. As fleets move increasingly to twin engine aircraft the impact of adverse noise impact tends to shrink back towards the boundary of the airport itself.

One of the problems which has grown in recent years with respect to noise impact is the proliferation of local noise regulations, especially those relat-

TABLE 3.4 Noise Classification of Selected Aircraft

Noise Class	*Aircraft Type*
Quiet propellor	DHC-7, ATR 42
Propellors	F-27, Viscount, C130, ATP
Chapter 3/Stage 3 short haul	B737-300, A320, BAC 146, F100, B757
Chapter 3/Stage 3 medium haul	A310, B767
Chapter 3/Stage 3 marginals	MD80, Hush kitted B727, 737s etc.
Chapter 3/Stage 3 heavy	late model DC-10, B747, A300, reengined DC8
Chapter 2/Stage 2 short haul	BAC 1-11 (hush kitted), B737-200, B727
Chapter 2/Stage 2 heavy	L1011, DC10, B747 early models
Uncertificated to Stage 2 requirements	SST Concorde, Uncertificated heavies: B707, DC8, VC10, IL62

**European Civil Aviation Commission*

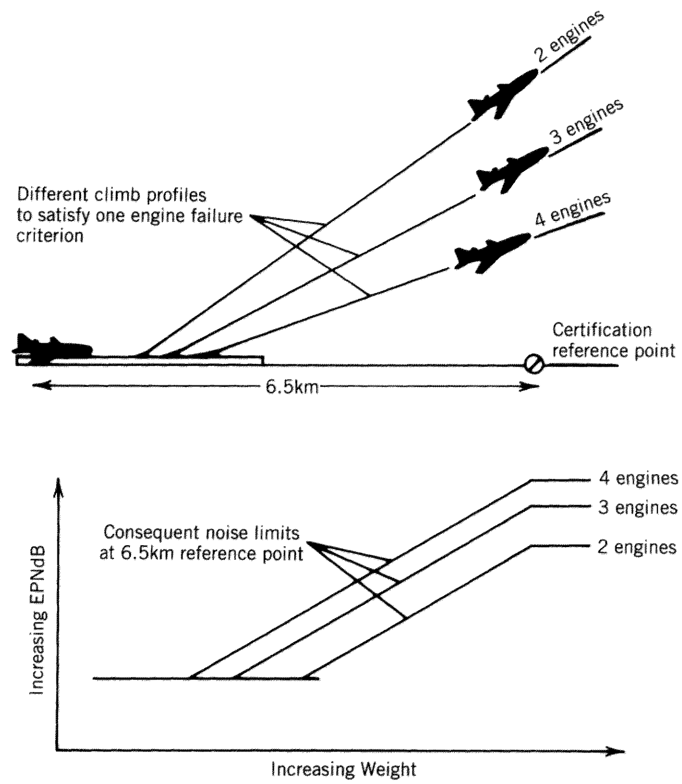

FIGURE 3.17 Stage 3 noise certification requirements.

ing to night time operations. These regulations involve both restrictions and curfews.

A number of communities have arranged that airports have night quota systems aimed at preventing increases in night time noise exposure (or noise "dose"). Such a quota system operates or is proposed on a 24 hour basis, for example at Minneapolis St. Paul and Stapleton airports 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 Manchester, for example, aircraft are designated into NN/C and NN/B classifications. Typically NN/C aircraft have a 95PNdB noise footprint of less than 5.2km^2. NN/B aircraft have footprints at the same level of between 5.2km^2 and 10.4km^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

This chapter has indicated that aircraft design has, in the past, improved productivity by increasing speed and size. The air transport product has now become much more diverse, with particular emphasis on aircraft-mile costs, as well as seat-mile costs. Several established trends have now been broken. 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 fuel efficiency of the turbofan makes it relatively more expensive as a consideration in supersonic flight. While it is undoubtedly feasible technologically, it is unlikely that the logarithmic growth of speed with time (Figure 3.18) will continue as a major stimulant to air travel.

Many advances in aerodynamics, structures, propulsion, systems, and control technology are moving from the development stage to production. These

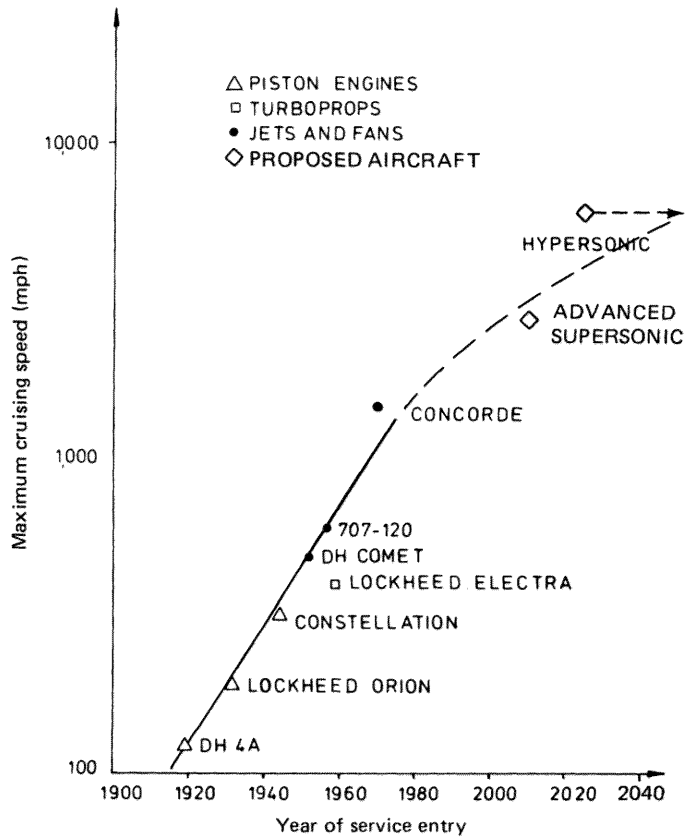

FIGURE 3.18 Historic and projected growth in air transport speed.

advances should allow a continuous improvement in fuel efficiency of at least 25% by the year 2000, allowing real unit costs to remain approximately constant. Technological development is now becoming so expensive that only a strong demand for fuel, causing a return to the fuel crises of the 1970s, is likely to warrant the development of advances like boundary layer control or a hydrogen technology.

The 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 build-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. Whether these designs are accepted into service will depend increasingly on their ability to match their runway strength and terminal design requirements to the airports' capabilities. The additional capacity is likely to be offered in the form of standard seating in extended upper decks of the Boeing 747, with all the subsequent problems for the airport of servicing this higher deck level. The other main problem for all sizes of airport is likely to be the increased span of new aircraft at a given seating capacity, as the aircraft manufacturers aim for greater aerodynamic efficiency.

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4

AIRPORT SYSTEMS PLANNING

4.1 AVIATION SYSTEMS PLANNING

Aviation systems 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 continuing one and it includes the monitoring of the development of the system and the replanning of its evolution. The aviation system planning process can be applied to planning national and statewide aviation systems as well as components of such systems as in the case of airport planning (1).

The aviation system is itself made up of a number of component systems:

Airways.
Airports.
Airlines.
Aircraft.
General aviation.
Air passenger.
Operating environment.

Ideally, the planning of the airport system should be subsumed into an aviation systems planning exercise. In practice this is seldom, if ever, feasible. The scale of the aviation system, even in a relatively undeveloped country or a small developed country, is very large. In many cases, part of the system is in the private sphere rather than the public sphere, which renders the whole exercise suspect.

Airport systems planning, however, frequently has to be carried out as part of the exercise of master planning at one or more airports within the system.

 Airport Engineering, Third Edition. Norman Ashford and Paul H. Wright

The aim of airport systems planning is to determine and plan for the scope of development of individual airports within a system in accordance with a scheme which is most likely to fit the individual facilities into an optimal overall development pattern.

4.2 LEVELS OF PLANNING

It is generally recognized that there are three levels at which planning can be carried out (see Table 4.1):

Strategic planning examines long-term structures and determines how well various structures fit with identified goals and objectives. A strategic plan sets out procedures to follow which will lead to an optimal long-term structure.

Tactical planning determines short- and medium-term courses of action which best fit into overall strategic plans and goals. Furthermore, tactical plans identify the best manner of carrying out these short- and medium-term courses of action.

TABLE 4.1 Levels in Aviation Planning

STRATEGIC PLANNING LEVEL	Set goals and objectives Inventory of existing strategic system Demand analysis Postulate options or scenarios Evaluation Select future strategic system	AVIATION SYSTEMS PLANNING
STRATEGIC PLANNING LEVEL	Inventory of existing systems Scenario and demand analysis Postulate options for system development Evaluation Select optimal airport system	AIRPORT SYSTEMS PLANNING
For Each Airport Facility:		
STRATEGIC AND TACTICAL PLANNING LEVEL	Inventory of facility Demand analysis Airport development options Option evaluations Select preferred option	AIRPORT MASTER PLANNING
TACTICAL AND PROJECT PLANNING LEVEL	Select individual projects Propose different project planning options Select preferred project plan Optimize execution of project	PROJECT PLANNING

Project planning is the identification of a defined aspect of a tactical plan and the determination of the optimum manner of executing this aspect in project form.

4.3 THE IDEALIZED PLANNING PROCEDURE

The three levels of planning discussed in Section 4.2 can be applied to an idealized planning structure for aviation systems planning and airport system planning. The former is clearly seen to be an exercise at the strategic level, which sets an overall structure for planning the individual elements of the system discussed in Section 4.1. The relationships among various types of planning are shown in Table 4.1.

Airport systems planning is strategic in nature. It is a process designed to make the best use of the airport's system in the medium and long term.

Airport master planning is a mixture of strategic and tactical planning. It is strategic in that the plan is long term in its view of the ultimate role of the airport in the overall plan. It is tactical in that it details the short-term steps to be taken toward the strategic plan.

4.4 RANGE OF CONTEXTS OF AIRPORT SYSTEMS PLANNING

At this point, some discussion would appear to be necessary concerning the structure and context of the national aviation system and its effect upon the planning procedure. There is a seemingly inexhaustible variety of scenarios for the structure of aviation, ranging from complete governmental monopoly of all activities to an unregulated structure where all elements in the system respond to the private market economy. A number of these scenarios will be examined:

1. Governmental regulated monopoly.
2. Deregulated free market.
3. Mixed public/private approach.

4.5 INTERACTION OF SYSTEM PLANNING AND ITS CONTEXT

Governmental 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 modelled 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 given factors including:

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

In practice, in countries where centralized planning and administration have been adopted, many problems have been encountered, such as the following:

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

Deregulated Free Market

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

1. Access to finance in the normal commercial financial markets.
2. Introduction of competition, bringing lowest costs to the passenger and maximum service levels.
3. A market-driven approach, with management objectives responsive to passenger consumerism.

Although as yet no completely free market can be observed to be operating in aviation, in the present drive toward deregulation, a number of potential problems have been observed:

1. Airlines have no long-term commitment either to routes or airports, which brings an inherent instability to the system.
2. The system can be subject to very large changes in transport supply, in terms of airline provision, at very short notice.

3. 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.
4. 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.
5. Airports which are entirely privatized can have goals which are not aviation oriented and which, furthermore, may conflict directly with aviation needs.
6. 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 nonaviation-oriented management.

Mixed Public/Private Approach

Most countries which are moving toward deregulation and privatization are doing so by a mixed public/private approach. This may be done in a number of ways, 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, French model).

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 is to be avoided.

4.6 DIFFERENT STRUCTURES OF AIR TRANSPORT SERVICE

In planning the structure of national air transport supply, even a relatively small system can give rise to a seemingly unlimited number of options for examination. In truth, these can all be expressed as variants of a lesser number of options:

1. A highly centralized system, with one dominant hub. Services from nonhub airports are largely or completely limited to flights to the hub, which is usually the capital city.

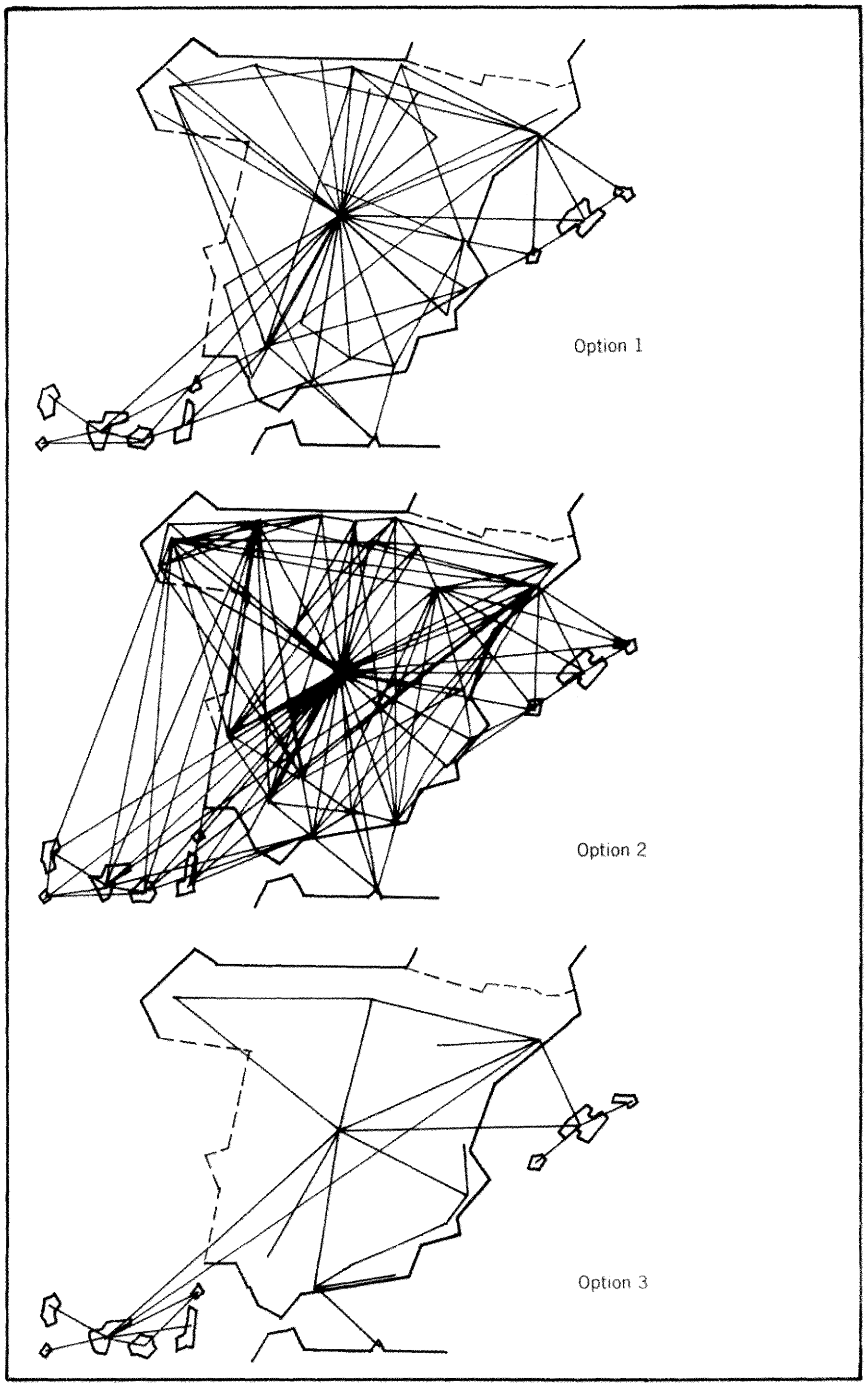


FIGURE 4.1 Three strategic options for the Spanish airport system. (*Source*: Spanish Airports Authority)

2. A multihub system, where hubs are distributed by geographical region and in accordance with urban centers. Direct service between nonhub airports is negligible.
3. Extensive point-to-point service, with only limited hubbing at a few transfer points.

A study for the planning of the Spanish airport system is a good example of three options which were evaluated as development options. Figure 4.1 shows the three main options which were examined:

Option 1. A highly centralized national system centered around the development of Madrid as the major hub, with minor hubs at Barcelona, Palma Majorca, Las Palmas Canaries, and Malaga. This option could be expected to produce a thin network of high-frequency routes, with dense loading and high aircraft load factors. There would be large volumes of transit and transfer traffic at the hubs, especially Madrid, and there would be a concentration of air traffic into the airspace at these hubs. The high frequency of service offered to the passenger would be offset by increased travel times, lack of direct service, and the inconvenience of required transit stops and transfers. The total number of aircraft operations in the system would likely be increased with this option.

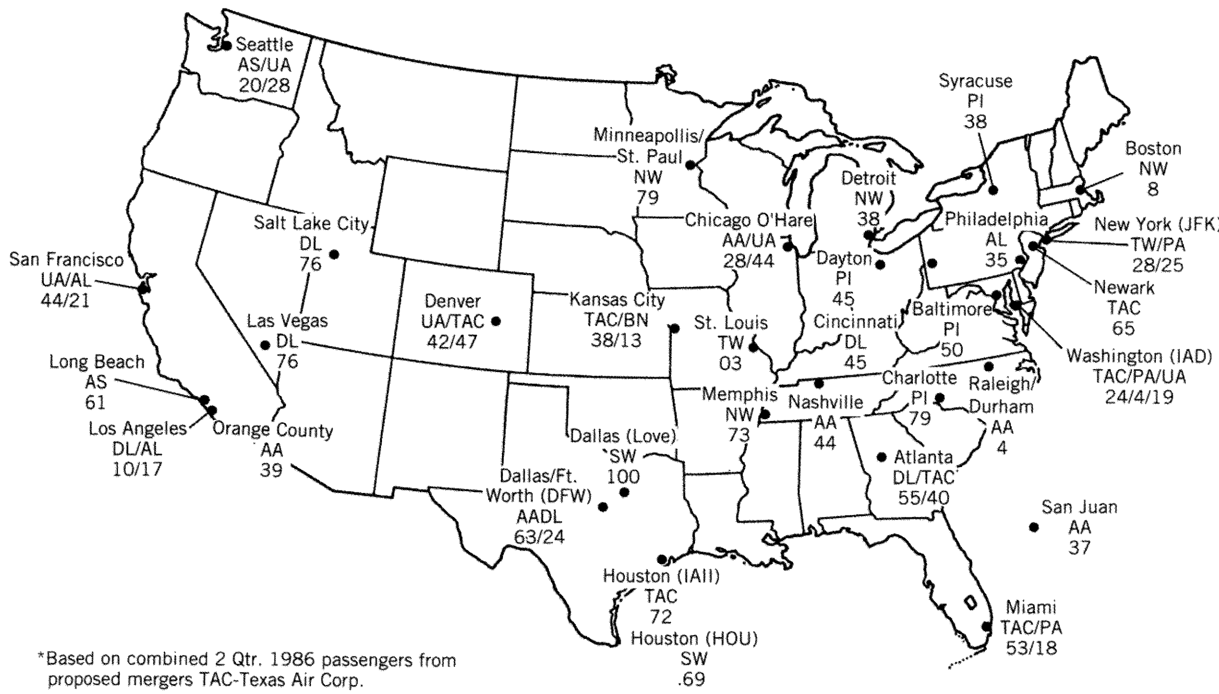
Option 2. This system proposed less concentration at the major and minor hubs of Option 1. More direct point-to-point services would be provided between the first-tier airports in the national system. This proposal would result in lower point-to-point travel times between the first-tier airports at the cost of lower frequencies and lower load factors. Air traffic would be more evenly spread in airspace.

Option 3. This option provided extensive point-to-point air service across the system. Air traffic would be extensively decentralized. Frequencies and load factors on many of the "thin" demand routes would be low. Hubbing activity at the four main airports of Option 1 would be low.

Since deregulation, the U.S. air system, which is more than an order of magnitude larger than that of Spain, has moved toward a multihub system based on a large number of hubs mainly situated east of the Mississippi. Figure 4.2 shows the structure of the U.S. hub system in 1986 and the shares of the major carriers at these hubs in that year.

4.7 EFFECT OF DEREGULATION ON U.S. AIRPORTS

In a totally deregulated environment, airport systems 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



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

FIGURE 4.2 Major U.S. hubs existing and planned (1986).

degree determines the number of air transport trips generated, their origin and destination airports, and the location of transit or transfers. The methodology used by system planners can model the effect of airline decisions reasonably well by use of airport choice and route choice models (see Sections 2.10 and 2.17, respectively). 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, and financial restructuring. It can be deduced therefore that airport systems planning will only work where there is a significant 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."

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, with feeder networks and schedules adjusted for inbound and outbound connections. These systems were designed to improve equipment productivity, but the efficiency gains from hub-and-spoke networks appear in practice to be very limited.
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 4.3, which indicates how the activities of three U.S. airlines (American Airlines, Northwest, and TWA) have concentrated into a few main hubs, with

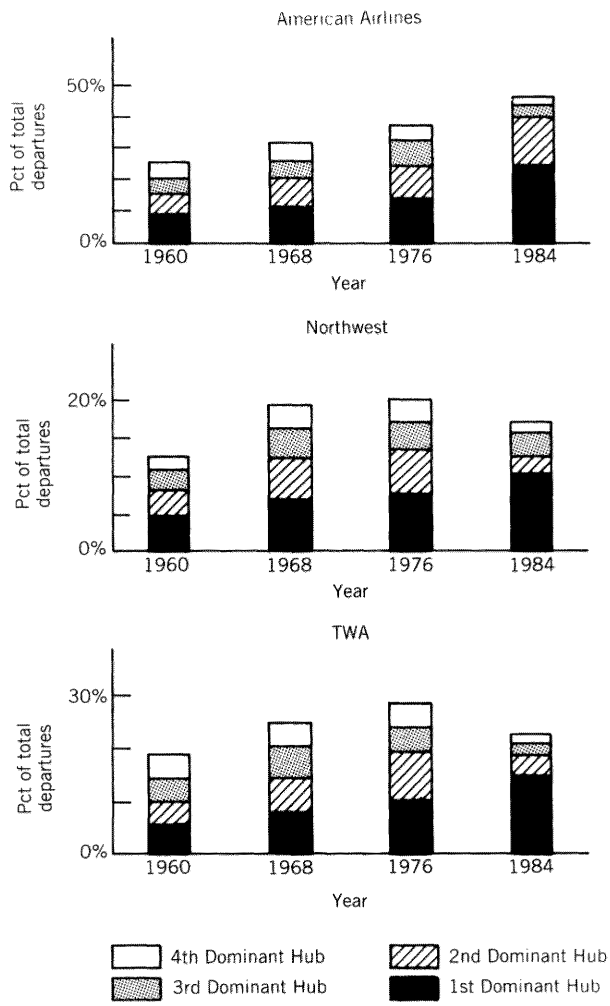


FIGURE 4.3 Trends in concentration of airline activity at various U.S. hubs.

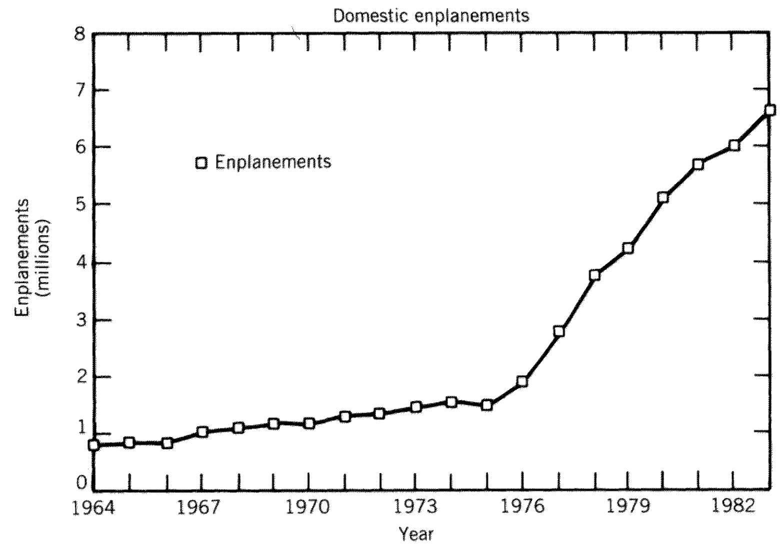


FIGURE 4.4 Enplanements at Charlotte,. S.C., 1964–1983. (*Source*: Reference 2)

major concentration at one facility. 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 (formerly Piedmont Airlines) and Raleigh-Durham (American Airlines); see Figures 4.4 and 4.5 (2). In other cases, there

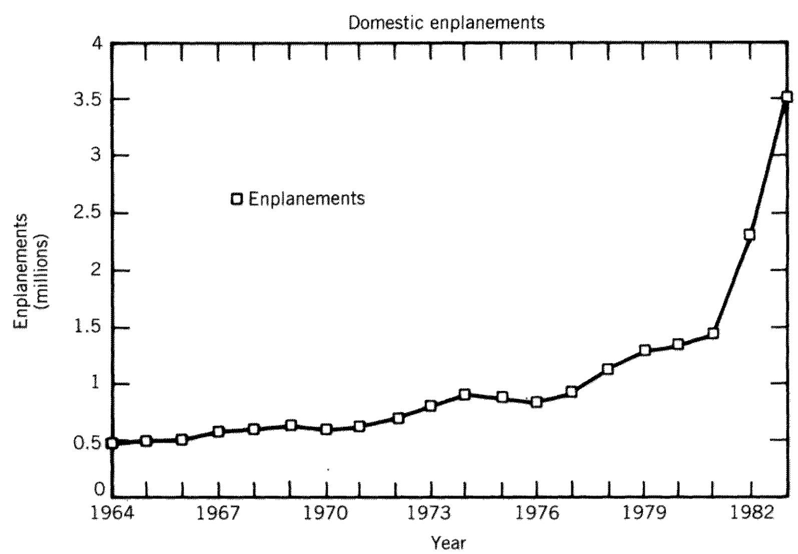


FIGURE 4.5 Enplanements at Raleigh-Durham, N.C., 1964–1983. (*Source*: Reference 2)

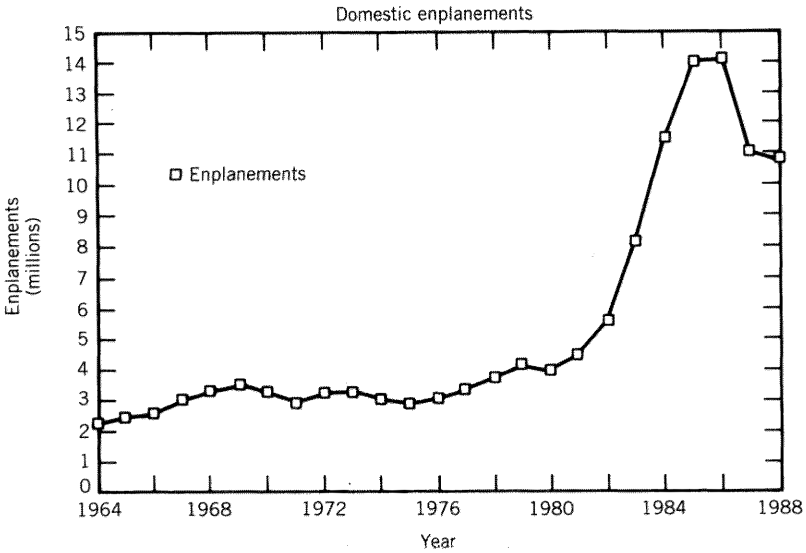


FIGURE 4.6 Enplanements at Newark, N.J., 1964–1988. (*Source*: Reference 2)

have been significant and sudden drops in traffic due to a failure of an airline or to some change in airline operating strategy. Figure 4.6 shows the 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 hub-

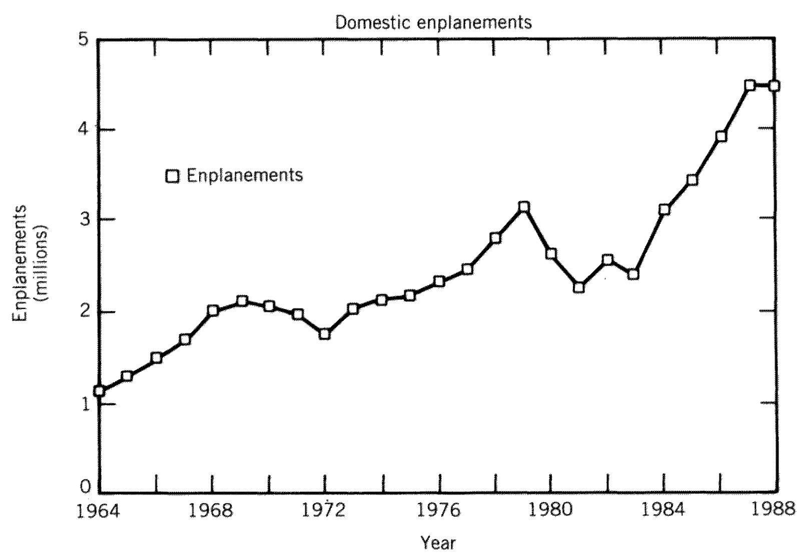


FIGURE 4.7 Enplanements at Kansas City, 1964–1988. (*Source*: Reference 2)

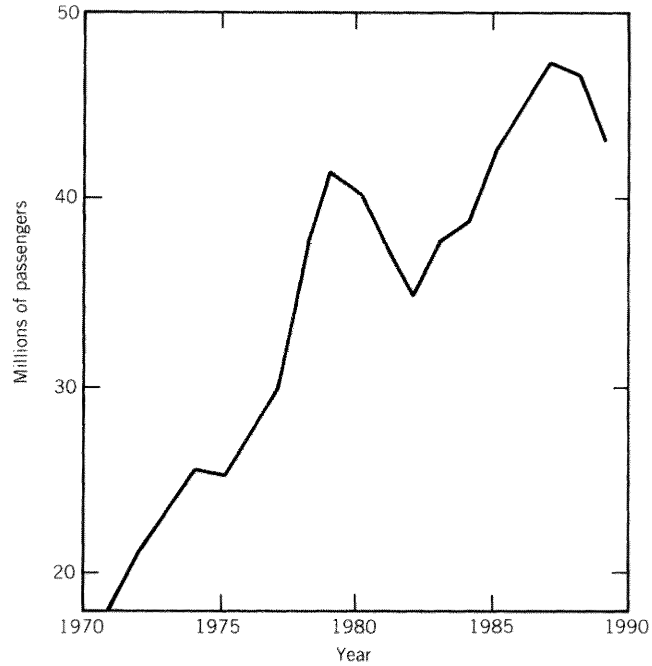


FIGURE 4.8 Total passengers at Atlanta Hartsfield International Airport, 1970–1989.

bing operation is shown in figure 4.7. The hiatus in long-term growth in Atlanta's traffic after 1979 was due to the deregulation itself, which permitted the monopoly of Atlanta's southeast hub to be broken by the development of other hubs within the region (see Figure 4.8).

De Neufville has 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 money has to be generated by revenue bonding, the interest rate paid must be consequentially higher and bond flotation becomes more difficult (2). To reduce risk, de Neufville recommends 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.

4.8 THE LONDON AREA—A CASE STUDY IN AIRPORT SYSTEM PLANNING

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 London; Gatwick, 25 miles south of London; Luton, 27 miles north of London; and Stansted, 31 miles northeast of London.

The terminal capacities of the individual airports were forecast as follows:

Heathrow:	45 mppa in 1995, rising to 50 mppa in 1990 and 55 mppa in 1995.
Gatwick:	26 mppa in 1995, increasing to 30 mppa in 2000 and rising no further.
Stansted:	9 mppa in 1995 and rising as required thereafter.
Luton:	5 mppa in 1995, rising no further.

Gatwick's capacity is constrained by the availability of a single runway; it is therefore fruitless to increase terminal capactiy beyond 30 mppa. The 5 mppa passenger limit at Luton is due mainly to the airport's proximity to Stansted. Air traffic airspace control limits the number of air transport movements (ATMs) to Luton as the new London airport, Stansted, expands.

The 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. 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 under three different assumptions.

1. *Case 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. *Case 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. *Case C.* Stansted would be limited to 20 mppa and other southeast airports not able to take significant additional traffic.

Table 4.2 shows how traffic is expected to divert from the London area and the southeast area under these different assumptions. Very high traffic diversion takes place to East Midlands and Birmingham airports, which are approximately 120 miles north and 100 miles northwest, respectively, of the London area. The locations of the airports used in this airport systems planning exercise are shown in Figure 4.9. 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. These would be trips either not made because passengers could not find a convenient airport or made by some other mode. This amounts to over 8% of all forecast trips.

TABLE 4.2 Strategic Planning for the London Area Air Traffic

		BASE YEAR		FORECAST YEAR		
		1987	2000	2005		
				Case A	Case B	Case C
Heathrow	LHR	34.8	49.4	54.8	54.8	54.8
Gatwick	LGW	19.4	30.0	30.0	30.0	30.0
Stansted	STN	0.7	16.6	33.3	19.9	19.9
Luton	LTN	2.6	5.0	5.0	5.0	5.0
Birmingham	BHX	2.6	9.9	8.7	11.4	13.6
Bristol	BRS	0.65	1.9	2.4	1.4	2.6
East Midlands	EMA	1.3	7.2	5.3	8.9	10.1
Leeds Bradford	LBA	0.6	0.25	0.39	0.6	0.8
Manchester	MAN	8.6	13.8	16.1	17.5	16.5
Newcastle	NCL	1.3	2.8	2.8	2.9	2.9
Southampton/ Bournemouth	SOU/ BOH	0.5	3.5	0.8	5.8	0.8
Other regional airports		15.4	27.1	28.7	28.7	28.7
Lost			7.3	14.1	15.7	16.6
Total		88.5	176.2	204.2	204.2	204.2

Case A: All London Area demand accommodated at Stansted.
Case B: Stansted limited to 20 mill. passengers.
Case C: Stansted limited to 20 mill. passengers, but other airports in S. E. England not able to take significant additional traffic.

4.9 ROLE OF INDIVIDUAL AIRPORTS

The role played by an individual airport within an airport system can be crudely expressed in terms of the number of passengers carried in comparison with the total demand. In any comprehensive analysis of an airport system, total system demand must be apportioned among the component airports according to observed characteristics of traffic sharing or traffic attraction. It has been found that traffic is attracted to airports explicitly by the level of air traffic service supplied (in terms of capacity, frequency, and cost) and implicitly by the airport facilites supplied to support this traffic.

Total demand at a facility is constituted of origin and destination traffic plus transit and transfer passengers. The former can be modeled by airport choice models, while the latter are predicted by route choice models. These rather advanced forms of demand models are covered in Sections 2.10 and 2.17. Figure 4.10 indicates the method of predicting an individual airport's share of total system traffic when scenario analysis is used:

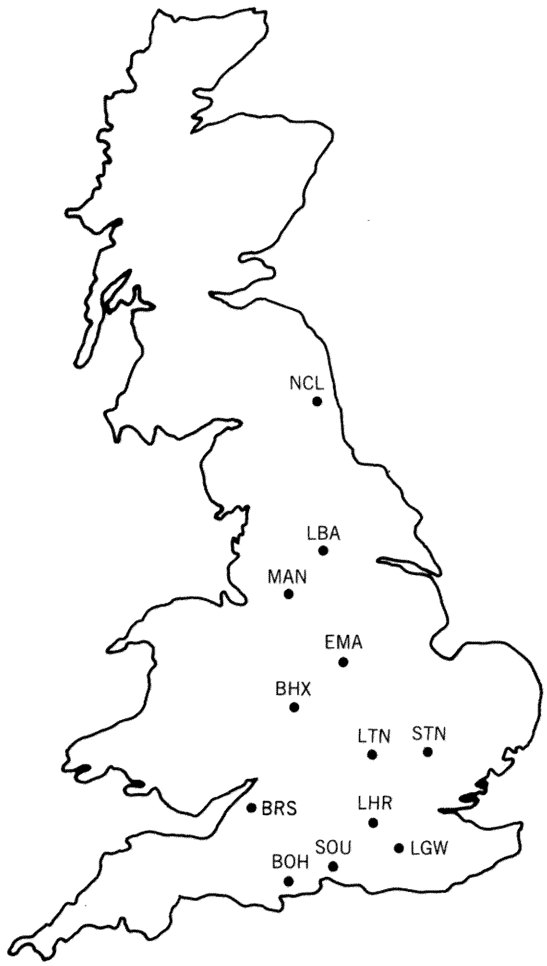


FIGURE 4.9 Airports used in CAA airports systems study in Britain (1989).

1. A scenario for the development of the airport is set out in conjunction with scenarios for all other airports in the system.
2. Airline service is postulated in terms of frequencies, capacity, equipment type (jet or turboprop), and fare levels.
3. Originating and destined passengers are predicted using airport choice models.
4. Transfer and transit passengers are predicted using route choice models.
5. The total demand at the airport is compared with the airline supply levels assumed. When these are in balance, the demand obtained is accepted.

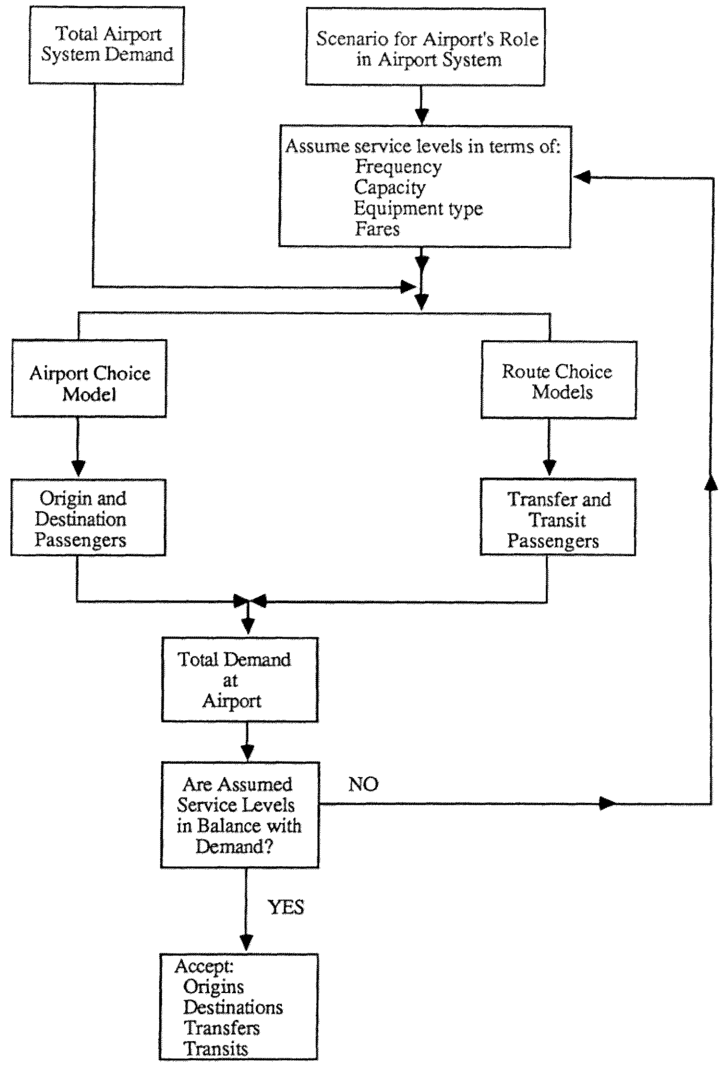


FIGURE 4.10 Flow chart of analysis for airport systems planning.

4.10 A DATA BASE FOR AIRPORT SYSTEM PLANNING (1)

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. The following is a comprehensive data base recommended by Kanafani:

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 basis, as well as on a monthly and daily basis. The data should cover both passengers, cargo tonnages, and aircraft operations. For the calibration of demand forecasting models, it is necessary to obtain traffic data for at least seven years.

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.
Temporal traffic patterns, including hourly distributions.
General aviation-based aircraft and fixed-base operators.
Airlines served.
Access traffic conditions and factility 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.

4.11 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 issues guidelines in preparing metropolitan and state aviation plans (3,4) and itself prepared in 1984 the National Plan of Integrated Airport System's (NPIAS), which is periodically updated (5), to replace the earlier National Airport System Plan. NPIAS is a bottom-up plan which integrates local airport master plans with state aviation system plans, as shown in figure 4.11. The whole plan is updated by a continuous planning procedure whereby interim and formal plan updates are prepared as reappraisal determines them to be necessary, see Figure 4.12.

The FAA form of 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 the type of dynamic structure recommended by de Neufville (2) to provide for dramatic upheavals in the industry, such as are occurring under deregulation, due to the fact that the basic building blocks of NPIAS are local airport master plans. These in the past have shown themselves to be incapable of predicting the impact of industry-wide changes (see Section 4.7). Even so, the NPIAS format has performed reasonably well 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

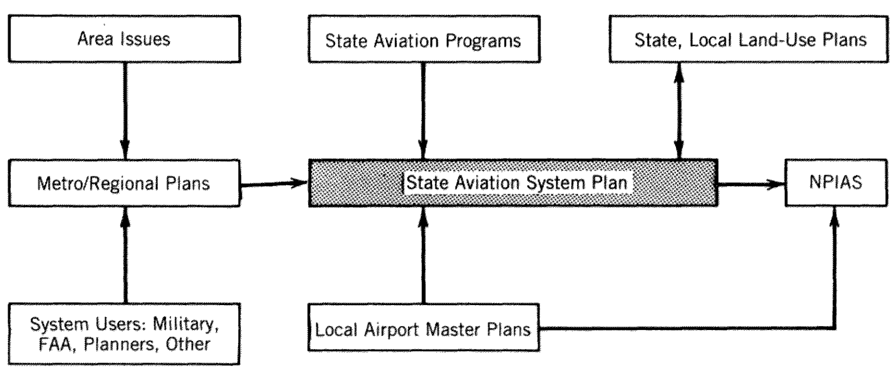


FIGURE 4.11 Planning relationships for a state aviation plan. (*Source*: FAA)

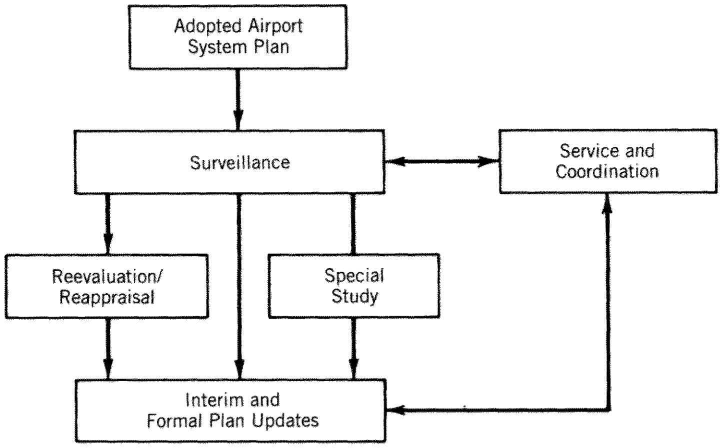


FIGURE 4.12 Continuous airport system planning process.

to a more strongly centralized approach (6). 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 (7):

1. Setting up of a long-term strategic planning process with FAA.
2. Immediate physical improvements to airport and aviation facilities to support a strategic planning process.
3. Definition of a set of short- and long-term goals for aviation.
4. 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:

- 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 serving as 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 nine strategies of system development:

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

Figure 4.13 shows a "top-down" planning approach which can be used for smaller airport systems where much development is still likely to take place. This approach has a number of identifiable steps:

1. The extent of the system to be considered should be identified.
2. 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 Section 5.5).
3. Develop a set of scenarios for the roles to be played by different airports.
4. Estimate total system demand under different demand growth scenarios (e.g., high, most likely, low).
5. 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.
6. Examine each scenario based on the following:
   a. Estimate air service levels in terms of capacity, frequency, and cost.
   b. Distribute system-wide demand using airport choice and route choice models (see Sections 2.10 and 2.17, respectively).
   c. Ensure that demand and supply, in terms of service levels, are in reasonable balance.
   d. Determine financial, economic, and environmental feasibility.
7. Select the most robust scenario.
8. Draw up a staged development plan.
9. Establish a long-term capital budget program.

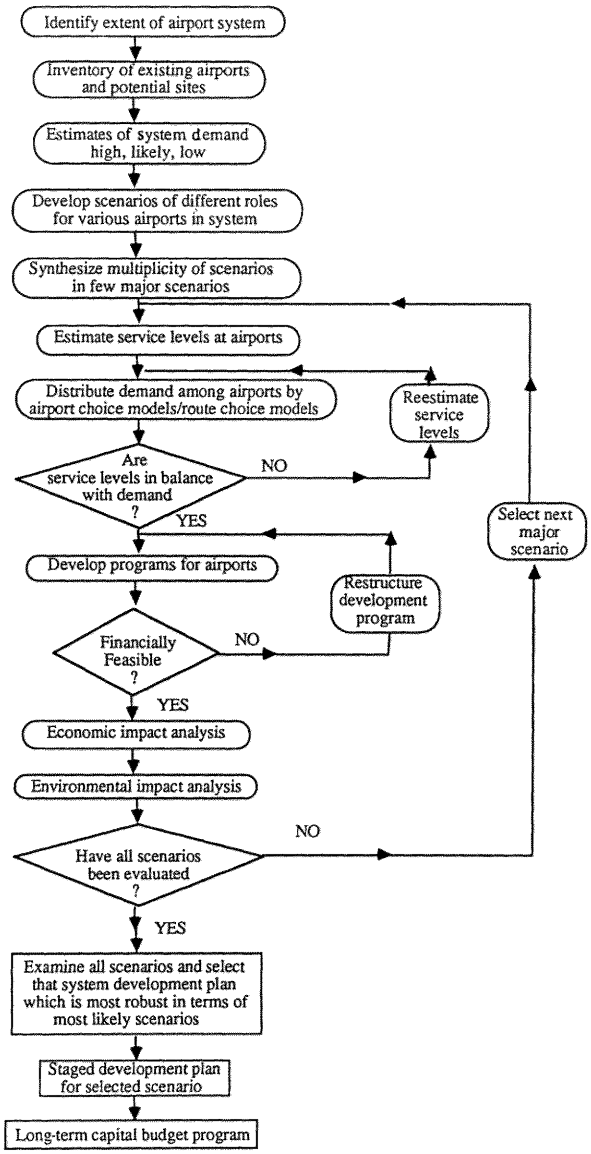


FIGURE 4.13 A comprehensive airport systems analysis. (*Source*: Reference 2)

4.12 SUMMARY

Two different types of airport system plans have been discussed. "Bottom-up" plans, such as NPIAS, serve developed systems reasonably well but are subject to very large local errors due to the intervention of the private sector in unanticipated of unpredictable ways. "Top-down" plans which make extensive use of scenario analysis can be useful for small, less developed airport systems. This type of comprehensive plan is, however, resource extensive in terms of data and manpower. For larger airport systems, such as those that exist in the developed countries outside the United States, the planning effort involved is likely to be greater than the utility of the derived plan. In such cases, an abbreviated analysis, such as that conducted by the CAA in the United Kingdom will be more appropriate. In spite of the extensive problems associated with the scale of work involved in comprehensive studies, limited system studies are frequently required prior to carrying out master plans for individual airports (8).

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5

AIRPORT MASTER PLANNING

5.1 THE 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. 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 guidelines for future airport development which will satisfy aviation demand in a financially feasible manner, while at the same time resolving the aviation, environmental, and socioeconomic issues existing in the community. Specific objectives of the master plan include (1)

1. Providing an effective graphic presentation of the future development of the airport and future land uses in the vicinity of the airport.
2. Establishing a realistic schedule for the implementation of the development proposed in the plan, particularly for the short-term capital improvement program.
3. Proposing an achievable financial plan to support the scheduled implementation program.
4. Justifying the plan technically and procedurally through a thorough investigation of concepts and options of a technical, economic, or environmental nature.
5. Presenting for public consideration, in a convincing and candid manner, a plan which adequately addresses the issues and satisfies local, state, and federal regulations.

Airport Engineering, Third Edition. Norman Ashford and Paul H. Wright

6. Documenting policies and future aeronautical demand for reference in municipal deliberations on spending, debt incurrence, and land use controls, (e.g., subdivision and deveolpment regulations, and the erection of potential obstructions to air navigation).
7. Setting the stage and establishing the framework for a continuing planning process. Such a process would monitor key conditions and adjust plan recommendations if required by changed circumstances.

5.2 THE 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 for assistance 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 THE AIRPORT MASTER PLAN: (FAA)

The Federal Aviation Administration specifies a number of elements which are generally to be included in any master planning exercise (1):

1. Organization and preplanning.
2. Inventory of existing conditions and issues.
3. Aviation demand forecasts.
4. Requirements analysis and concepts development.

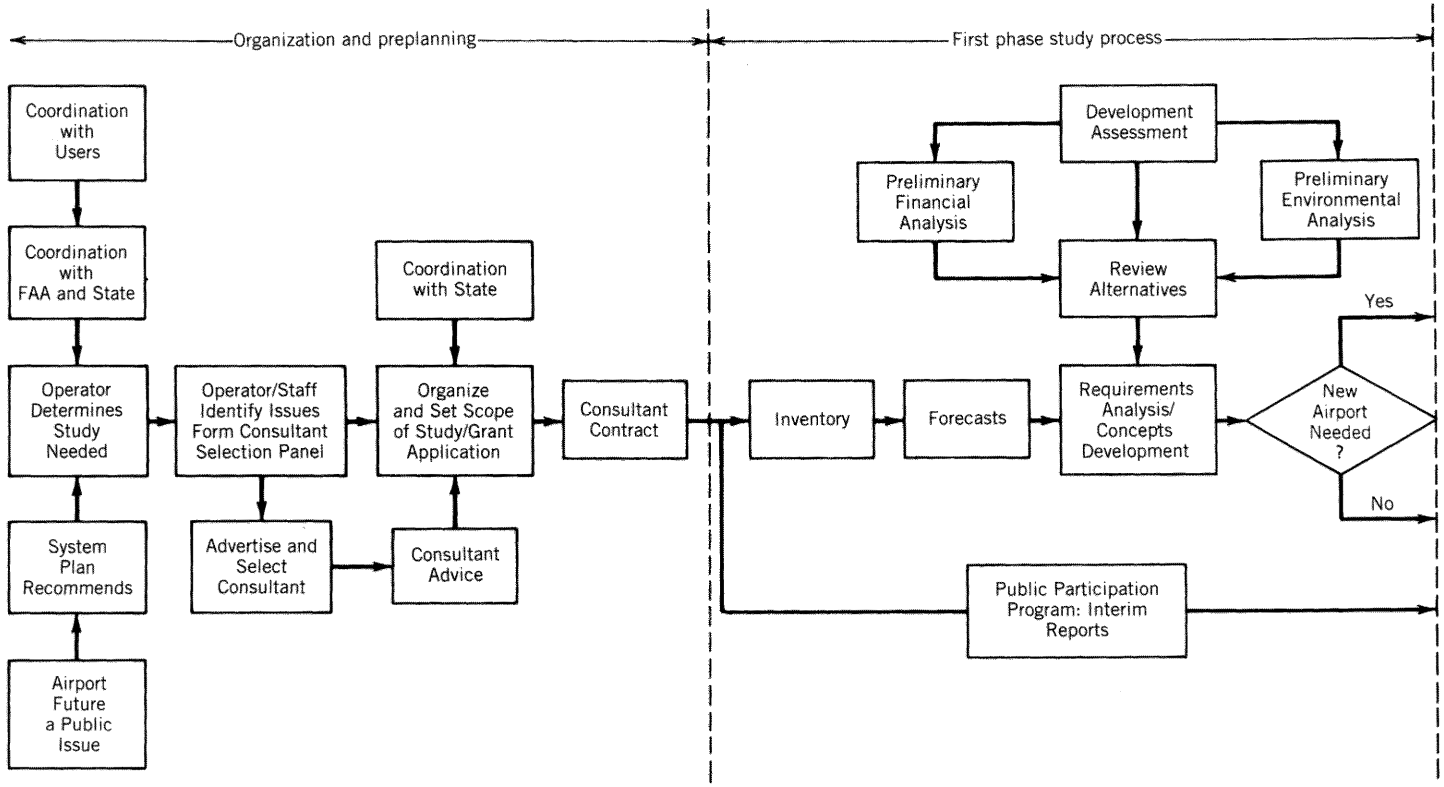


FIGURE 5.1 Airport master planning (FAA)—organization, planning, and first phase. (*Source*: Reference 1)

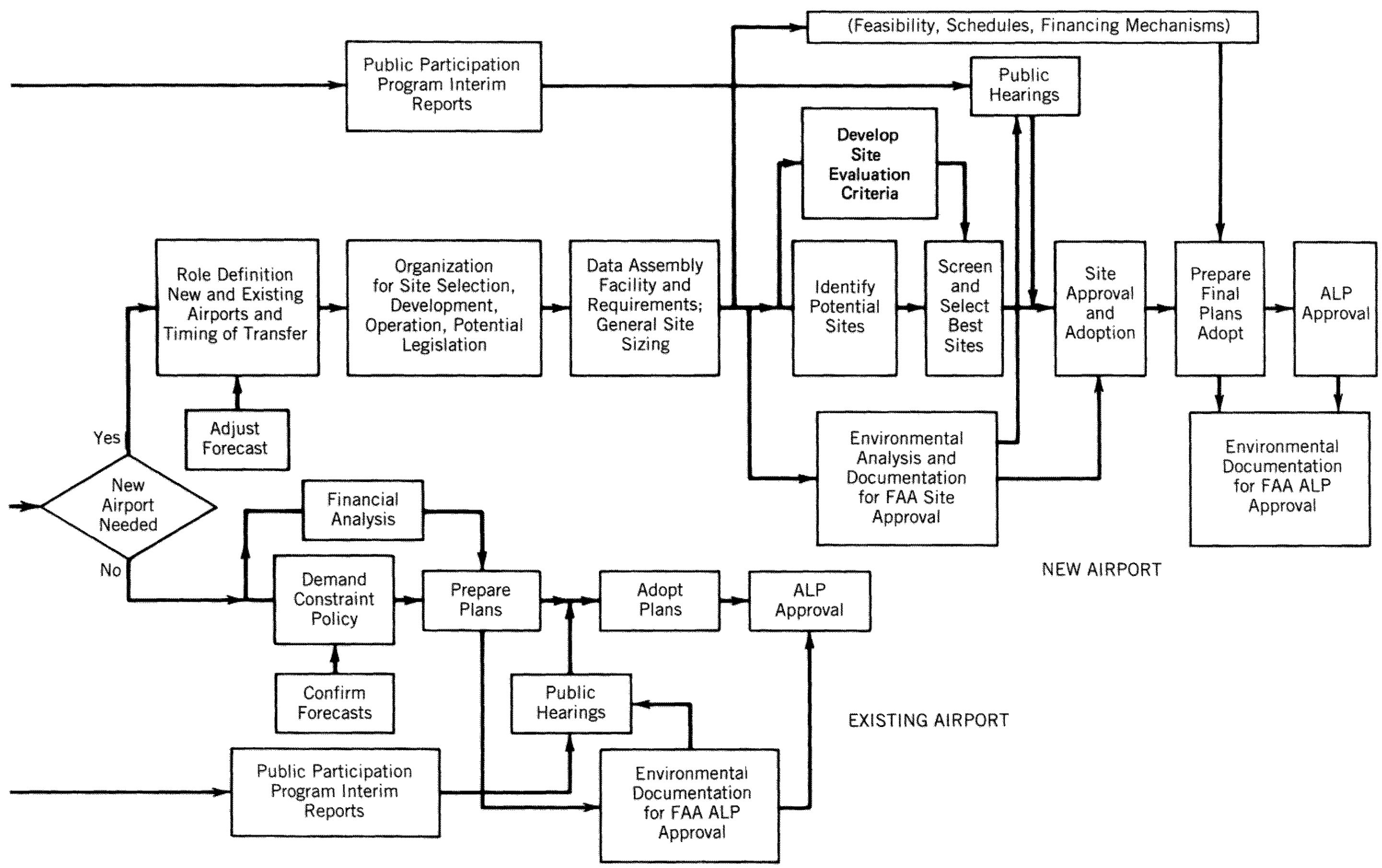


FIGURE 5.2 Airport master planning, second phase: new airport and existing airport. (*Source*: Reference 1)

5. Airport site selection.
6. Environmental procedures and analysis.
7. Simulation.
8. Airport plans.
9. Plan implementation.

The interrelationship of these elements is shown in Figures 5.1 and 5.2.

5.4 INVENTORY OF EXISTING CONDITIONS AND ISSUES

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 useful life. Data will be required on ground access, circulation, and parking. Additionally, historical data on weather conditions needs 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 indebtness.

5.5 AVIATION DEMAND 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 has need of 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-minute 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.

5.6 REQUIREMENTS ANALYSIS AND CONCEPTS DEVELOPMENT

In light of the forecasts of demand and the inventory of existing airport plant, planning continues as an investigation of the capability of the airport to meet forecast demand. Unconstrained air side and land side capacity needs are determined. Where there are financial, physical, or environmental constraints to expansion, the option of traffic diversion to other airports will be fully examined.

The time frames used for assessing development needs are usually considered as *short term* (up to 5 years), *intermediate* (up to 10 years), and *long term* (up to 20 years). Short-term planning is geared to immediate actions and necessarily includes a level of detail which is inappropriate for longer time periods. Long-term planning is concerned with the ultimate role and development of the airport. It deals therefore with development on the broad scale. Intermediate planning requires a level of detail somewhere between long-term and short-term considerations.

Demand-Capacity Analysis

With a 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 in 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:

1. Forecast of aircraft operations vis-à-vis airspace capacity (2, 3).
2. Forecast of aircraft operations vis-à-vis air traffic control facilities (4).
3. Forecast of aircraft operations vis-à-vis airfield capacity (5, 6).
4. Forecast of passenger movements vis-à-vis passenger terminal capacity (see Chapter 10).
5. Forecast of cargo volumes vis-à-vis air cargo terminal capacity (see Chapter 11).
6. Forecast of access traffic vis-à-vis surface access route capacity (7).

Facility Requirements

The type 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):

1. *Runways.* Length, width, clearances, clear zones, approach slopes, orientation, crosswind runway provision, grades, capacity, staged construction, cost implications of delay to aircraft, and cost effectiveness.
2. *Taxiways.* Width, location, clearances, design and location of exits, grades, effect on runway capacity, staged construction, and cost effectiveness.
3. *Terminal Area.* Clearances, grades, gate positions, aircraft parking clearances, space requirements, and terminal design concept.

In addition to the general application of land use criteria (see below), the following general considerations are important in integrating land side and air side functions (1).

General Aviation Airports

- Locate administration area close to parking and ground transportation.
- Separate fixed-base operators from administration area but maximize exposure to marketing opportunities.
- Coordinate general aviation functional areas.
- Minimize taxiing times.
- Locate itinerant operational and fueling areas close to administration building.

Commercial Service Airports

- Separate airline, general aviation, and commuter traffic on apron but provide easy land side connections.
- Consolidate general aviation functional areas.
- Facilitate interairline transfers of passenger and traffic.
- Separate special air carrier functions—commuter, charter international—but provide easy interconnections.
- Encourage joint airline use of facilities.
- Minimize walking distances.
- Provide public transport curbside interface.
- Keep land side vehicle traffic circulation simple.
- Centralize administration but provide convenient staff facilities (parking, restaurants, rest areas, etc.).
- Allow for growth of air cargo but facilitate cargo transfer and access.
- Provide for growth of helicopter/VTOL traffic.
- Provide for efficient apron handling operations.
- Locate crash, rescue and firefighting (CRFF) services where response time is low to all on-airport locations.
- Locate car rental areas in areas convenient to terminal.

Because of the importance of the terminal in terms of both cost and level of service implications, considerable emphasis must be placed on facility planning in the terminal area.

4. *Service and Hangar Areas.* Service equipment buildings, cargo facilities, and fire and rescue equipment buildings.
5. *Heliports.* Planning and design, rooftop and elevated pads.
6. *Obstructions.* Required standards for approach, horizontal, and other control surfaces, and clear zones.
7. *Drainage.* Structures, layout, and grades.
8. *Paving.* Fillets, jet blast protection, pavement types, and construction details.

9. *Lighting and Marking.* Approach lighting, runway lighting, taxiway lighting, runway and taxiway marking, helicopter landing area, and obstructions.
10. *Aids to Navigation.* Location and grading requirements.

In addition to facilities, at this stage it is necessary to consider land use criteria and meteorological conditions. *Land use criteria* should be adopted which

- Adhere to standards which support safe aircraft operation, including FAA design and obstruction standards, such as those set out in Federal Aviation Regulation, Part 77.
- Noninterference in required lines of sight for facilities such as FAA control towers, apron control towers, navigation aids, and weather equipment.
- Use of existing facilities and land uses where possible.
- Flexibility to accommodate changes in demand.
- Efficiency in ground access.
- Priority given to aeronautical activities where available land is limited.
- Encouragement of revenue-producing nonaeronautical activities.
- Flexibility of nonaeronautical uses to permit expansion of aeronautical uses at a future date.

Meteorological conditions: Historical records of visibility, wind, and precipitation over at least five years will permit a better evaluation of the site's capacity to support aviation activity.

Airspace and Air Traffic Control

In discharging its responsibility for managing the air traffic control system, the FAA performs a number of functions which directly bear on airport planning. The airport master plan and layout plan serve as a focal point for FAA recommendations with respect to the future development and operation of the airport. Terminal flight procedures will be reviewed by the FAA, guided by the "United States Terminal Instrument Procedures (TERPS) (2), for instrumental operations, and by Federal Aviation Regulation (FAR) Part 91 for VFR procedures." A similar document, "Procedures for Air Navigation Services Aircraft Operations" (PAN-OPS), is applicable for non-U.S. airports which operate under ICAO recommendations.

Consultation with the FAA is advised to ensure that potential airspace limitations are considered. These include

- Permanent obstructions to operations, such as high terrain, buildings, and construction.

- Need to restrict the use of airspace due to the proximity of another airport.
- Requirements of circuitous routings via intermediate control points.
- Overloading the air traffic control system due to peaking or adverse weather.
- Electromagnetic interference.

Review of Options

Where the assessment of an airport's capacity indicates that substantial expansion is necessary to accommodate projected demand, it is recommended that there be an assessment of options. The options should include the following:

1. The consequences, both social and economic, of the do-nothing option on aviation and the community in the short and long term.
2. The provision of separate "reliever" airports which will draw traffic from the busy commerical service airport.
3. The investigation of a new facility on a new site, examining the possibilities of both continuing or closing the existing airport.

5.7 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 communtiy 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 over the last 15 years, airports have come to be identified as land users that cause severe environmental deterioration to their neighbors, generate 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 location of the proposed fourth New York airport, the third London airport, the second Atlanta airport, the proposed Everglades (Miami) airport, and the second Sydney airport, to name only a few. Accordingly, site selection is now as complex as the problem it seeks to solve. In the master planning procedure, the FAA recommends a minimum site selection analysis that includes 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 Area-wide Planning: Impact on land use, effect on comprehensive land use and transportation plans at local and regional level.

5.8 ENVIRONMENTAL PROCEDURES AND ANALYSIS

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. A proposed project which cannot be considered with respect to individual work items, but only from a broader program context, will be classified into one of three categories:

1. Categorical exclusions.
2. Actions normally requiring an environmental impact assessment (FAA Order 5050.4).
3. Actions requiring an environmental impact statement (FAA Order 5040.4).

Although relatively few airport actions require an environmental impact statement, any federal actions regarding proposals with respect to airport development that significantly affect environmental quality must be accompanied by a statement of the following:

1. The environmental impact of the proposed action.
2. Any adverse environmental effects that could not be avoided if the proposals were implemented.
3. Alternatives to the proposed action.
4. The relationship between local short-term users of the environment and the enhancement of long-term productivity.

5. Any irreversible and irretrievable commitments of resources in the proposal.

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

Noise. This is the most common impact encountered. Aviation noise extends beyond the boundary of the airport into areas over which the airport operator has no authority but where the noise resulting from aircraft operations is still considered to be the airport's responsibility. If there are noise-sensitive activities within specified areas of noise impact, then there is a significant effect. The 1982 Airport and Airway Improvement Act requires appropriate action, including the adoption of appropriate zoning laws to restrict the use of land in the vicinity of airports to activities and purposes compatible with the landing and taking off of aircraft (8).

Socioeconomic Impacts. These include disruption of established communities, necessity for relocations, disruption of transportation patterns, and changes in employment patterns.

Impact on the Man-made Environment. Public parks, recreation areas, wildlife refuges, historical sites, cultural assets including sites of architectural interest must be considered in this category.

Air Quality. This is not usually a problem with airports, but where this is seen to be a significant problem, air quality analysis will be required (9).

Water Quality. The impact on water quality is more likely to be a problem than air quality. Much depends on current water quality and quantity. If the proposed development involves airport location, runway location, or a major runway extension, the governor of the state is required to certify that there is reasonable assurance that the project will be located, designed, constructed, and operated in compliance with applicable air and water quality standards. During the construction phase, soil erosion is a potentially heavy source of water pollution; during the operation phase, contamination is more likely to come from fuel spillage and leakage and in colder climates from the operational use of de-icing fluids.

Biotic Communities. These communities, which in the past were routinely inventoried in detail, no longer require this treatment as of right. Quality rather than quantity of biotic impact is now considered important. Also requiring consideration are rare and endangered species, wildlife and waterfowl habitats, and alteration of existing habitats and wetlands.

Other considerations are floodplains, coastal zone management programs, coastal barriers, prime or unique farmland, or farmland of state or local significance, wild and scenic rivers, light emissions, and solid waste disposal.

5.9 ICAO GUIDELINES FOR THE STRUCTURE OF THE 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 on 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 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.

*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.

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

TABLE 5.1 *Continued*

Planning Step	Description
	reporting, aircraft maintenance, rescue and fire-fighting, general aviation facilities, aircraft fuel facilities.
Security	Airside security: roads, fencing, isolated parking position, security parking area, emergency explosive holding area. Landside security: passenger buildings, public storage lockers.

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.

5.10 AIRPORT LAYOUT

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. The 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.

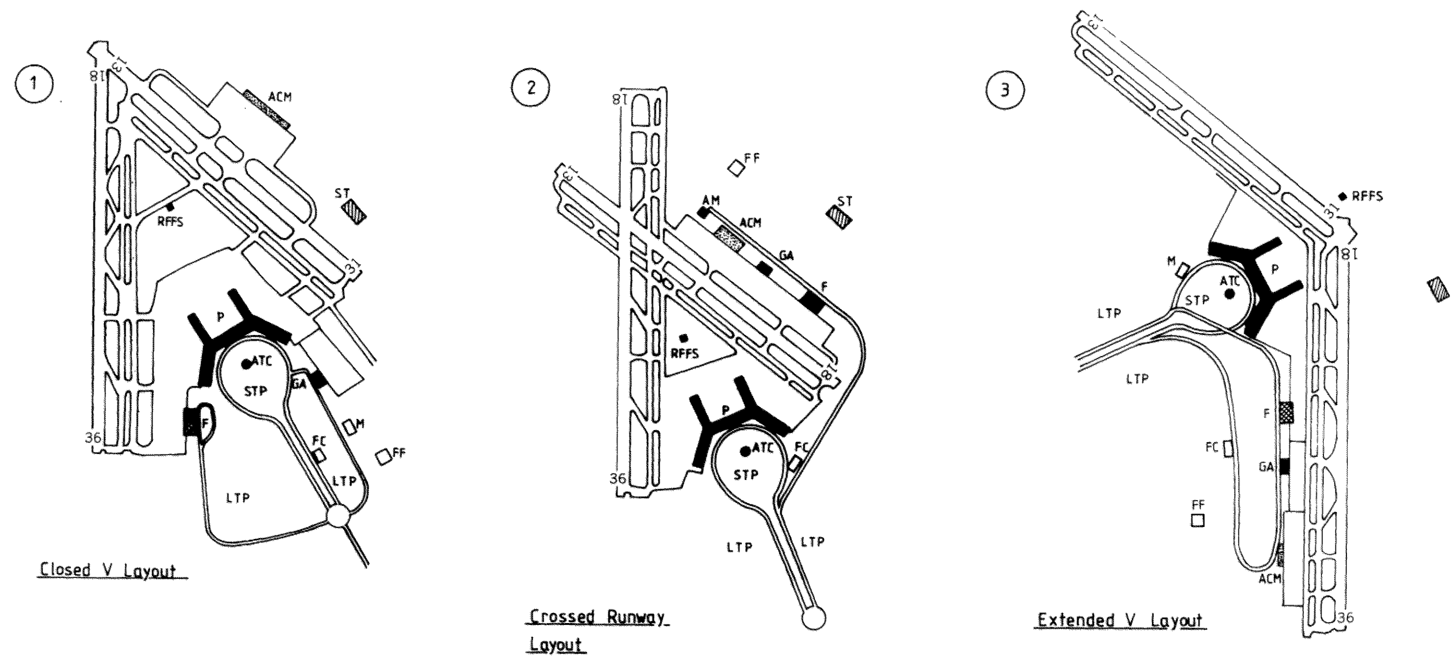
The principal facilities to be considered in an airport plan include

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.

Figure 5.3 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 air side.

5.11 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 data base. The collection and validation of data is therefore an important and time-consuming element of the master planning process. In a master planning exercise, the following data requirements could be expected:



Key

RFFS	Rescue & Fire Fighting Systems	ACM	Aircraft Maintenance
P	Passenger Terminal	ST	Sewage Treatment
ATC	Air Traffic Control Tower	LTP	Long Term Parking
F	Freight Terminal	STP	Short Term Parking
FC	Flight Kitchens	FF	Fuel Farm
M	Airport Maintenance, Engineering, Motor Transport		

FIGURE 5.3 Layout options for given runway lengths and orientation.

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.

Airlines' 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-economic base data on size and projected growth rates in 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 development.

Existing land uses and status of development in the airport environs.

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, and so on. 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/liability.

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.

5.12 AIRPORT PLANS: THE STRUCTURE OF THE MASTER PLAN REPORT

The presentation of the master plan is in the form of a report which describes the following:

Demand

Passenger traffic forecasts.

Cargo traffic forecasts.

Air transport movement forecasts.

General aviation and military movement forecasts.

Ground access traffic movements by public and private modes.

Capacity and Sequenced Facility Provision

The sequenced and staged provision of capacity in accordance with the development of demand. Capacity will be computed for:

Air side: Runways, taxiways, apron, holding areas, support facilities.

Terminals: Passenger and cargo.

Land side: Access modes and parking, support facilities.

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.

Maintenance areas.

It is usual to provide at least the following drawings for FAA purposes:

A. Airport Layout Plan (ALP).
   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.
      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 (3m or 10ft).
      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 to 1:7500 should be used depending on size of airport.
   4. Basic data table showing:
      a. Airport elevation.
      b. Airport reference print 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. Approach and runway clear zone drawing showing area under imaginary surface, approach and takeoff slopes, runway clear zones, approach zones, and surfaces with controlling structures and obstructions. Location and elevation of obstructions.
8. Property map, with ownership type size and routing of utilities.
9. Master utility drawing showing type size and routing of utilities.
10. Phased layout plans where applicable. Figures 5.4a and b show examples of a simple airport layout plan for a small airport in a developing country. Figure 5.5 shows the ultimate layout plan for a large international facility with a high ultimate design capacity.

B. Terminal Area Plan (1:5000 to 1:10,000) (staged where applicable).
   1. Conceptual drawings of terminals, passenger and cargo.
   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. Regional Land Use Plan.

(a)

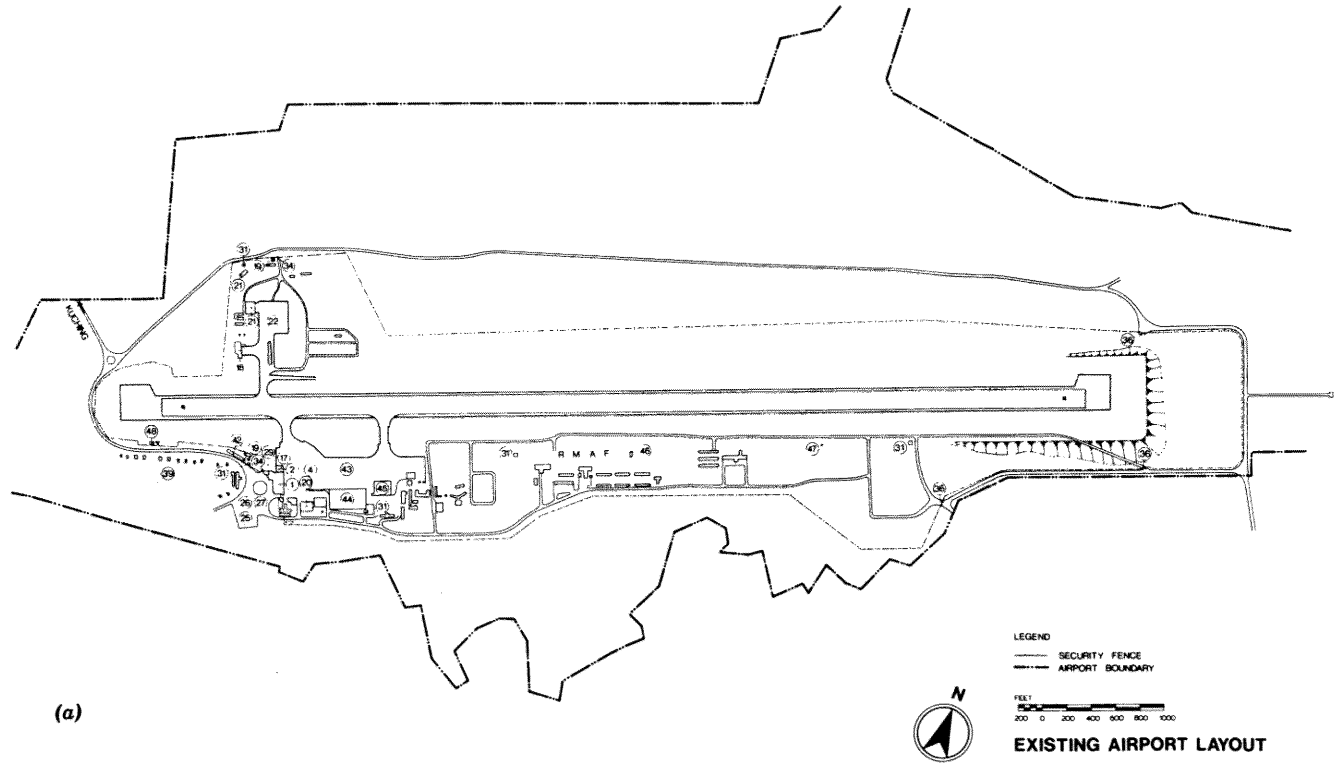


FIGURE 5.4a Example of airport layout plan—current facilities. (*Source*: Malaysian Associate Architects and Sir Frederick Snow and Partners by permission of Department of Public Works, East Malaysia)

(b)

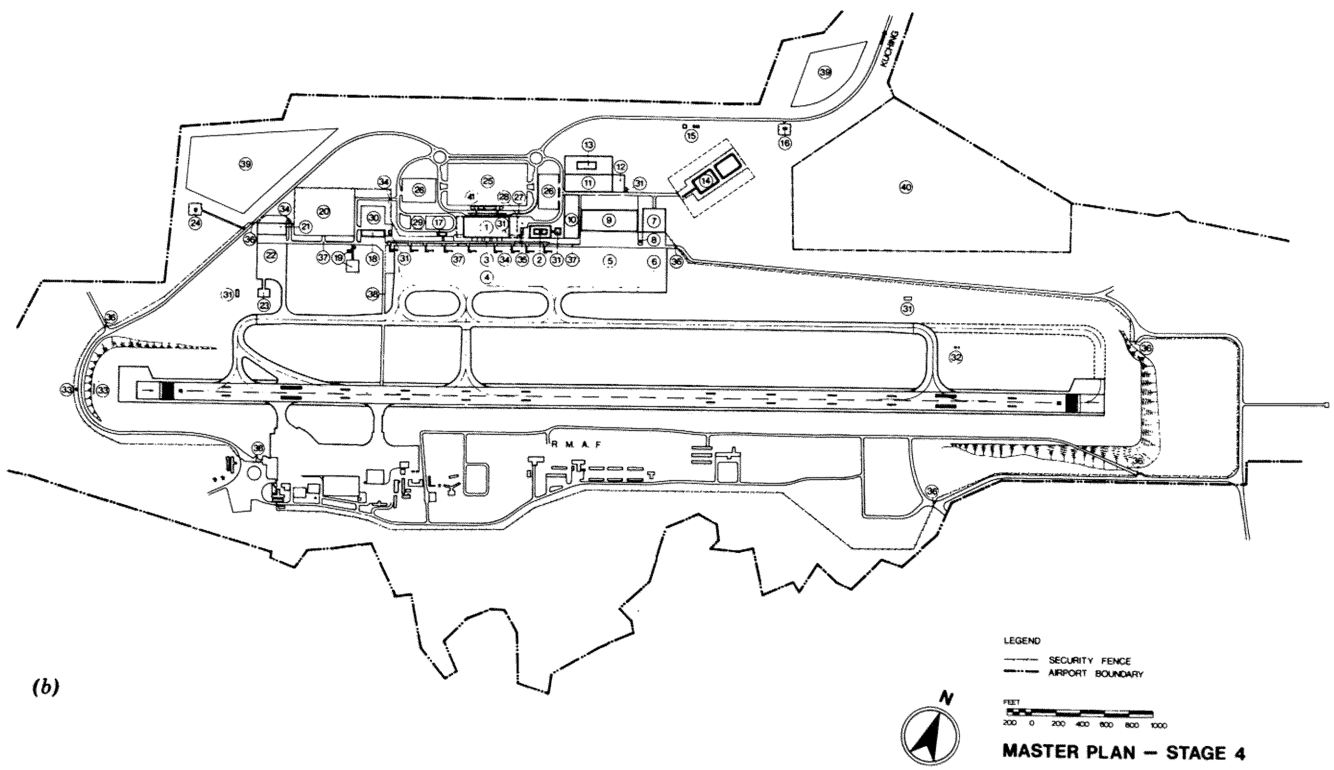


FIGURE 5.4b Example of airport layout plan—ultimate development. (*Source*: Malaysian Associate Architects and Sir Frederick Snow and Partners by permission of Department of Public Works, East Malaysia)

5.13 PLAN IMPLEMENTATION

Development and Costs

Schedules of proposed development and estimates of costs can now be developed on the basis of short-, intermediate-, and long-range aeronautical demand. Normally these are the 5-, 10-, and 20-year planning horizons. Quantity estimates are made from the staged airport layout plans previously drawn up and, from these, preliminary cost estimates can be made for the staged developments. Table 5.2 gives a typical preliminary estimate, broken into broad categories of construction and other costs that could be presented in the master plan. Such costs would be based on more refined estimates, but for master planning purposes, it is necessary to present only the broad-based costs, which are needed for economic and financial planning.

Economic Feasibility

Economic feasibility is considered at every stage of the master planning process: in the determination of whether to expand an existing airport or to develop a new site, in the selection of the site itself, and in the choice of design concept in the access-terminal-airfield system. In each case, preliminary cost elements must be used to assess capital investments and revenues. In the last phase of master planning, a final economic evaluation must be made of the 5-, 10-, and 20-year stage plans, to predict whether at each stage the planned development will be able to produce revenues to cover the annual capital and operating costs, supplemented as they may be by federal, state, and local subsides and grants in aid. In general, revenue comes from user charges, lease rentals, and concession revenues from the various airport operations. An examination of the estimated contributions enables the planner to determine whether the respective areas would be contributing a proportionate or proper share of costs, according to the policy that is to be adopted.

Investment is either *nondepreciable* or *depreciable.* Nondepreciable investment has an infinite economic life—in other words, it never wears out. Land acquisition is a good example. For items of permanent value, the annual capital costs are simply the interest on the investment. Normally, no interest costs are assumed in the economic analysis for investments using federal grant funds under the Federal Aviation Act of 1958 or the Airport and Airway Development Act of 1970. With investments of a finite economic life or capital that must be repaid in a shorter period, the annual capital costs are the interest plus a depreciation cost. Again, interest and depreciation costs are not computed when federal grant funds are computed. Airport revenues can be estimated to be available from the landing area, the terminal apron, airplane parking areas, the passenger terminal building, public car parking areas, aviation fuel sales, hangars, commercial facilities, concessions, and a variety of minor sources.

Examination of capital costs and revenues will indicate whether the staged

TABLE 5.2 Example of a Master Plan Cost Estimate for a Typical Project with Three-Stage Expansion of Existing Facility

Type of Expenditure	Stage 1 1992–1996	Stage 2 1997–2001	Stage 3 2002–2111
Paving			
Airfield (includes lights)			
Runway	$ 3,146,850	$ 720,630	$ 8,530,110
Taxiways	5,650,880	3,158,530	8,052,450
Aprons	1,372,220	1,233,385	6,925,500
Roads			
Terminal and service	1,328,400	1,215,000	5,637,600
Parking lot	364,500	—	1,174,500
Buildings			
Expansion of existing terminal	9,072,000	3,075,000	—
New terminal	—	—	51,030,000
Fire and crash equipment	—	—	810,000
Airport maintenance	—	—	1,336,500
Relocation			
Fixed-based operator	1,620,000	—	—
Military	324,000	810,000	—
Airport maintenance	283,500	—	—
Miscellaneous			
Electrical	1,093,500	178,200	680,400
Utilities	364,500	—	1,620,000
Drainage	243,500	121,500	1,417,500
Landscaping	—	—	1,215,000
Fencing	81,000	—	324,000
Site preparation	1,830,600	1,085,400	4,779,000
Total estimate for construction	26,774,950	11,600,645	93,532,560
Legal, administrative, engineering costs	5,738,515	2,548,575	20,577,165
Total project	32,513,465	14,149,220	114,109,725
Land acquisition	13,061,250	—	—
Total estimated cost	$45,574,715	$14,149,220	$114,109,725

development program is realistic; if it is not, it must be adjusted. In the early days of civil aviation growth, there was a tendency to underestimate potential revenues; consequently, development plans were too modest. Subsequently, many aviation forecasts were too buoyant, producing development programs that have proved to be financially troublesome to some airports (12, 13).

Implementation Schedule

The implementation schedule and cost estimate evolve jointly from technical considerations. Technical considerations include the time it would take to acquire land, to develop a completed design, to arrange for contractors, and to complete construction, as well as to obtain all necessary planning and environmental approvals.

Financial considerations which may affect scheduling include the availability of capital financing. Federal and state aid may be limited; current indebtedness could preclude further debt incurrence, or the level or interest rate in the financial markets may inhibit further debt financing. Implementation schedules should be drawn up on short- (up to 5 years), intermediate- (up to 10 years) and long-term (up to 20 years) development requirements. Table 5.2 shows an example of a Master Plan Cost Estimate for three-stage expansion over a 20-year period. It would be normal for the Master Plan to show layout drawings of the airport at the completion of the three cost development stages.

Financing

Once economic feasibility has been determined, a financial analysis must be made of the forms of capital available for carrying out the development. These in the United States include the following:

General obligation bonds.
Revenue bonds.
Private finance.
Financing from specially formed nonprofit corporations.
Industrial development authority bonds.
Federal grants.
State and municipal grants.
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 to 1.5% higher than general obligation bonds. They can be used only where facilities generate a sufficient operating surplus.

Private financing can be arranged for facilities such as hangars, hotels, fuel distribution systems, and so on. 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 municipality 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.

Industrial development authority bonds are issued and underwritten by a corporation located at the airport. The municipality is not involved in this financing.

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 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 form revenue-generating activities.

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 14.

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6

AIR TRAFFIC CONTROL, LIGHTING, AND SIGNING

6.1 PURPOSE OF AIR TRAFFIC CONTROL

The two factors underlying the need for air traffic control (ATC) are safety and efficiency. The individual user must have enough airspace to avoid the risk of near misses or collisions, but, to maintain sufficient capacity of movement in heavily trafficked areas, efficiency demands that the individual use of airspace be minimal within the constraints of safety. Furthermore, any ATC system must consider and balance the needs of all users of airspace: the military, the commercial carriers, and general aviation.

Air traffic control measures were instituted only 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 air carrier and general aviation aircraft. As the number of general aviation aircraft continues to increase, the range of air carrier technology embraces a great variety of aircraft types, which includes CTOL, VTOL, SST, STOL and giant conventional subsonic aircraft. The air traffic control system, which must accommodate the wide variety of airspace needs, is responsive in its development to the underlying factors of safety, technology, regulation, and financing.

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 air traffic control, 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

Airport Engineering, Third Edition. Norman Ashford and Paul H. Wright

Federal Aviation Administration 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 air traffic control in the United States.

6.2 VISUAL FLIGHT RULES (VFR) AND INSTRUMENT FLYING RULES (IFR)

Air traffic moves under visual flight rules (VFR) or instrument flight rules (IFR), depending on weather conditions, as well as on the location and altitudes of flight paths. In general, VFR operations prevail when weather conditions are good enough for the aircraft to be operated by visual reference to the ground and to other aircraft, 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) fall 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.

6.3 THE U.S. AIRWAYS SYSTEM

Flights from one part of the United States to another are normally channeled along navigational routes that are as well identified as the surface road system. Two separate route systems can be identified: (1) VOR and L/MF airways* and (2) the jet route system.

VOR Airway Systems

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 (1).

*VOR = very high frequency omnidirectional range.
L/MF = low and medium frequency.

The VOR system, known as the Victor airways, 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 (see Section 6.5). 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 1/2° about the centerline joining the two ground stations.

The Jet Route System

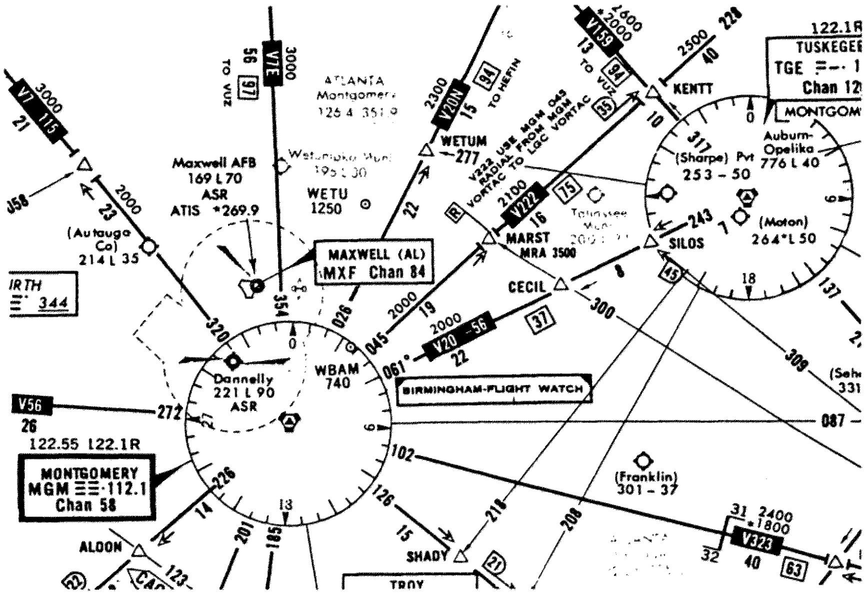
Airways from 18,000 ft above mean sea level (MSL) to 45,000 ft (flight level* FL450), designed for aircraft that customarily operate at these altitudes, comprise the jet route system. These routes also operate using VOR ground navigation stations, but the system requires significantly fewer stations, 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 6.1a show a portion of a typical Victor airways chart; a jet route chart in the same area appears in Figure 6.1b.

6.4 CONTROLLED AND UNCONTROLLED AIRSPACE

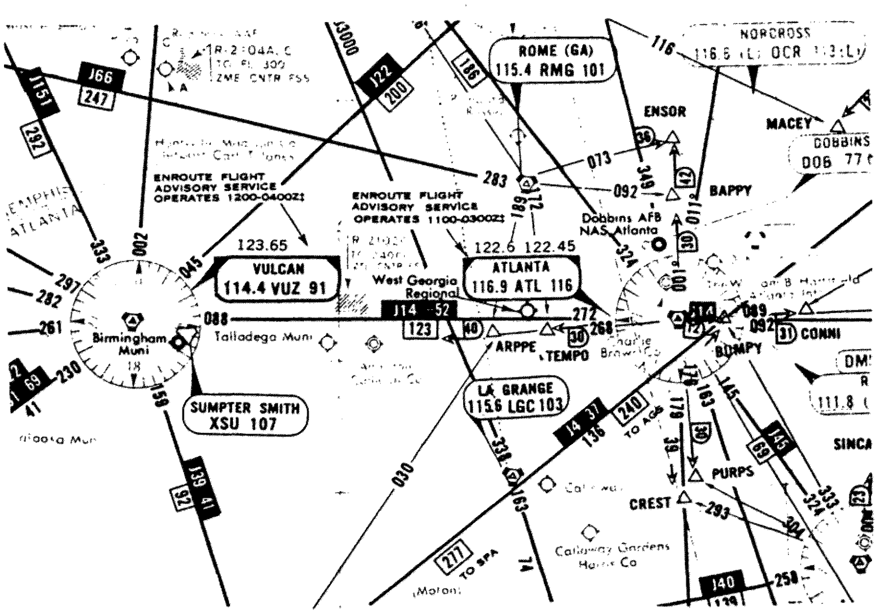
Airspace is both controlled and uncontrolled: in controlled airspace, flight is conducted in accordance with promulgated altitude and heading combinations (Figure 6.2). Controlled airspace, extending upward from 1200 ft above ground level (AGL) and, in a few areas from 700 ft AGL, exists in almost all 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 points up the need for shared airspace. Increased communications have aided and will become more important as they link computers and automatic air traffic control systems. 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 are higher performance aircraft, usually jet powered. In Positive Control Areas, above 18,000 ft MSL, all aircraft are controlled by continuous surveillance and are required to have certain equipment to permit the higher aircraft densities of the higher performance aircraft.

Three different types of control in terminal areas are in current use in the United States:

*Flight level = altitude above mean sea level ÷ 100 (in feet).



(a)



(b)

FIGURE 6.1 (a) Portion of a Victor airways chart. (*Source*: FAA)
(b) Portion of a jet route chart. (*Source*: FAA)

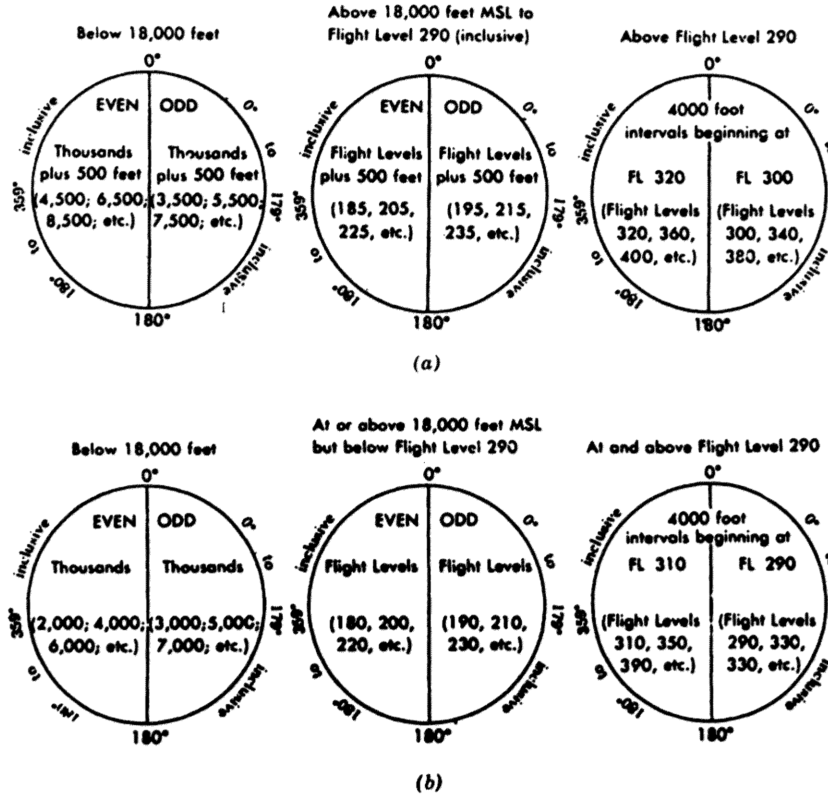


FIGURE 6.2 IFR and VFR altitudes and flight levels. (a) Under VFR at 3000 ft or more above surface, controlled and uncontrolled airspace. (b) Under IFR, outside controlled airspace. (*Source*: Reference 2)

Terminal control area (TCA).
Terminal radar service area (TRSA).
Airport radar service area (ARSA).

A *terminal control area,* such as those shown in Figures 6.3a and 6.3b, consists of controlled airspace extending upward from the surface or higher to specified altitudes, within which all aircraft are subject to operating rules and where there are requirements on pilot qualification and aircraft equipment. Terminal control areas are designated around major aviation hubs, and they include at least one primary airport around which the TCA is located. In 1987, there were 9 Group I TCAs and 14 Group II TCAs in the United States. The requirements for the Group I areas are more stringent than those for Group II.

In order to facilitate the flow of air traffic in terminal areas, the FAA initiated the concept of *terminal radar service areas,* and originally there were

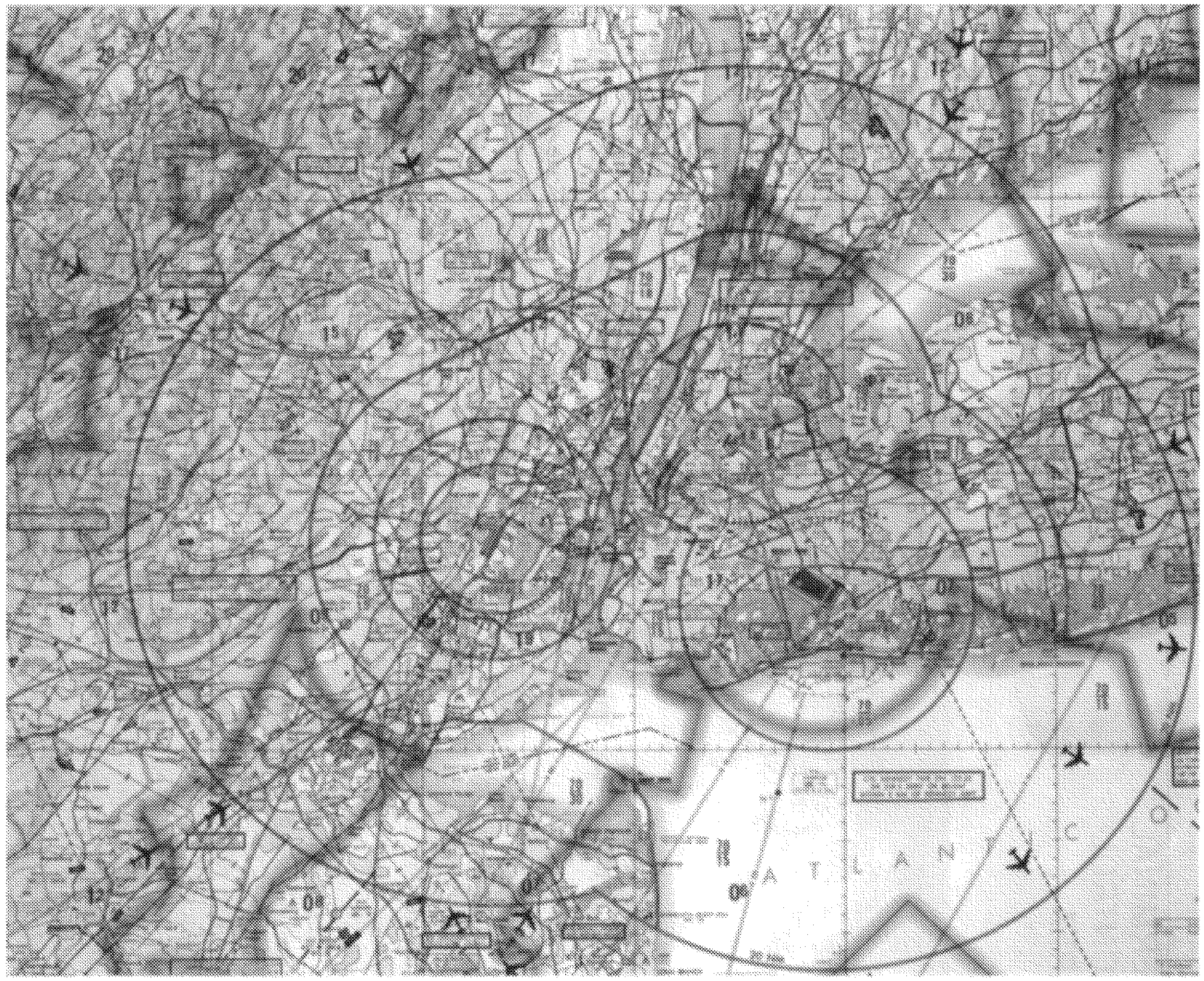


FIGURE 6.3a The New York terminal control area (TCA). (*Source*: FAA)

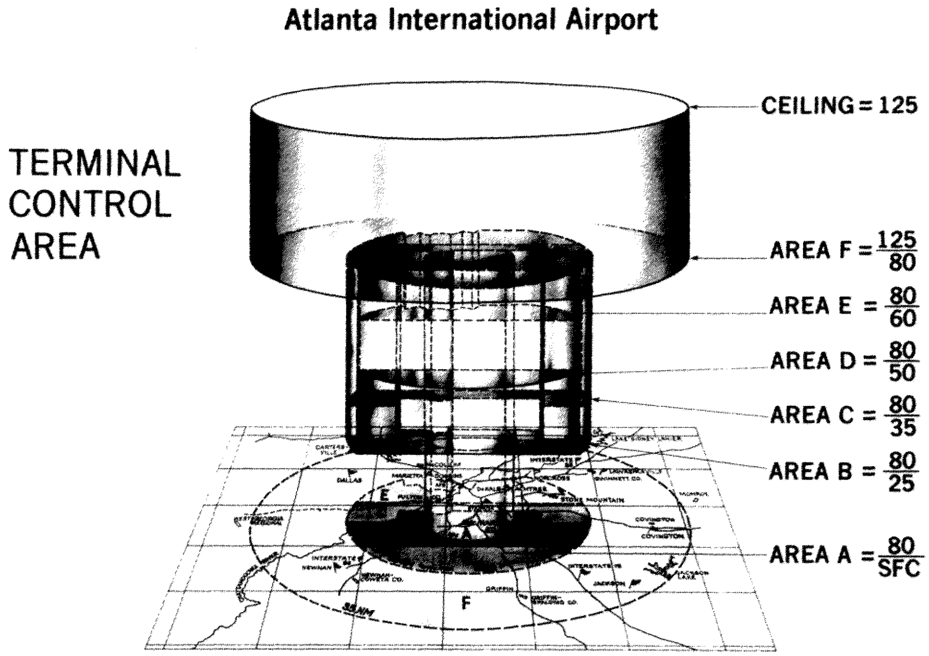


FIGURE 6.3b The Atlanta terminal control area. (*Source*: FAA)

over 200 U.S. airports where approaching aircraft could use this advisory service. Within the airspace surrounding the designated TRSA airports, air traffic control provides radar vectoring, sequencing, and separation for all IFR and participating VFR aircraft. Pilot participation is urged but is not mandatory. Figure 6.4 show the location and size of the TRSA at Augusta, Georgia in 1987.

Increasingly, *airport radar service areas* are replacing terminal radar service areas. ARSAs are being established in busy smaller 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 ARSA airspace is defined as 0–4000 ft height above an airport within an inner circle of 5 nm and between 1200 and 4000 ft height above an airport between 5 and 10 nm from the airport. 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. Figure 6.5 shows the location of the Daytona Beach ARSA.

Although airspace may be designated as controlled, it does not necessarily mean in the United States that ATC instructions are mandatory in all circumstances. Pilots may elect to fly according to visual flying rules on a "see and avoid" basis. There is increasing pressure, however, to remove this option

FIGURE 6.4 The Augusta, Georgia, terminal radar service area (TRSA). (*Source*: FAA)

for traffic operating inside the busiest terminal areas. It is interesting to note that this option has not been available for many years in major European countries.

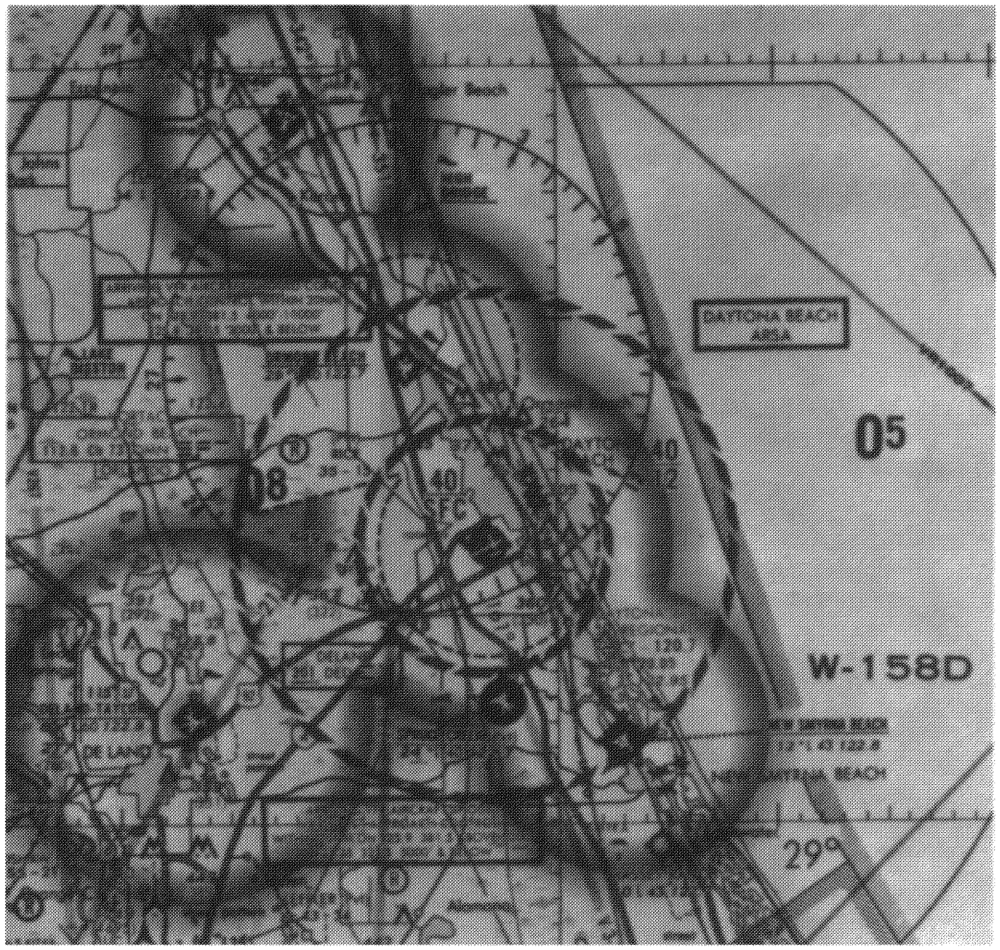


FIGURE 6.5 The Daytona Beach airport radar service area (ARSA). (*Source*: FAA)

6.5 NAVIGATIONAL AIDS

As air traffic activity continues to grow, there is an increasing need for navigational aids to narrow the limits of navigational error in horizontal or vertical separation. At low-traffic densities, the degree of navigational sophistication required is generally quite low, but as air traffic congestion grows, more navigational aids are needed to give all-weather operation that is highly reliable and safe. Navigational aids that are either ground based or airborne may be conveniently functionally classified as en route navigation aids and terminal area navigation and landing aids.

En Route Air Navigation Aids (2)

A number of locational aids, operating outside terminal areas, permit in-flight aircraft to achieve accurate navigation using instruments only.

Automatic Direction Finding (ADF), sometimes known as nondirectional radio beacon (NDB), 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 reception of 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 $\pm 1°$. The numbering system for Victor airways is even numbers for East and West and odd numbers for North and South.

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). These navigational aids represent the incorporation of VOR and DME functions into a single channelized system, utilizing frequencies in the ultra-high frequency range. 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. TACAN is independent of conventional VOR facilities but is similarly constrained to line-of-sight operation.

VORTAC is a combined facility composed of two different components: VOR and TACAN. 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. 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 existing 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.

Communications (3). Communications are accomplished by radio receivers and transmitters located both in the aircraft and on the ground. 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 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.

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 are being installed on a nationwide basis with a range of 200 mi; they will eventually produce an increase in airways' capacity by permitting a reduction in separations between aircraft flying at the same altitude.

Air Traffic Control Radar Beacon System (ATCRBS). ATCRBS is a system having three main components: *interrogator, transponder,* and *radar-*

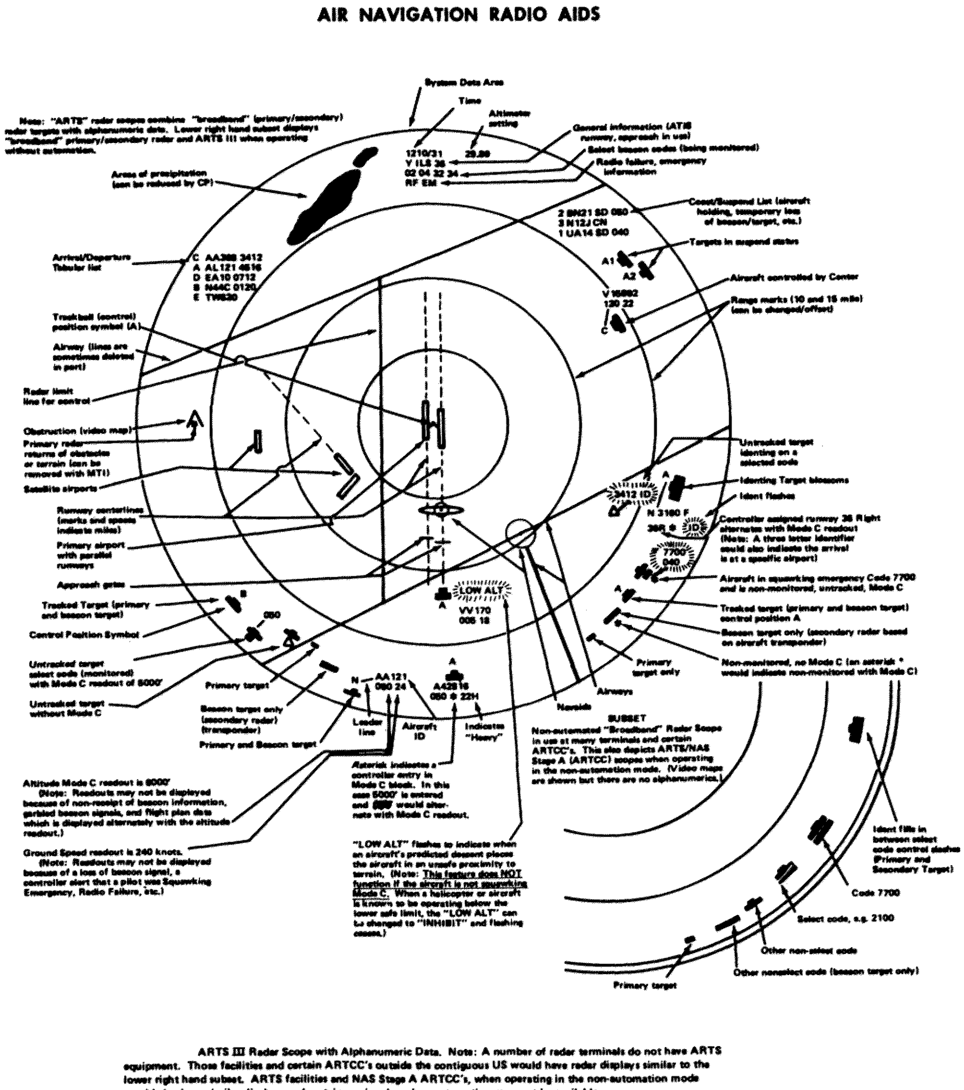


FIGURE 6.6 Controller's secondary surveillance radarscope display. (*Source*: Reference 2)

scope. This system is frequently termed *secondary* surveillance radar. Whereas primary radar, a passive system, relies on the bouncing back of the transmitted radar signal, the ATCRBS 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) 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 (Figure 6.6). Radarscopes are also equipped to indicate aircraft identification and altitude on an alphanumeric display. The advantage is obvious; the controller is able to differentiate between aircraft rapidly and with certainty, and to be assured of correct identification of equipped aircraft in the airspace under surveillance.

Other Aids

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, companion to LORAN C, 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.

Inertial navigation systems (INS). Large modern air transports are fitted with INS which computes latitude and longitude from an on-board inertial device, which needs no ground equipment. This rapid navigatonal aid is especially useful for very long-range flights and long transoceanic sectors.

Terminal Area Navigation and Landing Aids

In the immediate area of the terminal, special aids are necessary to assist in the operations of landing and takeoff, and to provide safe navigation in the crowded air space.

Instrument Landing System (ILS). ILS is an approach and landing aid designed to identify an approach path for exact alignment and descent of an aircraft making a landing. It is the most commonly used system for instrument landings. Functionally, the system is composed of three parts:

1. *Guidance Information.* Localizer, glide slope.
2. *Range Information.* Marker beacons.
3. *Visual Information.* Approach lights, touchdown zone and centerline lights, runway lights.

Figure 6.7 depicts the layout of the nonvisual elements of the ILS system. 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.

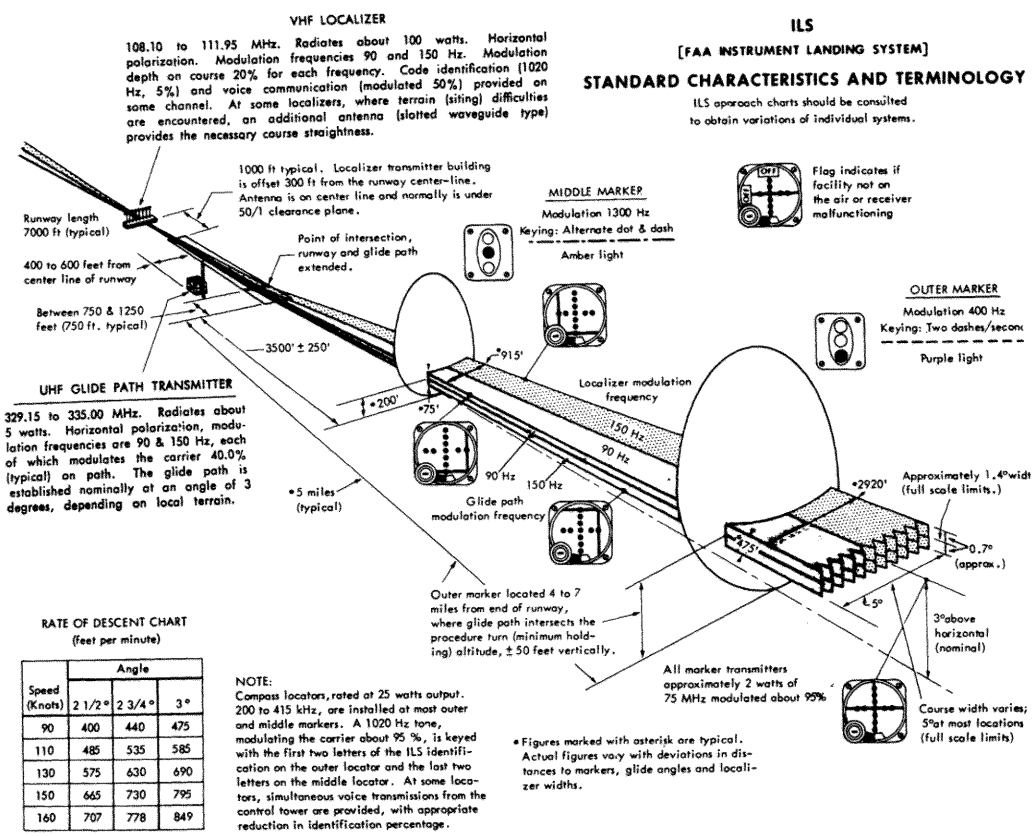
The *localizer* transmitter is located typically 1000 ft beyond the end of the runway; it emits signals that give the pilot course guidance to the runway centerline. Deviation to the left or right of the extended centerline is indicated on the VOR receiver display, as shown in Figure 6.7. The UHF glide 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.

To help the pilot further on an ILS approach, two low-power fan markers furnish range information, to indicate how far along the approach path the aircraft has progressed. The glide path is normally adjusted to 3° above 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 ILS systems (ICOA categories II and III: see below), there is an inner marker (IM) close to the threshold.

The ICAO promulgates 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 system. It is not possible to categorize a facility until equipment has been installed 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 6.1 shows the ICAO and FAA categories in terms of RVR and decision heights.

Microwave Landing Systems (MLS). The ILS system, 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 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 them-



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 6.7 FAA instrument landing system (ILS). (*Source*: Reference 2)

TABLE 6.1 Visibility Minima by ILS Categories

ILS Category (CAT)	Lowest Minima RVR	Lowest Minima 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 and FAA.

selves with the runway axis from many miles out. This forces them to form a single "queue" to the final approach, with a corresponding restriction on landing rates.

MLS, which overcome most of the problems associated with ILS, are at the testing stage. 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 system, which gives only point locations over the markers. MLS systems with continuous information to the cockpit are ideal for "hands-off" landings. Also important, however, is the multipath approach facility provided by MLS systems (see Figure 6.8). Since international agreement on the form of MLS to be used has only recently been reached, the depth and width of approach coverage is not yet known. However, it is clear that there is no need for a unique approach path. There can be multiple paths, which may add to runway approach capacity.

There is still much to be achieved before MLS systems can be universally adopted. Clearly, the implictions of a changeover, not only of ground equipment, but also of airborne facilities, are substantial. The ICAO has indicated that present ILS systems will be current at least until 1995. Even if some MLS facilities are introduced in the 1990s, it will be many years before the full potential of this form of approach aid is achieved.

Precision Approach Radar (PAR). Frequently called ground-controlled approach (GCA), PAR is independent of airborne navigation equipment. PAR equipment is located on the ground adjacent to the runway. These facilities may be used as a primary landing aid or, as frequently, in conjunction with ILS. Two antennas are used, one of which scans the vertical plane and the other of which 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,

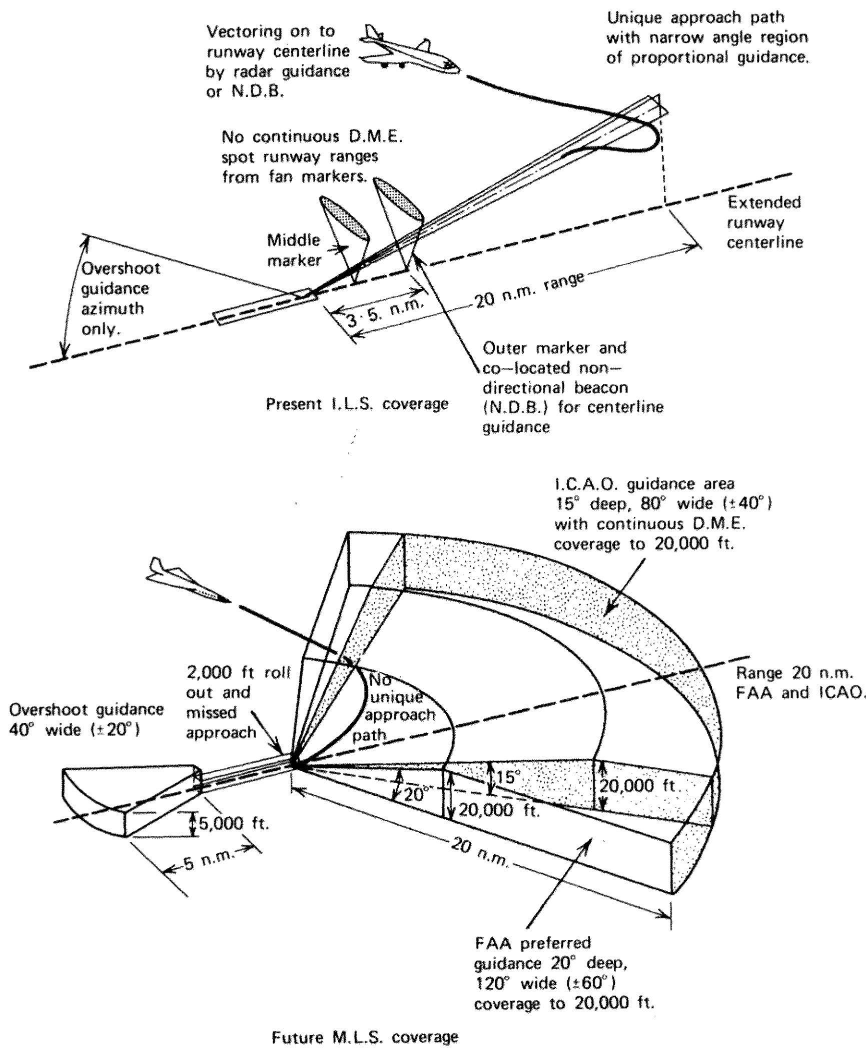


FIGURE 6.8 Microwave landing system (MLS). (*Source*: FAA)

azimuth to 20°, and elevation to 7°. Therefore, the PAR equipment can be used only on the final approach area, where corrections to the approach are given to the pilot by voice communication from the monitoring air traffic controller.

Airport Surveillance Radar (ASR). Airport tower operators receive their terminal area traffic control and aircraft location information from ASR. Within a range of 30 to 60 mi, ASR provides information for aircraft transiting from the airways to holding areas through to the final approach. It is a two-dimensional aid and does not give information on aircraft altitude. Surveillance radars scan through a full 360 of azimuth, presenting target information on radar displays in the control tower or the air traffic control center. The equipment is used in conjunction with other navigational aids for instrument approaches.

Airport Surface Detection Equipment (ASDE). ASDE is a specially designed radar system for use at large, high-density airports to aid 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. At the moment, ASDE is available only at a very few of the world's busier airports.

Instrument Approach Procedures and Standard Instrument Departures. Though these are not navigational aids, they afford the means of using the en route as well as the terminal area navigational aids. They are not only indispensable to IFR landing approaches, but also are helpful to the VFR pilot landing at an unfamiliar airport. Instrument approach charts diagram every airport in the country that has some kind of instrument landing aid installation (NDB, VOR, DME, TACAN, VORTAC, PAR/ASR, ILS, etc.).

The charts indicate prescribed 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—and even a simple airport has several—is designed for use with a specific type of navigational aid. The pilot's choice of procedure depends on instrumentation and prevailing weather conditions. To aid pilots on takeoff, standard instrument departures (SID) have been developed to facilitate the transition between takeoff and en route operation, alleviating the need for extensive oral communication between controllers and pilots.

6.6 AIR TRAFFIC CONTROL FACILITIES

Air traffic control facilities provide the basis for communication with aircraft and the relay and clearance of flight plans for air traffic. There are three basic types of manned facilities: the air route traffic control center, the airport traffic control tower, and the flight service station.

Air Route Traffic Control Centers (ARTCC)

There are 22 domestic air route traffic control centers that control the movement of aircraft along the airways. Each center has control of a definite geographical area and is concerned primarily with the control of aircraft operating under IFR. At the boundary points marking the limits of the control area of the center, the aircraft is released either to an adjacent center or to an airport control tower. At present, much of the aircraft separation is maintained by radar. With radar, off-airways vectors can be utilized, maintaining positive control of the aircraft, and thus the ARTCCs can accommodate more aircraft.

Each ARTCC is broken down into sectors in order to increase the efficiency of personnel in the center. Sectors are smaller geographic areas, and air traffic is monitored in each sector by remote radar units at the geographic location. 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.

Central Flow Control Facility (CFCF)

Formerly called the National Flow Control Center, the Central Flow Control Facility is established at the FAA Headquarters Office in Washington, D.C., to maintain overall flow control of the airways and to coordinate the work of the ARTCCs in cases of disaster or severe weather conditions. Access to the CFCC in Washington is by telephone. 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

Airport traffic control towers are the 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- to 15-mi radius.

Some control towers have approach control facilities and associated airport surveillance radar (ASR) which guide aircraft to the airport from a number of specific positions, called "fixes," within approximately 25 mi of the airport. The aircraft are brought to these positions by the ARTCCs. 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 and they are turned over to the control tower after they have started their landing approach.

Flight Service Stations (FSS)

The flight service stations (FSSs), which are increasingly totally automated, are located along the airways and at airports. Their function may be described as follows:

1. Relay traffic control messages between en route aircraft and the air route traffic control centers.
2. Brief pilots, before flight and in flight, on weather, navigational aids, air-

ports that are out of commission, and changes in procedures and new facilities.
3. Disseminate weather information.
4. Monitor navigational aids.

6.7 AIRPORT LIGHTING

Visual Approach Slope Indicator System (VASIS)

An important visual aid to final approach to the runway threshold is the visual approach slope indicator system (VASIS),* which is frequently supplied in addition to other visual and nonvisual approach aids. VASIS is usually installed when one or more of the following conditions exist (4):

1. The runway is used by turbojet aircraft.
2. 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.
3. There are serious hazards in the approach area that would endanger the aircraft if it sank below the normal approach path.
4. Serious hazard would occur in the event of undershooting or overshooting.
5. Turbulence is found to exist because of terrain or meteorological conditions.

A VASIS installation basically consists of two wing bars of lights on either side of the runway. Figure 6.9a gives the locations of these bars: one set of bars 500 ft from the runway end (downwind bars) and a second set of bars 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

*In FAA literature, these systems bear the reference acronym VASI.

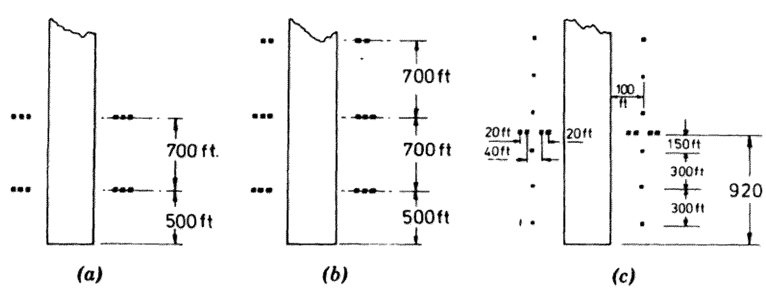


FIGURE 6.9 (a) Layout of a VASIS system. (b) Layout of a three-bar VASIS system. (c) Layout of a T-VASIS system. (*Source*: Reference 4)

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 VASIS-type systems are recognized by the FAA and the ICAO.

A variation of the basic VASIS configuration is necessary for such large aircraft as the 747 or the Concorde. VASIS gives an 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 VASIS configuration (see Figure 6.9b) 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-VASIS configuration (see Figure 6.9c), consisting of one wing bar on either side of the runway, 920 ft from the threshold (4). Six "fly-up" and six "fly-down" lights are located at

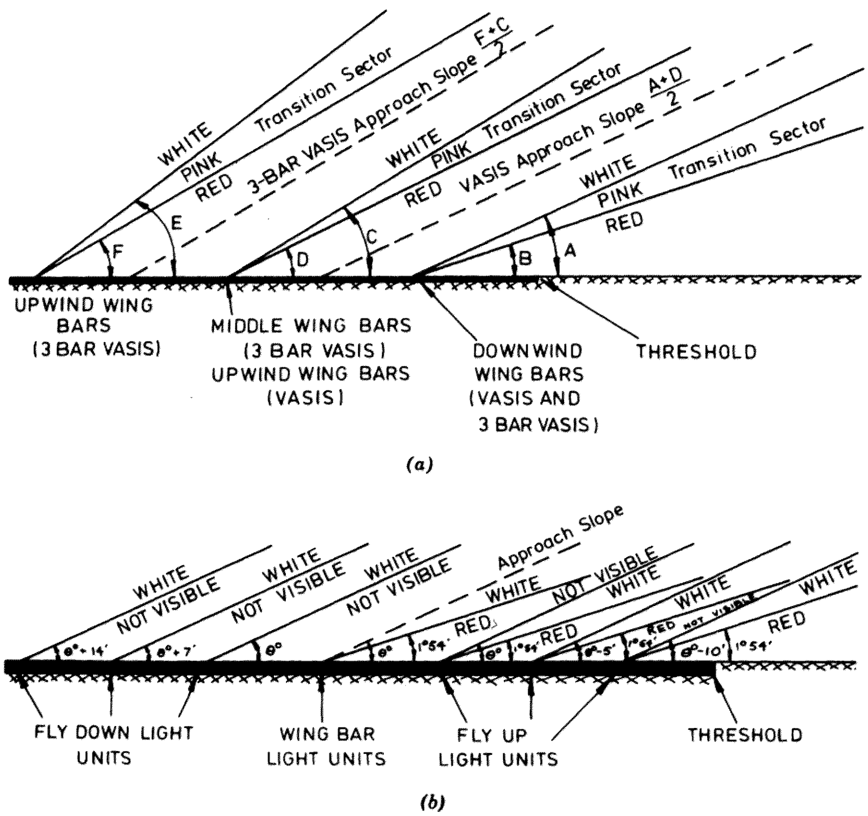


FIGURE 6.10 Light beams and angle of elevation settings. (a) VASIS and three-bar VASIS. (b) T-VASIS. (*Source*: Reference 4)

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 6.10 shows the arrangement of the split light beams for three-bar VASIS and T-VASIS.

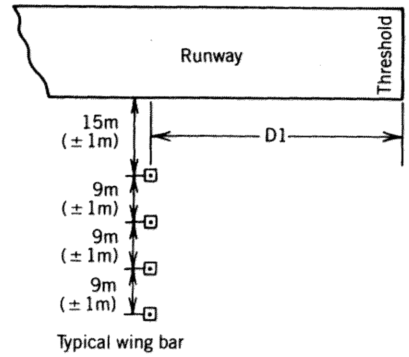
Precision Approach Path Indicator (PAPI) System

Although VASIS and T-VASIS give pilots considerable visual assistance on final approach, experience indicates that they are not without criticism. VASIS especially tends to give rise to an oscillatory approach as the pilot moves between the upper and lower limiting approach planes. Both VASIS and T-VASIS are imprecise below 60 m (200 ft) and are not suitable for a nonstandard approach. The three-bar VASIS 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. T-VASIS overcomes some of the problems of VASIS; for example, T-VASIS is more suited to multipath approaches 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 6.11 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 mutipath 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, Great Britian, France, and Russia to be more precise and more flexible than VASIS. PAPI systems are expected to replace VASIS at large airports in the early 1990s.

Runway End Identifier Lights (REIL)

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:

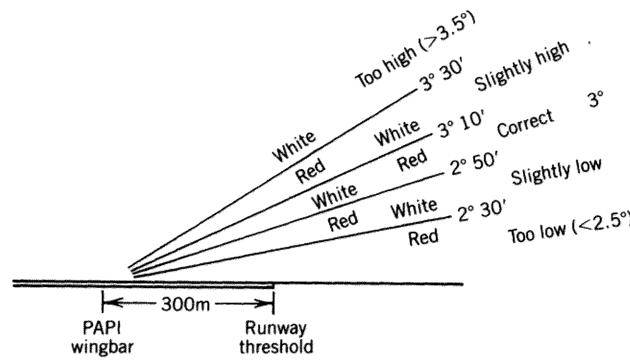
1) 9 m where the code number is 3 or 4; and

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.



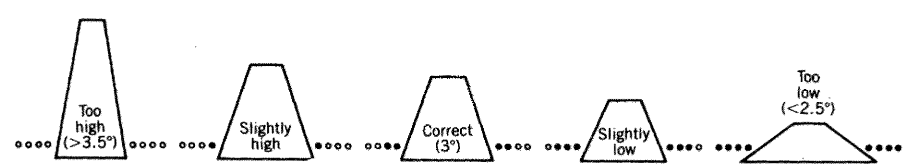


FIGURE 6.11 PAPI—location of lights and visual indications to pilot. (*Source*: Reference 4)

Approach Lighting Systems (ALS) (4, 5)

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 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. 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: high-intensity and medium-intensity systems.

FAA High-Intensity Systems. Designed for operation with ILS approaches categories I, II, and III, the FAA high-intensity system comes in a single standard layout (see Figure 6.12):

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 ALS are specified for U.S. airports; MALSR, MALSF, and MALS configurations. 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 ICAO.

1. *MALSR.* A medium-intensity ALS with runway alignment indicator lights. It is the U.S. standard configuration for ILS operations during

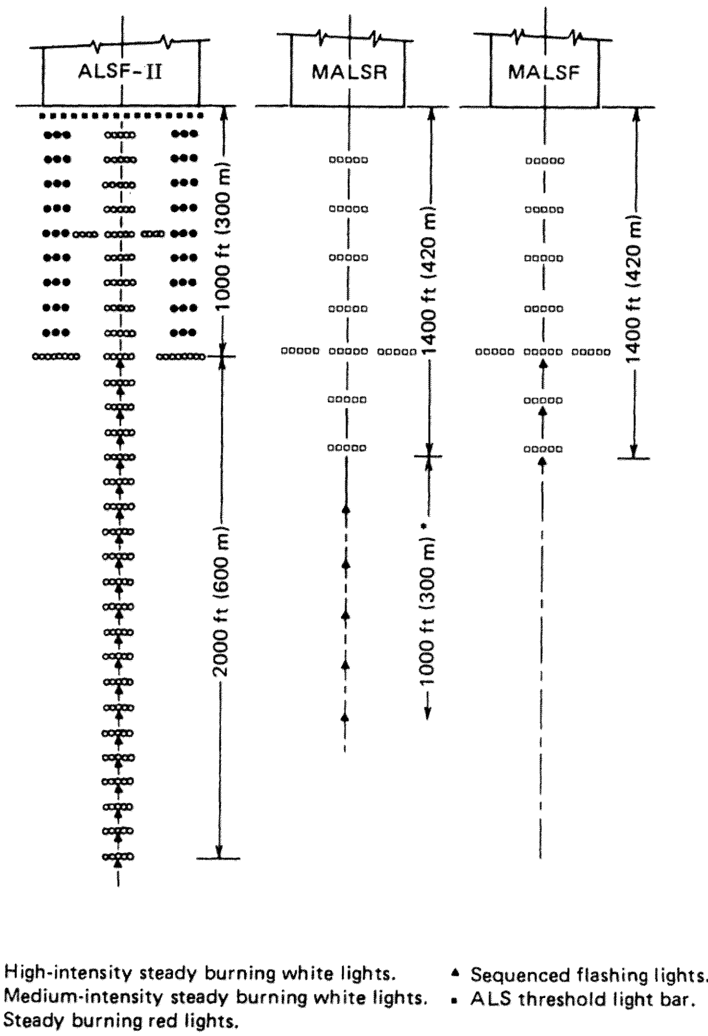


FIGURE 6.12 FAA approach light systems. (*Source*; Reference 5)

category I visibility minima. Eight flashing units are installed along the extended runway centerline, at 200 ft spacings extending to the end of the configuration, from 1400 ft from the threshold.

2. *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.
3. *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 those that have traditionally been in the British sphere of influence, 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

Runway centerline and touchdown zone lighting systems facilitate landings, rollouts, and takeoffs (6). The touchdown zone lights are primarily for landing, and centerline lights assist in after touchdown rollout and furnish primary takeoff guidance. Both systems are designed for use in conjunction with the electronic precision aids and the standard approach lighting systems under limited visibility.

Runway Centerline Lighting. Runway centerline lights are semiflush units set into the pavement and offset by a maximum of 2 ft to clear centerline paint markings. Centerline lights are white, except for the last 3000 ft. From 3000 ft to 1000 ft from the runway end, the lights are alternately red and white; they are red for the final 1000 ft. All lights are bidirectional; therefore, red lights in the 3000 ft zone show white toward the runway end for approaches from the other direction. Light spacing is set at 50 ft centers.

ICAO requirements for centerline lights are generally similar to those of the FAA. Centerline lights are required for precision runways categories II of 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.

To prevent pilots from losing orientation after passing over the threshold bar, airports install touchdown zone lighting. For example, if an aircraft were still a substantial height above an airport that did not have transverse bars, the pilot would lack roll guidance, given only the longitudinal runway edge lights. Added to this would be a "black hole" effect after passing out of the zone of high-intensity approach and threshold lighting. Flush-mounted transverse pavement light bars for the first 3000 ft of the runway ensure continuous visual roll guidance. Rows of light bars are set symmetrically about the centerline, each bar consisting of three unidirectional lights. The first row is mounted 100 ft from the threshold. A standard FAA touchdown zone configuration appears in Figure 6.13. 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.

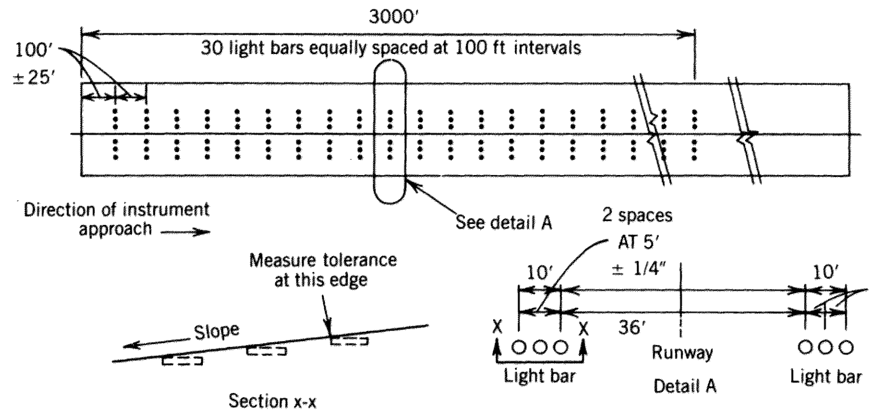


FIGURE 6.13 FAA touchdown zone lighting configuration. (*Source*: Reference 6)

Runway Edge, Threshold, and Runway End Lighting (7)

Lighting at the runway edges gives pilots locational information in both the landing and takeoff operations. The FAA specifies three types of runway edge lighting: low, medium, and high intensity. 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.

Edge lights are white, except that the last 2000 ft of an instrument runway has bidirectional yellow-white lights, with the yellow pointing toward a departing pilot, indicating a caution zone. 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 non-instrument runways. Edge lights are normally elevated single lights, although semiflush installations are permitted. Semiflush units are installed at the intersections of runways and taxiways.

Bidirectional lights at the runway ends indicate red in the direction of the runway and green in the direction of the approach. Figure 6.14 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.

For ICAO requirements, which are generally similar, the reader is referred to Annex 14 (4).

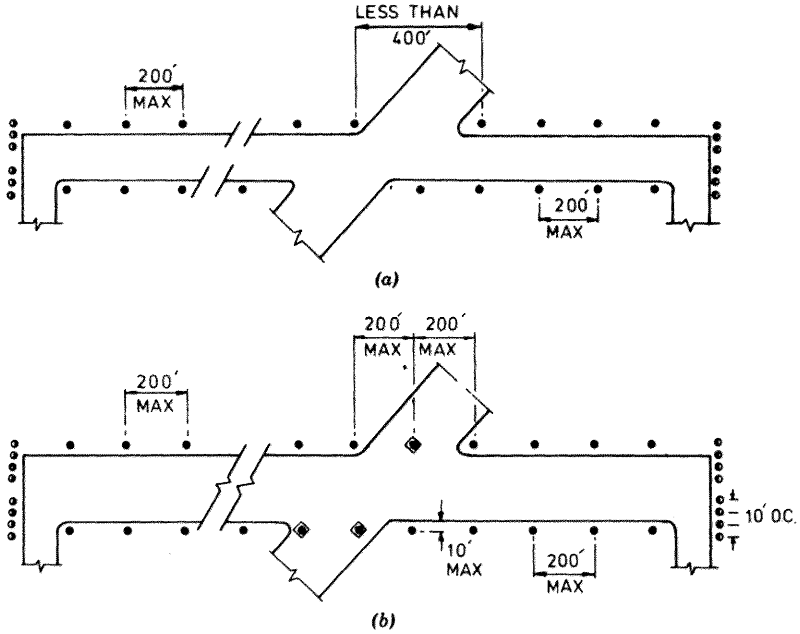


FIGURE 6.14 FAA medium-intensity runway and threshold lighting system: solid circles 360° white, except for last 2000 ft of the instrument runway; half solid circles, red 180°, green 180°; circle in square, semiflush bidirectional. (a) Application of single elevated lights. (b) Application of single elevated lights and semiflush lights. (*Source*: Reference 6)

Taxiway Edge and Centerline Lights

In the interests of safety and efficiency, the locations and limits of taxiways must be indicated clearly. 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 (7), set at a maximum distance of 10 ft from the taxiway edge. On long tangents, spacing can be up to 200 ft centers (Figure 6.15). On shorter tangents, spacings are kept below 200 ft. Figure 6.16 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, either from 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.

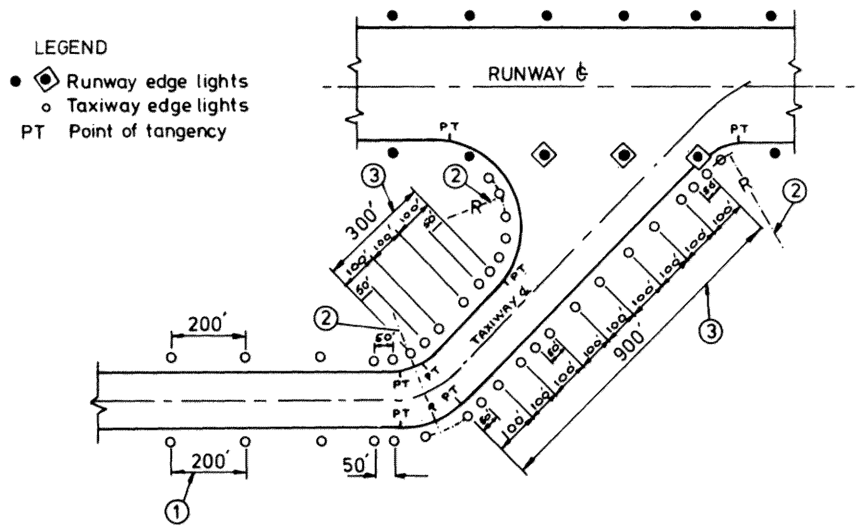


FIGURE 6.15 Typical FAA taxiway lighting configuration. (*Source*: Reference 7)

ICAO Annex 14 specifies the use of taxiway centerline lights on high-speed exit taxways 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. On long tangents, the maximum spacing is 200 ft, varying down to 50 ft maximum at lower RVRs. Spacings down to a maximum of 25 ft are indicated on curved taxiway sections. For futher details of the recommendations of the international agency, the reader is referred to the pertinent sections of the ICAO document.

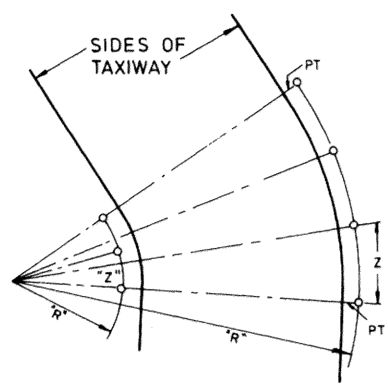


FIGURE 6.16 FAA spacing of lights on curved taxiway edges: PT is point of tangency. (*Source*: Reference 7)

Obstruction Lighting and Airport Beacons

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 depends principally on structure height. FAA standards for the lighting obstructions are given in the advisory circular *Obstruction Marking and Lighting* (8).

The location and presence of an airport at night is 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.

6.8 RUNWAY AND TAXIWAY MARKING

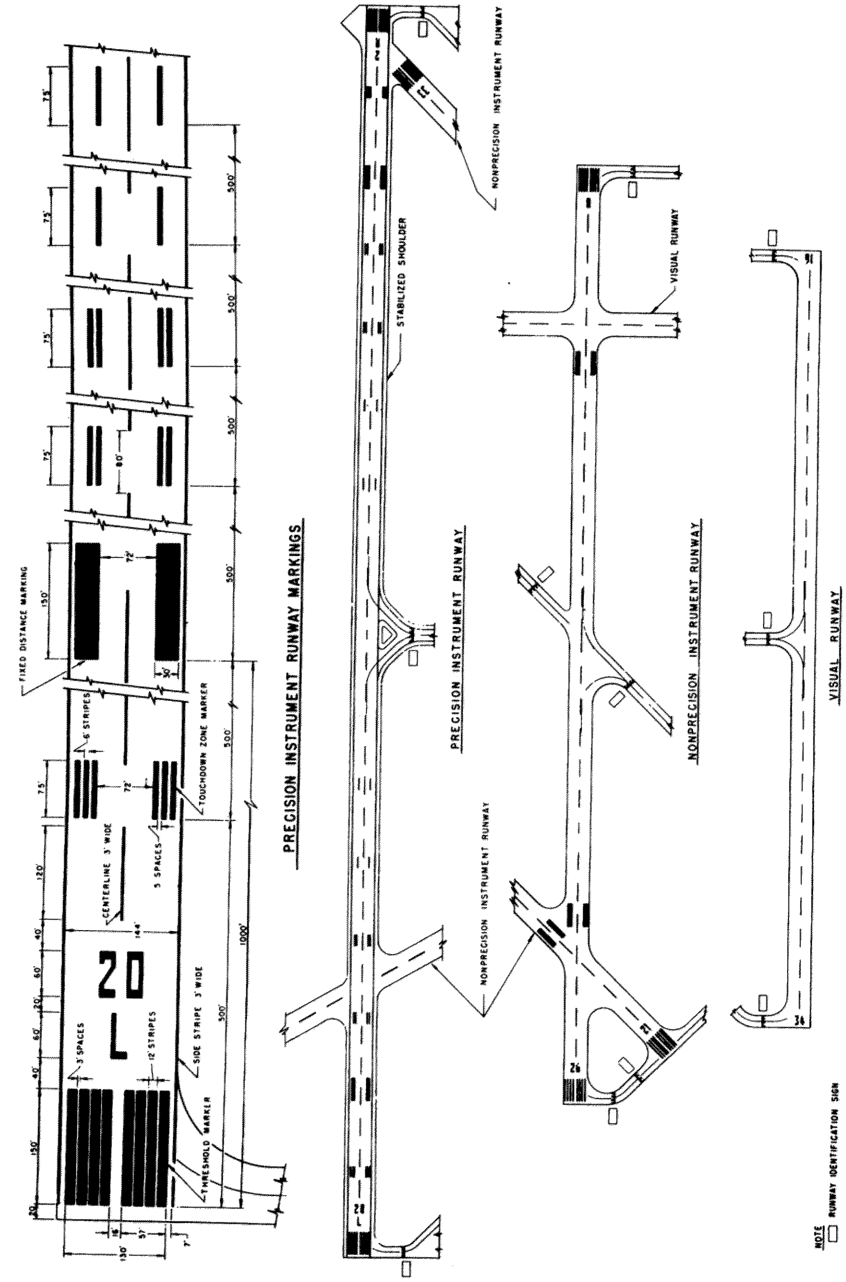
Markings are applied to the paved areas of runways and taxiways to identify clearly the functions of these areas and to delimit the physical areas for safe operation. We can cover this topic only briefly; for a complete discussion, the reader is referred to ICAO Annex 14 and Reference 9. Our description relates to the FAA specifications, which are generally similar in function and form to the international standards; where differences occur, they are not sufficiently great to cause confusion.

Runways

Three types of runway marking can be provided: *basic* or *visual, nonprecision instrument,* and *precision instrument.* This categorization conforms with that outlined in Chapter 7. Figure 6.17 shows the standard patterns of markings for each type.

1. *Basic Runways.* These unpaved runways have runway stop markers only. Paved basic runways are marked with the runway number and centerline.
2. *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.
3. *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


PRECISION INSTRUMENT RUNWAY MARKINGS
FIXED DISTANCE MARKING
6' STRIPES
TOUCHDOWN ZONE MARKER
CENTERLINE 3' WIDE
5 SPACES
3' SPACES
12' STRIPES
SIDE STRIPE 3' WIDE
THRESHOLD MARKER
20
L
PRECISION INSTRUMENT RUNWAY
STABILIZED SHOULDER
NONPRECISION INSTRUMENT RUNWAY
NONPRECISION INSTRUMENT RUNWAY
VISUAL RUNWAY
VISUAL RUNWAY
NOTE
RUNWAY IDENTIFICATION SIGN

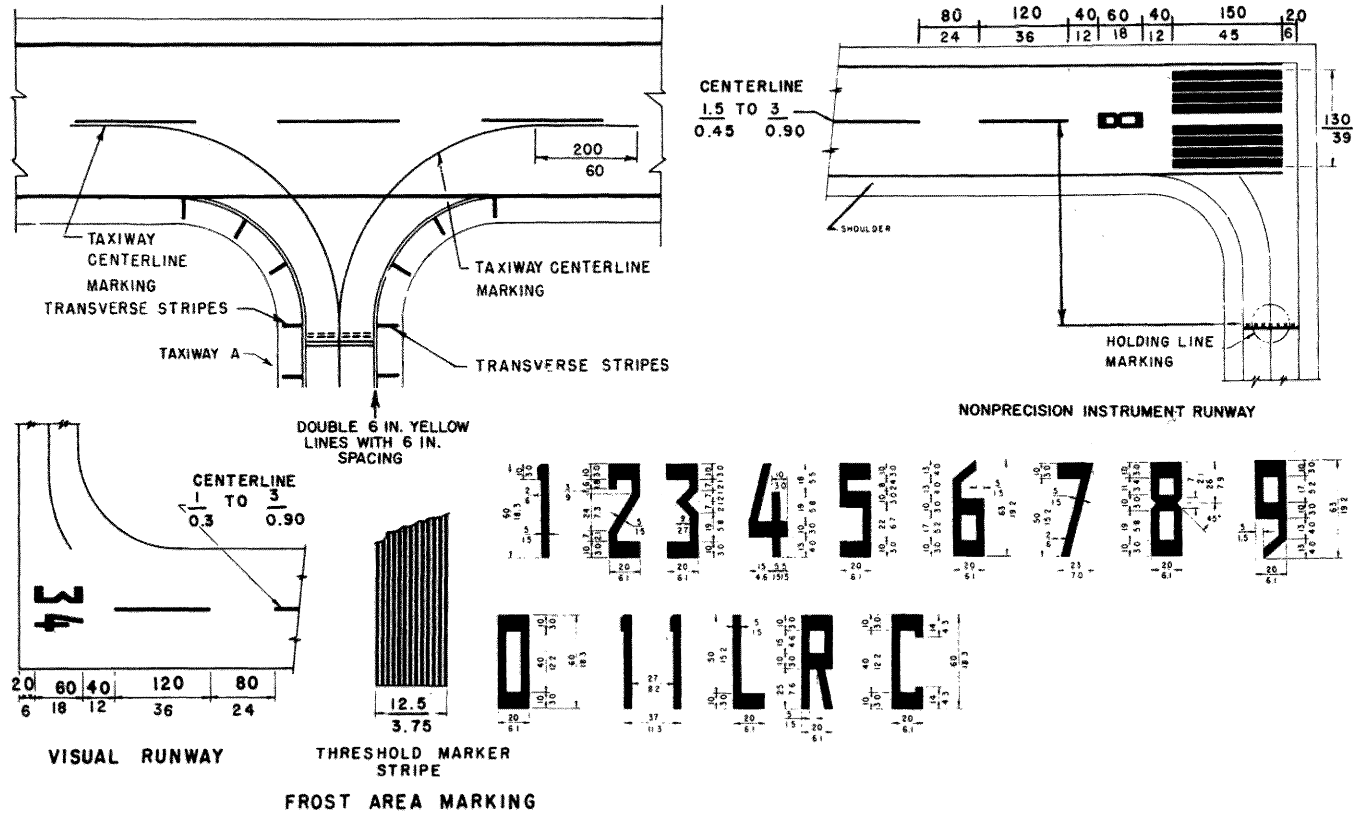


FIGURE 6.17 Typical FAA runway markings. In detail A, all runway centerline spacing should be laid out from both ends toward the center, and the holding line should be 100 ft from the edge of the runway or 150 ft from the edge of the runways where "heavy" jets operate. With respect to the frost area marking, all stripes and spaces are to be of equal width: maximum 6 in, minimum 4 in. All dimensions of numerals and letters (detail C) 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*: Reference 9)

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 6.17 gives marking dimensions.

Taxiways

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.

6.9 TAXIWAY GUIDANCE SIGNING (10)

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 standarized 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.

For some time, 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.

Good experience has been obtained in recent years with retro-reflective signs, which 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 retro-reflective 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.

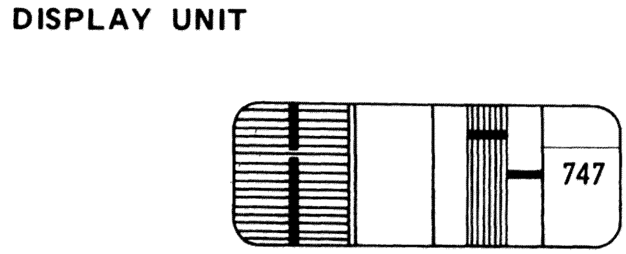
6.10 AIRCRAFT SELF-DOCKING SYSTEMS

A number of aircraft nose-in self-docking systems are available to cut down the required apron manpower and to reduce human error in the final positioning of aircraft on the apron.

The Burroughs optical lens docking system (BOLD: Figure 6.18) is a visual system for parking and guidance. Two display units have been installed at Schiphol Airport, Amsterdam, one on top of the other. The upper display serves the 747, for example, and the lower display serves other aircraft (e.g., DC-10, DC-8, L-1011). The elements for centerline guidance and determination of the stop position are mounted in one unit. The centerline guidance is obtained from two vertical light bars: a fixed bar indicating the centerline and below it a bar indicating the observer's position (e.g., left or right, or on the centerline). Stop position is determined by a horizontal light bar (stop bar) that moves down from the top of the display when the aircraft approaches the stand; showing simultaneously is a fixed bar with the type designation of the aircraft attempting to dock.

Azimuth guidance for nose-in stands (AGNIS; Figure 6.19) is a system that allows the pilot to park the aircraft accurately on stands served by the air jetty. The centerline guiding system consists of a light unit that emits red and/or green beams through two parallel vertical slots; it is 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.



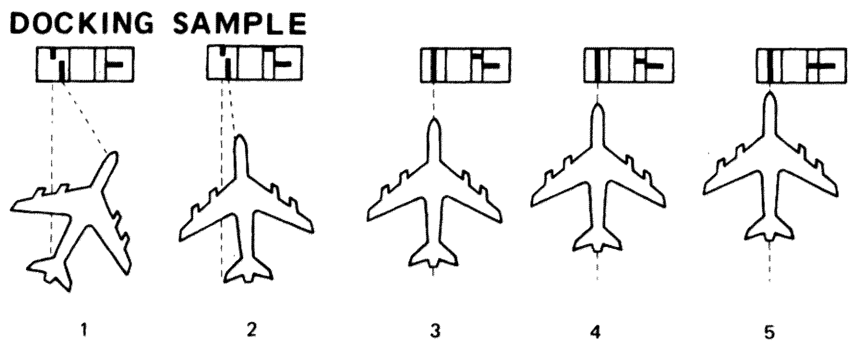


FIGURE 6.18 BOLD nose-in aircraft self-docking systems as used at Schiphol Airport Amsterdam. Docking proceeds as follows: Position 1—Pilot turns and proceeds toward gate; Position 2—aligns lower vertical bar with upper datum bar, horizontal stop cue bar comes into view; Position 3—maintains centerline alignment, horizontal bar moves down right bar; Position 4—25 ft to stop and horizontal bar moving downward; Position 5—horizontal bar in line with right stop-cue bar. This is perfect alignment. (*Source*: Jeppesen Sanderson Inc., Denver, Colorado)

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, BAC 1-11 and DC-9 aircraft are not served by the side marker board; a mark on the air jetty itself shows the correct stopping position.

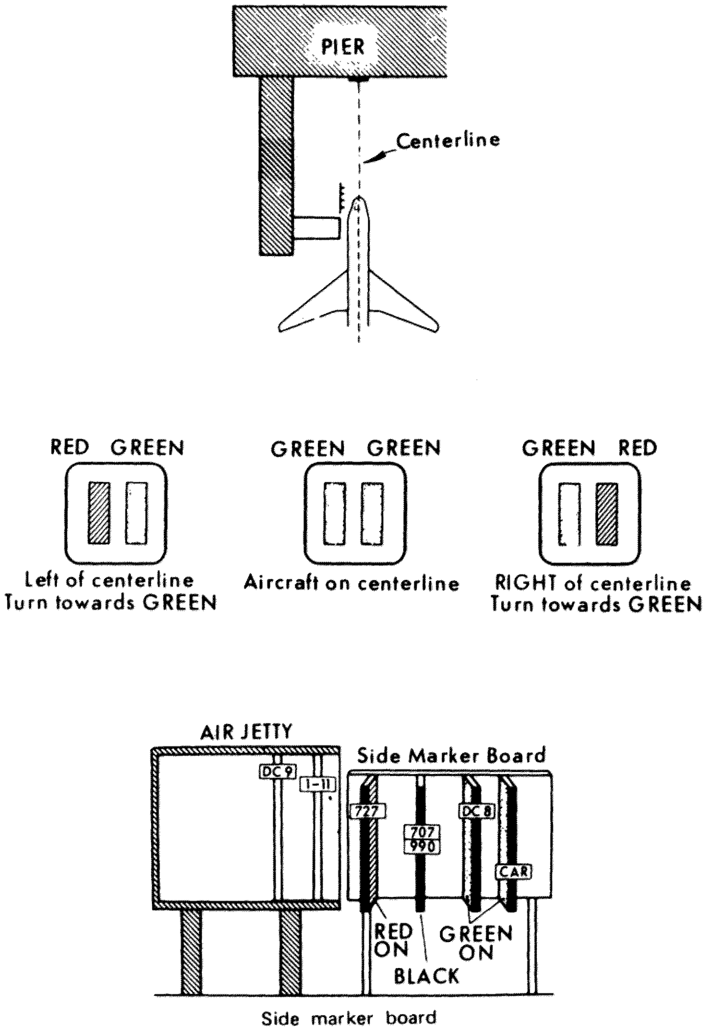


FIGURE 6.19 Nose-in aircraft self-docking system used at Brussels and London Heathrow airports, consisting of centerline guidance system AGNIS and side marker boards, as described in text. (*Source*: Jeppesen Sanderson Inc., Denver, Colorado)

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7

AIRPORT CAPACITY AND CONFIGURATION

7.1 INTRODUCTION

In 1990, the U.S. air transport system carried about 1.3 million domestic and international passengers per day. By some time early in the next century, the number could reach 2.5 million passengers per day or nearly 1 billion per year. If this growth continues, the system would need to carry 4 to 5 million passengers daily by the year 2040, more than triple the present volume of traffic (1).

The extraordinary increase in air passenger travel in the decade of the 1980s has resulted from several factors: a robust economy, airline deregulation, reduced fares, and an increasing propensity for the public to use air transportation for trips further than 200 miles.

The growth in air travel is outstripping the capacity of the airport and air traffic control system, 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 great 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 form 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 understanding and accommodating the needs of air passenger carriers.

It is recognized that bottlenecks and delays can result from inadequacies in any component of the airport system—air side or land side. However, this

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chapter is restricted to the analysis of the capacity of the air side facilities: the runway, taxiway, and apron-gate components.

Airport capacity analyses are undertaken for two purposes: (1) to measure objectively the capability of various components of an airport system for handling projected passenger and aircraft flows, and (2) to estimate the delays experienced in the system at different levels of demand. Thus, capacity analyses make it possible for the airport planner to determine the number of required runways, to identify potentially suitable configurations, and to compare alternative designs.

This chapter defines airport capacity, assesses the various factors that influence capacity, and describes approaches to performing airport capacity analyses. In addition, we discuss airport configuration, which, from the viewpoint of the airport planner, is the most important determinant of the capacity of an airport system.

7.2 CAPACITY, DEMAND, AND DELAY

The term "capacity" refers to the ability of a component of the airfield to accommodate aircraft. 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 one hour under specified operating conditions. Capacity depends on a number of prevailing conditions, such as ceiling and visibility, air traffic control, aircraft mix, and type of operations. To determine the capacity, the prevailing conditions must be specified.

The FAA previously recommended (2, 3) the concept of a "practical capacity" measure that corresponds to a "reasonable" or "tolerable" level of delay (e.g., delays to departing aircraft average 4 min during the normal two peak adjacent hours of the week). The preferred measure (4) and that employed in this chapter, is the *ultimate* or *saturation* capacity, the maximum number of aircraft that can be handled during a given period under conditions of continuous demand.

Capacity should not be confused with demand. Capacity refers to the physical capability of an airfield and its components. It is a measure of supply, and it is independent of both the magnitude and fluctuation of demand and the amount of delay to aircraft (5). Delay, however, is dependent on capacity and the magnitude and fluctuation in demand. One can reduce aircraft delays by increasing capacity and by providing a more uniform pattern of demand (i.e., by reducing the peaks in demand). These relationships are illustrated in Figure 7.1.

As demand approaches capacity, delays to aircraft increase sharply. Because of the congestion that may be associated with these increases in delay, planners should exercise caution when planning for airports where the level of airport demand is expected to approach capacity for more than short

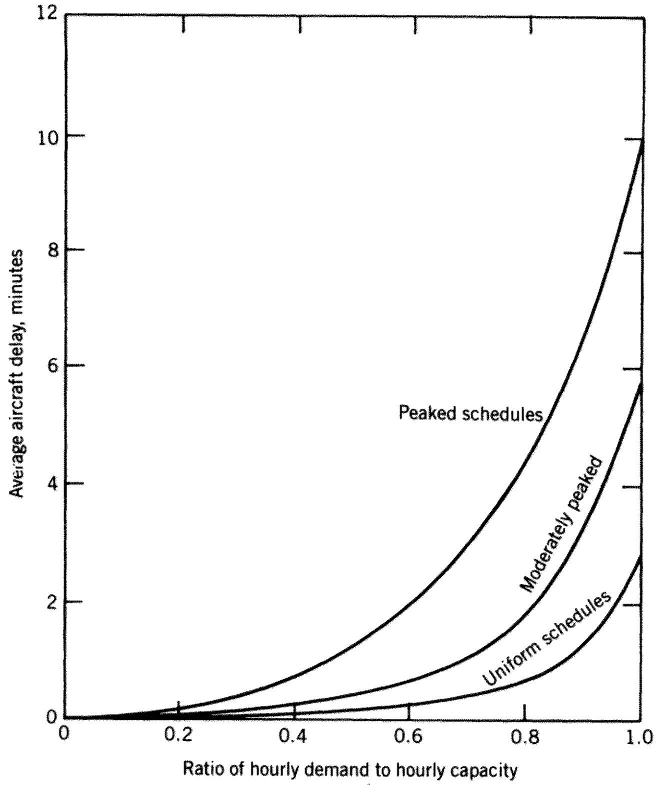


FIGURE 7.1 Relationship of demand-capacity ratio and demand fluctuatoin to average hourly aircraft delay. (*Source*: Adapted from Reference 8)

periods of time. Furthermore, estimating the magnitude of delays and their economic impact is more important in justifying airport improvements than a determination of capacity.

Runway Capacity

Runway capacity is normally the controlling element of the airport system capacity. In succeeding sections, various aspects of this key element of capacity are examined: (1) factors that affect runway capacity, (2) procedures for estimating hourly and annual capacities, and (3) procedures for estimating delays.

7.3 FACTORS THAT AFFECT CAPACITY

There are a large number of factors that influence the capacity of a runway system. These factors can be grouped into four classes, those related to: (1) air traffic control, (2) characteristics of demand, (3) environmental conditions in the airport vicinity, and (4) 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 to 5 nautical mi, depending on the aircraft size, availability of radar, and the sequencing of operations. Since no two airplanes are allowed on the runway at the same time, the runway occupancy time may also influence the capacity.

Consider the following hypothetical example. A runway serves aircraft that land a speed at 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. Let us examine the effect of these factors on the runway capacity. The minimum spacing is (3 X 6076 ft nautical mi) = 18,228 ft. In terms of time, the minimum arrival spacing is 18,228 ft ÷ (165 X 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 ÷ 75 sec/arrival = 48 arrivals/hr.

Figure 7.2 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 the figure illustrates, if the runway is used for arrivals only, it will remain unoc-

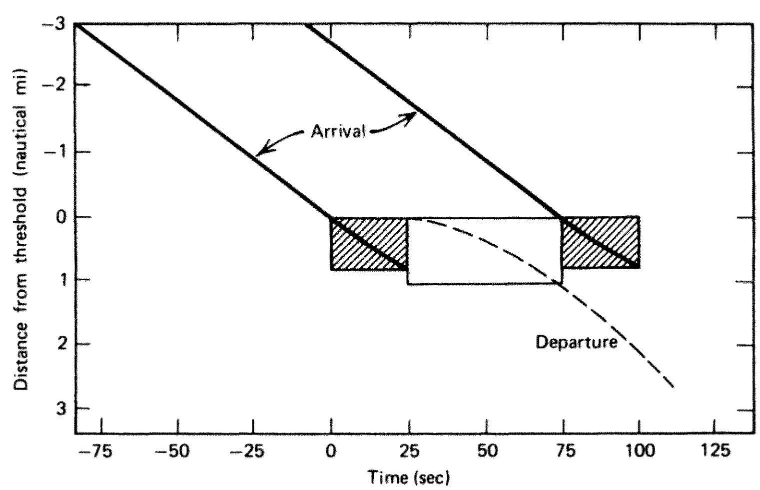


FIGURE 7.2 Time-distance diagram for two approaching and one departing aircraft: open box, runway occupied by departure; cross-hatched box, runway occupied by arrival.

cupied 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.

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 7.2 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 are as follows:

1. The length of the common path from the ILS gate to the threshold, normally 4 to 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, and braking capability, as well as pilot technique. The effect of aircraft size is reflected both in the wing-tip vortex phenomenon and in differences in approach and touchdown speeds. As 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 7.2, 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" (6). In capacity calculations, empirical correction factors are applied to allow for the presence of touch-and-go traffic.

Another 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.

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 separations and greater runway occupancy times result, and runways with marginal crosswinds are less likely to be used. When the visibility or 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 (7). Objectionable 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. The number, spacing, length,and orientation of runways.
2. The number, locations, and design of exit taxiways.
3. The design of ramp entrances.

Further discussion of these factors and their relationship to capacity is given later in this chapter and in Chapter 8.

7.4 DETERMINATION OF RUNWAY CAPACITIES AND DELAYS

A number of different approaches may be employed to estimate runway capacities and delays, including the following:

1. Empirical approaches.
2. Queueing models.
3. Analytical approaches.
4. Computer simulation.

The simplest approach is to base capacity and delay estimates on the results of extensive traffic surveys performed at existing airports. Such surveys may serve as the sole basis for graphs and tables from which estimates may be directly made (see, for example, Reference 6). Empirical surveys are also a vital component in the development and validation of both analytical and simulation models (8).

Examples of simple queueing models are given in Section 7.5. Queueing models may be used to estimate queue lengths and average delays to aircraft in simple systems. Such estimates may serve as a component or a building block of a computer simulation model. The runway capacity models described in Section 7.6 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 (5).

A computer simulation model was used to produce estimates of aircraft delays for Reference 8. This approach is discussed more fully in Section 7.10.

7.5 QUEUEING THEORY APPROACHES

It has long been recognized that a simple runway system can be described by mathematical models or formulas of queueing theory. In 1948, Bowen and Pearcey (9) made an empirical study of aircraft arriving at the Kingsford-Smith Airport in Sydney and found that arrivals could be satisfactorily described by the Poisson probability distribution. Since flights on civil airlines are scheduled, one would intuitively suspect that aircraft arrivals are regular; however, it was found that the difference between the expected and actual times of arrival was large and that the process was more random than regular.

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 "length of time the most recent arrival blocks the runway from receiving any subsequent arrival" (10). It depends on the runway occupancy time, or more commonly, the minimum separation necessitated by air traffic rules.

Assuming Poisson arrivals and constant service times, Bowen and Pearcey derived an equation for average (steady state) landing delay:

$$W = \frac{\rho}{2\mu(1 - \rho)} \tag{7.1}$$

where

ρ = the 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:

$$W = \frac{\rho(1 + C_b^2)}{2\mu(1 - \rho)} \tag{7.2}$$

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 help us to understand delay-capacity relationships, they do 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 give "steady state" solutions. As Harris (10) has demonstrated, many hours may be required to achieve steady state conditions.

7.6 DETERMINATION OF RUNWAY CAPACITIES—ANALYTICAL APPROACH

During the past several years, researchers have developed a number of analytical models for the calculation of runway capacity. The simplest model of this 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 separations as specified by air traffic regulations.

The simplest model assumes error-free approaches; that is, it is assumed that controllers are able to deliver aircraft to the entry gate exactly at scheduled times and that pilots are able to maintain the required separations and speeds precisely.

Two situations are considered: (1) the overtaking case, in which the trailing aircraft has a speed equal to or greater than the lead aircraft, and (2) opening case, in which the speed of the lead aircraft exceeds that of the trailing aircraft. Harris (10) has shown that for the error-free case the following minimum separation function applies:

$$m(v_2, v_1) = \frac{\delta}{v_2} \text{ for } v_2 \geqslant v_1 \tag{7.3}$$

$$m(v_2, v_1) = \frac{\delta}{v_2} + \gamma\left(\frac{1}{v_2} - \frac{1}{v_1}\right) \text{ for } v_2 < v_1 \tag{7.4}$$

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

Time-space diagrams for the overtaking and opening situations are shown in Figures 7.3 and 7.4. With the aid of these figures, the reader is advised to develop equations 7.3 and 7.4.

In computing the saturation capacity, 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.

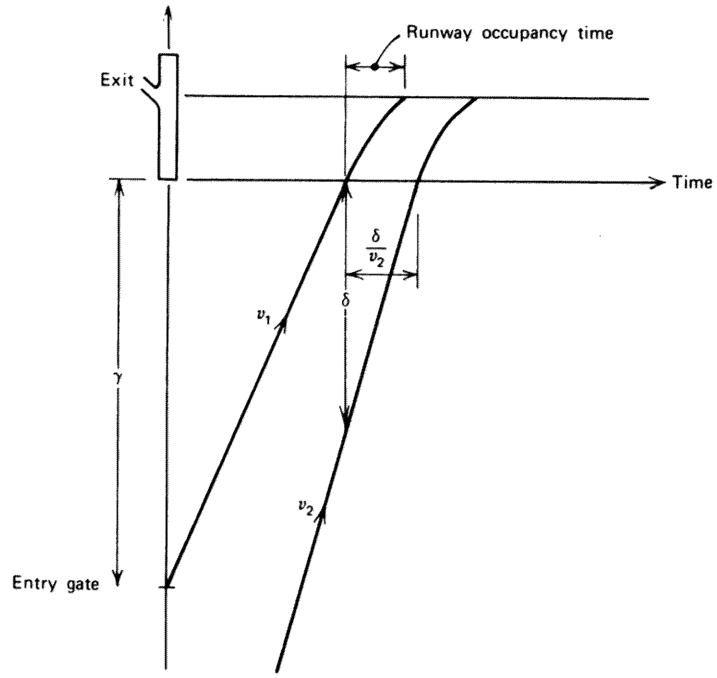


FIGURE 7.3 Time-space diagram for overtaking situation.

$$M = [m(v_i, v_j)] = \begin{Bmatrix} \text{matrix of minimum intervals,} \\ m_{ij}, \text{ for speed class } i \\ \text{following speed class } j \end{Bmatrix}$$

Associated with each of the n speed classes is a 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

$$\overline{m} = \Sigma_{ij} P_i \, m_{ij} \, P_j \tag{7.5}$$

The hourly saturation capacity is the inverse of the weighted mean service time.

$$C = \frac{1}{\overline{m}} \tag{7.6}$$

Consider the following example, which has been adopted from Reference 10.

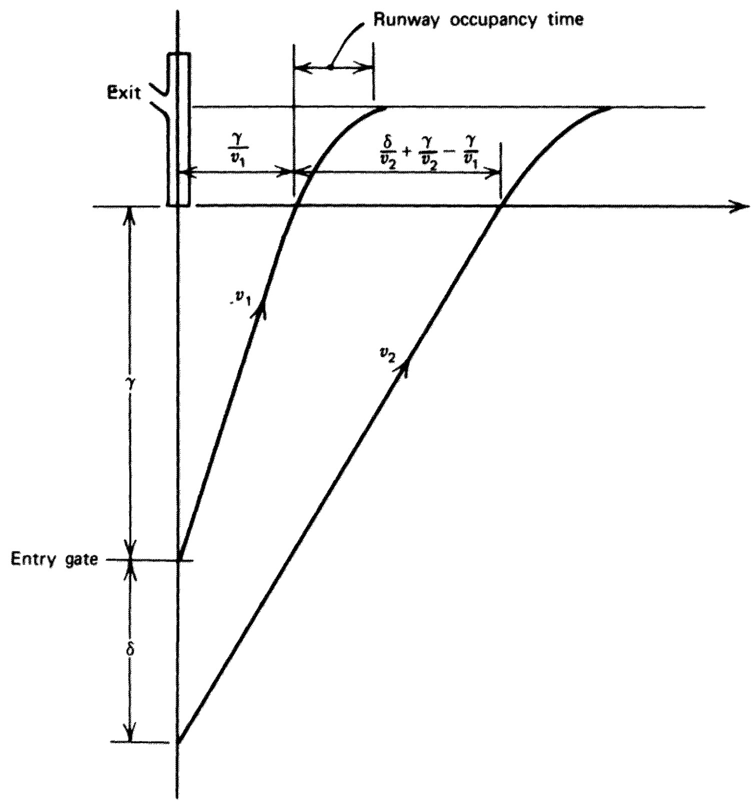


FIGURE 7.4 Time-space diagram for opening situation.

EXAMPLE 7.1 ULTIMATE 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 7.3 and 7.4, 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

$$m(v_j, v_i) = \frac{\delta}{v_j} + \gamma\left(\frac{1}{v_j} - \frac{1}{v_i}\right)$$

$$= \frac{3}{100} + 6\left(\frac{1}{100} - \frac{1}{135}\right) = 0.0456 \text{ hr} = 164 \text{ sec}$$

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, P_i		0.2	0.2	0.6	

This shows the minimum time separation for each combination of approach speeds.

The next step is to compute a weighted average separation, by equation 7.5, based on the probabilities associated with each pair of aircraft speeds.

$$\begin{aligned}\bar{m} = {} & (108 \times 0.2 + 90 \times 0.2 + 80 \times 0.6)0.2 + \\ & (144 \times 0.2 + 90 \times 0.2 + 80 \times 0.6)0.2 + \\ & (164 \times 0.2 + 110 \times 0.2 + 80 \times 0.6)0.6 = 98.16\end{aligned}$$

Finally, the ultimate capacity is computed by equation 7.6:

$$c = \frac{1}{\bar{m}} = \frac{1}{98.16} = 0.0102 \text{ arrivals/sec} = 36.7 \text{ arrivals/hr}$$

In an effort to provide more realism, Harris (10) postulated normally distributed errors in aircraft interarrival times at the approach gate and at the threshold. Ultimate capacity models were developed that allowed time separa-

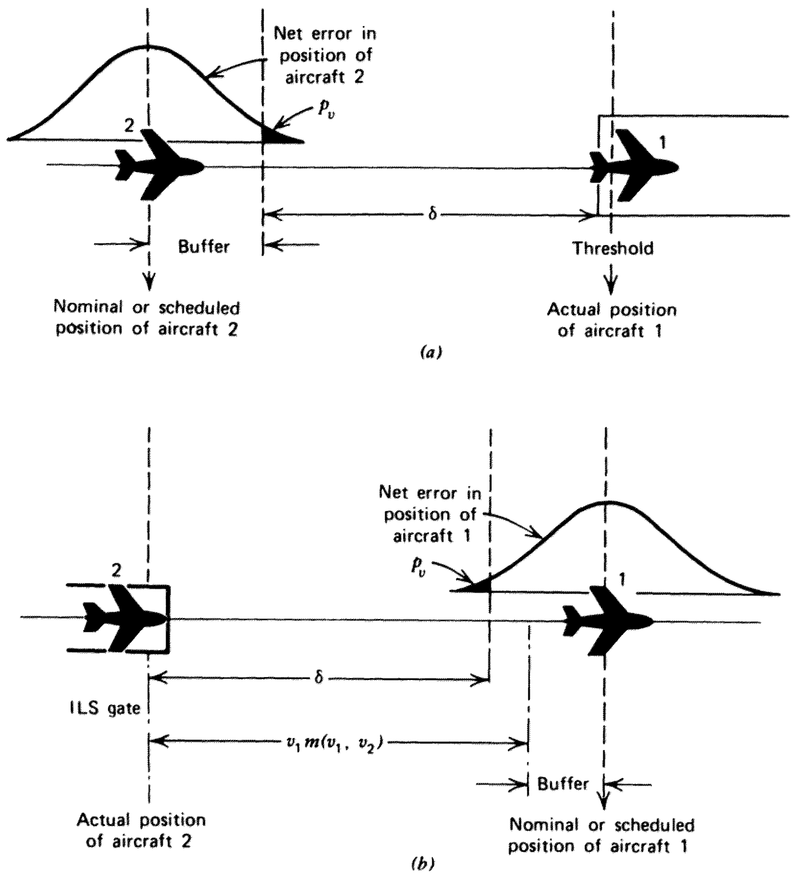


FIGURE 7.5 Error distribution and separation buffering. (a) Overtaking, $v_2 \geqslant v_1$. (b) Opening, $v_2 < v_1$. (*Source*: Reference 10)

tion buffers to account for such errors. As Figure 7.5 illustrates, these buffer times are a function of the probability that the buffer zone will be violated.

In the overtaking case ($v_2 \geqslant v_1$), the buffer zone

$$b(v_2, v_1) = \sigma_0 q(p_v) \tag{7.7}$$

where

σ_0 = standard deviation of the normally distributed buffer zone
$q(p_v)$ = the value for which the cumulative standard normal distribution function has the value $(1 - p_v)$
p_v = probability that the 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

$$b(v_2, v_1) = \sigma_0 q(p_v) - \delta\left(\frac{1}{v_2} - \frac{1}{v_1}\right) \tag{7.8}$$

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

$$l(v_2, v_1) = m(v_2, v_1) + b(v_2, v_1) \tag{7.9}$$

Using matrix notation

$$B = [b(v_i, v_j)] = \left\{\begin{array}{l}\text{matrix of buffer zones,}\\ b_{ij}\text{, for speed class } i\\ \text{following speed class } j\end{array}\right\}$$

The matrix of scheduled landing intervals becomes

$$L = M + B \tag{7.10}$$

EXAMPLE 7.2 ULTIMATE 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 σ_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 7.7, 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 7.8, 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

$$B = \begin{bmatrix} 33 & 15 & 5 \\ 33 & 33 & 23 \\ 33 & 33 & 33 \end{bmatrix}$$

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

$$\begin{aligned} \overline{m} = {} & (141 \times 0.2 + 123 \times 0.2 + 113 \times 0.6)0.2 + \\ & (159 \times 0.2 + 123 \times 0.2 + 113 \times 0.6)0.2 + \\ & (169 \times 0.2 + 123 \times 0.2 + 113 \times 0.6)0.6 = 125.88 \text{ sec} \end{aligned}$$

and the ultimate capacity

$$c = \frac{1}{\overline{m}} = \frac{1}{125.88} \text{ arrivals/sec} = 28.6 \text{ arrivals/hr}$$

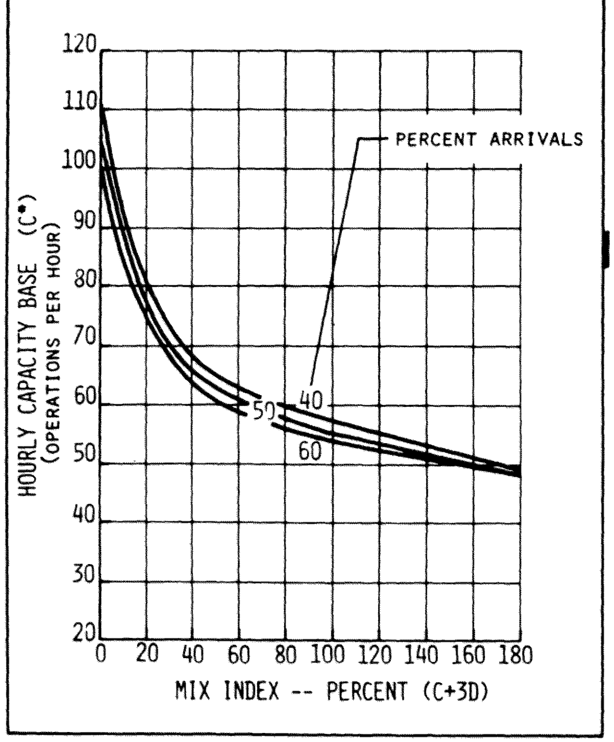
More complex models have been published (10) that account for speed errors along the approach or variations in times required to fly the common path. Such models, which are conceptually similar to those given above, are available for exclusive arrival and departure runways, as well as for mixed operations runways. Analytical models have also been developed for multiple runway configurations using the ultimate capacity concept (1, 11).

7.7 DETERMINATION OF RUNWAY CAPACITIES—HANDBOOK APPROACH

In 1976, the FAA published a comprehensive handbook (8) that contains procedures for the determination of ultimate airfield capacities and aircraft delays for purposes of airport planning. The handbook and its companion reports (5, 12, 13) 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, Inc.

The handbook contains 62 graphs, exemplified by Figure 7.6, for the estimation of hourly capacities. Based on analytical models, the graphs account for the effects of the following variables:

HOURLY CAPACITY BASE C*



TOUCH & GO FACTOR T

Percent Touch & Go	Mix Index-- Percent (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* x T x E = Hourly Capacity

EXIT FACTOR E

To determine Exit Factor E:

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 feet
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-- Percent (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 to 20	2000 to 4000	0.72	0.87	0.94	0.70	0.86	0.94	0.67	0.84	0.92
21 to 50	3000 to 5500	0.79	0.86	0.94	0.76	0.84	0.93	0.72	0.81	0.90
51 to 80	3500 to 6500	0.79	0.86	0.92	0.76	0.83	0.91	0.73	0.81	0.90
81 to 120	5000 to 7000	0.82	0.89	0.93	0.80	0.88	0.94	0.77	0.86	0.93
121 to 180	5500 to 7500	0.86	0.94	0.98	0.82	0.91	0.96	0.79	0.91	0.97

FIGURE 7.6 Hourly capacity diagram for a single-runway in VFR conditions. (*Source*: Reference 8)

1. Aircraft mix.
2. Runways serving both arrivals and departures.
3. Touch-and-go operations.
4. Different exit taxiway configuration.
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: Class C: large aircraft, more than 12,500 lb and up to 300,00 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 as an Advisory Circular (4).

Consider the following example, taken from Reference 8.

EXAMPLE 7.3 ULTIMATE RUNWAY CAPCITY, USING FIGURE 7.6

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

$$\text{percentage } (C + 3D) = 30 + (3 \times 5) = 45$$

From Figure 7.6, the hourly capacity base C^* in VFR conditions is 65 operations/hr. Also from Figure 7.6, 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

$$65 \times 1.10 \times 0.84 = 60 \text{ operations/hr}$$

7.8 ANNUAL SERVICE VOLUME

The concept of annual service volume has been proposed 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 a deterioration in the level of service. Annual service volume is the level of annual aircraft operations that will result in an average aircraft delay on the order of 1 to 4 min.

The recommended procedure for the calculation of annual service volume is outlined below (8).

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 the greatest percentage of the year (i.e., 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:

$$C_w = \frac{\sum_{i=1}^{n} C_i W_i P_i}{\sum_{i=1}^{n} W_i P_i} \tag{7.11}$$

where

P_i = the proportion of the year with capacity C_i
W_i = the weight to be applied to capacity, chosen from the table accompanying item 3.

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	Hourly Ratio
0–20	7–11
21–50	10–13
51–180	11–15

7. Compute annual service volumes ASV from the following formula:

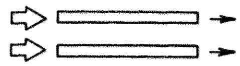
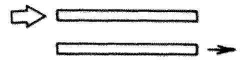
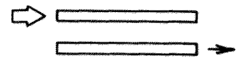
$$ASV = C_w \times D \times H \tag{7.12}$$

where

C_w = weighted hourly capacity
D = daily ratio
H = hourly ratio

EXAMPLE 7.4 ANNUAL SERVICE VOLUME FOR RUNWAYS (8)

Determine the annual service volume of a dual parallel runway configuration under the following operation 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

Based on historical traffic records,

Total annual operations	= 367,604
Average daily operations	= 1,050
Average peak hour operations, peak month	= 75

The predominant capacity occurs in Operating Condition No. 1 and is 93 operations per hour. From the table in paragraph 3, 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 (7.11), the weighted hourly capacity,

$$C_w = \frac{(0.70 \times 93 \times 1) + (0.20 \times 72 \times 15) + (0.10 \times 62 \times 15)}{(0.70 \times 1) + (0.20 \times 15) + (0.10 \times 15)}$$

$C_w = 72$ 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 7.12, the annual service volume

$$ASV = 72 \times 350 \times 14 = 352{,}800 \text{ operations per year}$$

7.9 PRELIMINARY CAPACITY ANALYSES

The FAA (8) has published approximate estimates of hourly capacity and annual service volumes for a variety of runway configurations. These estimates, exemplified by Table 7.1, are suitable only for preliminary capacity analyses. In addition to runway configuration, the capacities in Table 7.1 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 7.1, it is necessary to group the aircraft being served into four aircraft classes and to express aircraft mix as a mix index. (See Section 7.7).

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.
3. Availability of sufficient taxiways to expedite traffic on and off the runway system.
4. Touch-and-go operations ranging from 0 to 50%, depending on the mix index.

Reference 8 provides additional information on the performance of preliminary capacity analyses.

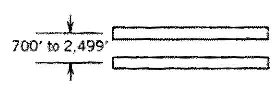
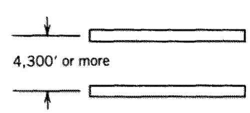
7.10 DETERMINATION OF HOURLY DELAYS

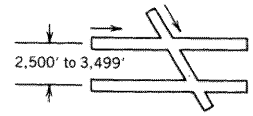
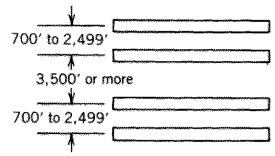
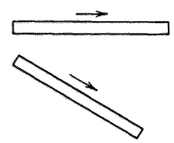
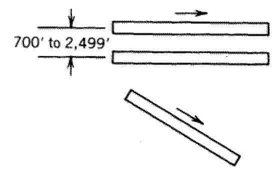
Capacity analyses, though useful for initial screening of alternative proposals, should not be used as the sole criterion for evaluating and phasing airfield improvements. Detailed and objective analyses should be made of alternative improvements, and, to the extent possible, the costs and benefits of each solution should be quantified. A major requirement for such analyses is the estimation of the magnitude of aircraft delays.

"Aircraft delay" is defined 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 (5).

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 in Reference 8, by which aircraft delays can be

TABLE 7.1 Capacity and Annual Service Volume for Long-Range

Configuration	Runway Configuration Diagram	Mix Index—Percent (C + 3*D*)	Hourly Capacity (Operations per Hour)		Annual Service Volume (Operations per Year)
			VFR	IFR	
A Single Runway		0–20	98	59	230,000
		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 Dual Lane Runways		0–20	197	59	355,000
		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 Independent IFR Parallels		0–20	197	119	370,000
		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 Parallels plus Crosswind Runway		0–20	197	62	355,000
		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 Four Parallels		0–20	394	119	715,000
		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 Open V Runways		0–20	150	59	270,000
		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 Parallels plus Crosswind Runway		0–20	295	59	385,000
		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.

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 (5).

The following graphical procedure is recommended (4, 8) for the estimation of hourly delays:

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 7.7. 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:

$$ADF = ADI \times [D/C] \tag{7.13}$$

4. Calculate the departure delay factor, *DDF*, by the following formula:

$$DDF = DDI \times [D/C] \tag{7.14}$$

5. Determine the demand profile factor, defined as the percent of hourly demand occuring in the busiest 15-minute period.
6. Estimate the average hourly delay for arrival and departure aircraft from Figure 7.8.
7. Compute the total hourly delay to aircraft, *DTH*, by the following formula:

$$DTH = HD\{[PA \times DAHA] + [(1 - PA) \times DAHD]\} \tag{7.15}$$

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

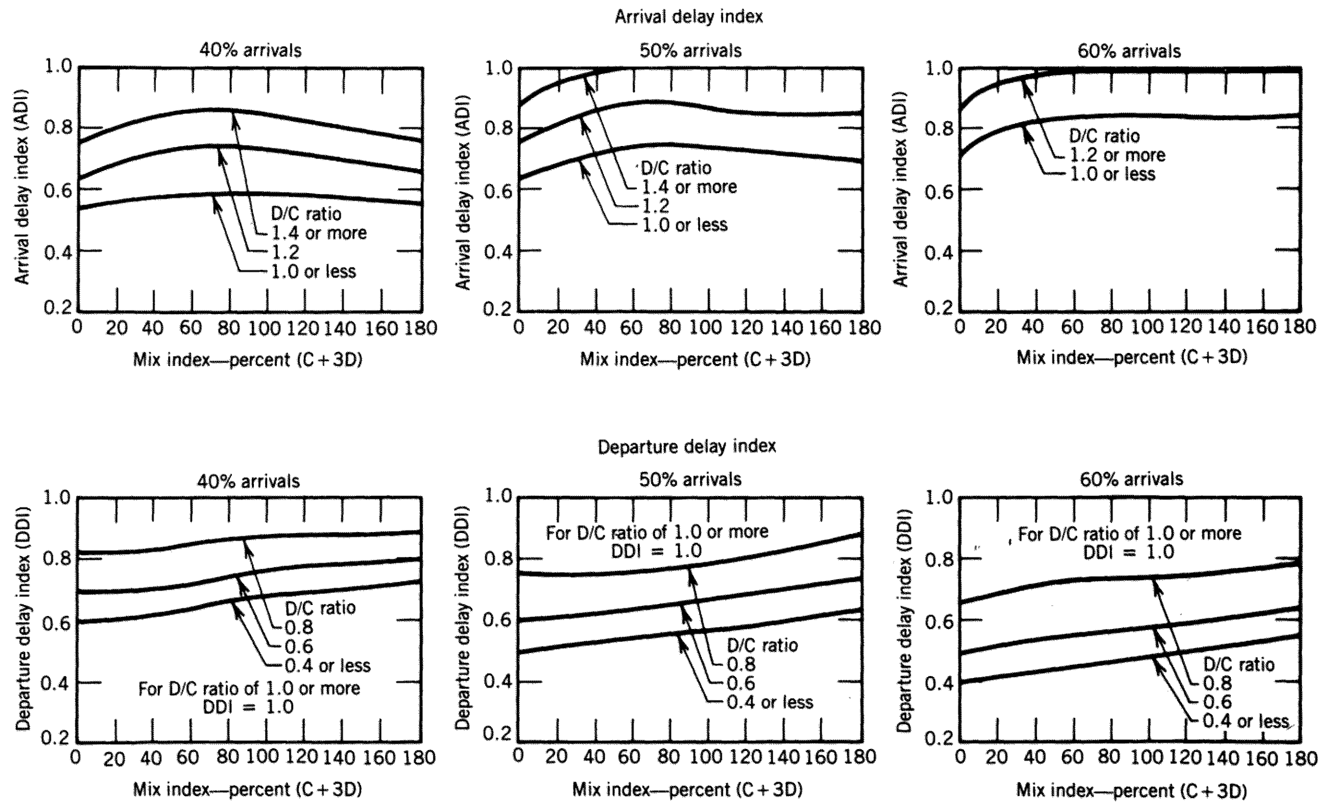


FIGURE 7.7 Delay indices for runway use diagram. (*Source*: Reference 8)

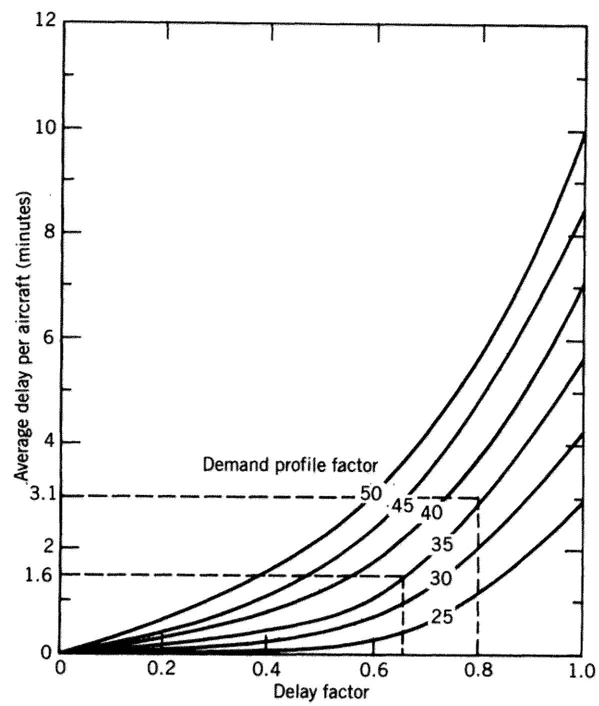


FIGURE 7.8 Average aircraft delay in an hour. (*Source*: Reference 8)

the demand on one or more components exceeds its capacity, delays to aircraft for a period of more than one hour should be considered. The recommended procedure for such analyses is not covered here, but see Reference 8.

Consider the following example that is modeled after one from the capacity and delay handbook (8).

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

Hourly demand = 59 operations per hour
Peak 15-minute demand = 21 operations
Hourly capacity = 65 operations per hour
Percent arrivals = 50%
Mix index = 45

The ratio of hourly demand to hourly capacity is 59/65 = 0.91.

From Figure 7.7, for a mix index of 45, the arrival delay index is 0.71 and the departure delay index is 0.88.

By equations 7.13 and 7.14, 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-minute demand, the demand profile factor is $(21/59) \times 100 = 36$. Therefore, from Figure 7.8, 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 7.15, the total hourly delay to aircraft on the runway is

$$DTH = 59\{[0.50 \times 1.6] + [(1 - 0.50) \times 3.1]\} = 139 \text{ min}$$

7.11 ESTIMATION OF ANNUAL AIRCRAFT DELAY

The annual delay to aircraft on runways, gates, and the airfield 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 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 capacity and delay handbook (8), 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 (5, 8).

Reference 8 also presents a simplified procedure for obtaining annual delay to aircraft when an approximate estimate is all that is needed.

7.12 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. 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.

Gate occupancy time depends on the following variables:

1. The type of aircraft.
2. Whether the flight is an originating, turnaround, or through flight.
3. The number of deplaning and enplaning passengers.
4. The amount of baggage and mail.
5. The efficiency of apron personnel.
6. Whether each gate is available to all users or is allocated for exclusive use of one airline or class of aircraft.

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 inverse of the service time: $C_A = 1/T_A = 3.0$ aircraft/hr. Similarly, $C_B = 1.5$ and $C_C = 1.0$. 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

$$C = \min_{\text{all } i} \left[\frac{G_i}{T_i M_i} \right] \tag{7.16}$$

where

G_i = the 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/hr. The capacity is therefore 10 aircraft/hr.

Reference 8 gives a graph that makes it possible to estimate the hourly gate capacity in operations per hour.*

7.13 TAXIWAY CAPACITY

Empirical studies have shown that the capacity of a taxiway system generally far exceeds the capacities of either the runways of the gates (11). There is one notable exception, namely, taxiways that cross an active runway. For such a situation, the taxiway capacity depends on the runway operations rate, the aircraft mix, and the location of the taxiway relative to the departure end of the

*One aircraft using a gate represents two operations—an arrival and a departure.

runway. Graphical solutions for capacities of taxiways that cross active runways, omitted from this book, are given in Reference 11.

7.14 AIRPORT CONFIGURATION

It was stated earlier that a major determinant of airport capacity is the overall layout and design of the system. Foremost in this class of factors is airport configuration, which is the general arrangement of the various parts or components of the airport system.

7.15 PRINCIPLES OF AIRPORT LAYOUT

The layout of an airport must be suitable for the shape and acreage of available land. It must contain enough runways to meet air traffic demand, and the runways must have adequate separation to ensure safe air traffic movements. Runways should 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 automobiles, as well as space for freight and baggage handling and storage, and for aircraft maintenance and service. The configuration should facilitate safe and expeditious movements of aircraft and ground transportation vehicles.

7.16 RUNWAY CONFIGURATION

A wide variety of runway configurations exist; however, most runway systems are arranged according to some combination of four basic configurations: (1) single runways, (2) parallel runways, (3) open-V runways, and (4) intersecting runways. Examples of runway configurations appear in Table 7.1.

The simplest runway configuration is a single runway system, illustrated as configuration A, Table 7.1. Although capacity varies widely with aircraft mix, the hourly capacity is 51 to 98 operations per hour under VFR conditions, and 50 to 59 operations per hour under IFR conditions (8).

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 (10). 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 (configuration B) would increase capacity without introducing undue hazard.

The attractiveness of the dual-lane approach stems from the fact that an over 50 percent 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), the savings in land may yield an extremely high benefit/cost ratio for the dual-lane configuration (10).

The dual-lane configuration would operate in the following way. The upper runway in Figure 7.9 would have high-speed exits and would be used for arrivals. The lower runway in Figure 7.9 would 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 (14). To achieve maximum capacity capability, the FAA has suggested a minimum centerline spacing of 1000 ft for dual-lane runways (15).

Layout B is an "IFR-dependent" configuration; that is, under instrument flight rules, 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.

Layout C in Table 7.1, with a spacing of 4300 ft, is an independent IFR configuration. With this layout, simultaneous precision instrument approaches are permitted.

Other variations of the parallel configuration result from differences in the location of the terminal building relative to the runways. A common arrangement is to place the terminal facilities to one side of a pair of runways. This layout has the objectionable feature of causing aircraft to taxi across an active runway. This disadvantage is overcome by an *open parallel* runway system in which the terminal building, apron, and taxiways are placed between the two runways.

Where prevailing winds are from one direction a large percentage of the time, 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 makes it possible to reduce taxiing distances by using one runway exlusively for takeoff operations and the other runway for landings. This configuration, however, requires a great deal of land.

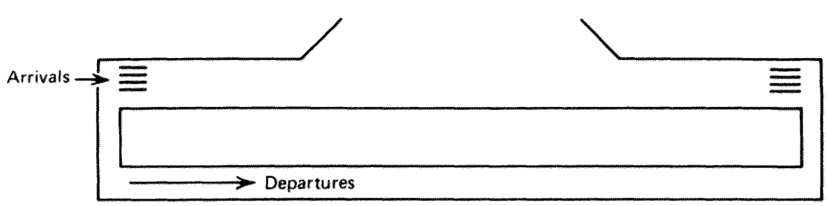


FIGURE 7.9 Dual-lane runway concept; departures are released on departure after arrival touchdown; parallels are spaced at less than 1000 ft, centerline to centerline. (*Source*: Reference 10)

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 the type of air traffic control system. More detailed information on the required separation of parallel runways is given in Section 8.6.

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. Layout D illustrates dual parallel runways with an intersecting crosswind runway. An example of the nonintersecting configuration, termed "open-V," is shown as layout F. Parallel runways plus a crosswind runway is illustrated as layout G.

The capacities of open-V and intersecting runway configurations depend to a great extent on the direction of operations and the amount of wind. 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.

Large airports may require three or more runways. The best configuration for a multiple-runway system depends on the minimum 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.

The world's airports are characterized by varied configurations, ranging from virtually unimproved landing strips or fields to complex runway-taxiway-apron configurations accommodating more than 2000 aircraft movements each day and serving 20 to 30 million passengers each year.

7.17 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

TABLE 7.2 FAA Maximum Permissible Crosswind Components

Airport Reference Codes[a]	Allowable Crosswind Component
A-I and B-I	10.5 kt
A-II and B-II	13.0 kt
A-III, B-III, and C-I through D-III	16.0 kt
A-IV through D-VI	20.0 kt

[a] Airport Reference Codes are defined in Section 8.5.

Source: *Airport Design*, FAA Advisory Circular AC 150/5300-13, including CHG 1, June 5, 1991.

right angle 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. The recommendations of the FAA (15) and the ICAO (16) regarding maximum permissible crosswind components are given in Tables 7.2 and 7.3, respectively.

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.

Wind Rose Method

A graphical procedure utilizing a wind rose typically is used to determine the "best" runway orientation insofar as prevailing winds are concerned. (See Figure 7.10).

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 7.4. This table indictes 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, northerly winds in the 4–15 mph range can be expected 4.8% of the time.

TABLE 7.3 ICAO Maximum Permissible Crosswind Components

Reference Field Length	Maximum Crosswind Component
1500 m or over[a]	37 km/h (20 kt)
1200 m to 1499 m	24 km/h (13 kt)
<1200 m	19 km/h (10 kt)

[a] When poor runway braking action owing to an insufficient coefficient of friction is experienced with some frequency, a crosswind component not exceeding 24 km/h (13 kt) should be assumed.

Source: Aerodromes, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., Montreal: International Civil Aviation Organization, July 1990.

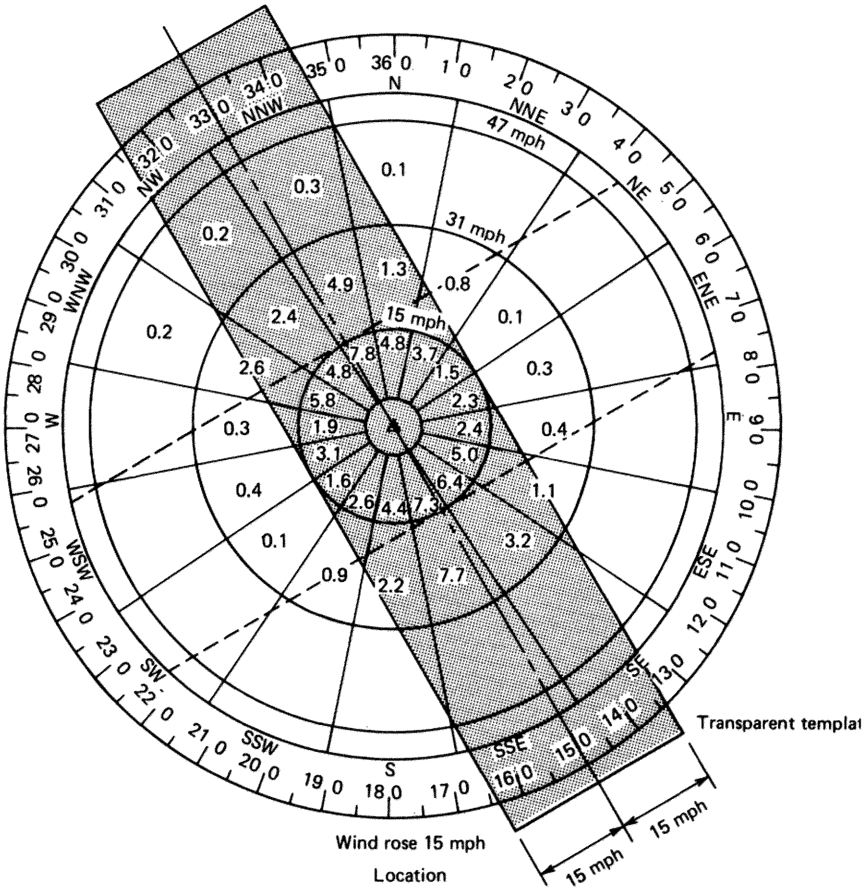


FIGURE 7.10 A typical wind rose for an allowable crosswind of 15 miles per hour.

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 miles per hour, and the radial lines indicate wind direction. The data from Table 7.4 have been plotted properly in Figure 7.10.

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., 15 mph).

The following steps are necessary 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.

TABLE 7.4 Typical Wind Data

Wind Direction	Percentage of Winds 4–15 mph	15–31 mph	31–47 mph	Total
N	4.8	1.3	0.1	6.2
NNE	3.7	0.8	—	4.5
NE	1.5	0.1	—	1.6
ENE	2.3	0.3	—	2.6
E	2.4	0.4	—	2.8
ESE	5.0	1.1	—	6.1
SE	6.4	3.2	0.1	9.7
SSE	7.3	7.7	0.3	15.3
S	4.4	2.2	0.1	6.7
SSW	2.6	0.9	—	3.5
SW	1.6	0.1	—	1.7
WSW	3.1	0.4	—	3.5
W	1.9	0.3	—	2.2
WNW	5.8	2.6	0.2	8.6
NW	4.8	2.4	0.2	7.4
NNW	7.8	4.9	0.3	13.0
Calms		0–4 mph		4.6
Total				100.0%

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 150°–330° or S 30° E, 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 changed to a 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.

A more refined breakdown of wind data than that shown in the example (Table 7.4 and Figure 7.10) should be used. The FAA recommends that 36 wind directions and the standard speed groupings of the Environmental Data Ser-

*The magnetic variation can be obtained from aeronautical charts.

vice (EDS) be used. The standard wind speed groupings used by EDS are 0-3, 4-6, 7-10, 11-16, 17-21, 22-27, 28-33, 34-40 knots, and so forth.

A computer program has been prepared by the FAA for wind analysis (15). The program employs a LOTUS 1-2-3 spreadsheet and may be used on an IBM PC compatible computer.

7.18 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 (17). A somewhat similar set of international standards is promulgated by the ICAO in Annex 14. In FAA terms, protected airspace around airports is made up of five principal imaginary surfaces. These are illustrated in Figure 7.11; Table 7.5 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.
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, nonprecision instrument, or precision instrument runways). A *visual* runway is a facility designed for operation under conditions of visual approach only. A *nonprecision instrument* runway has limited instrument

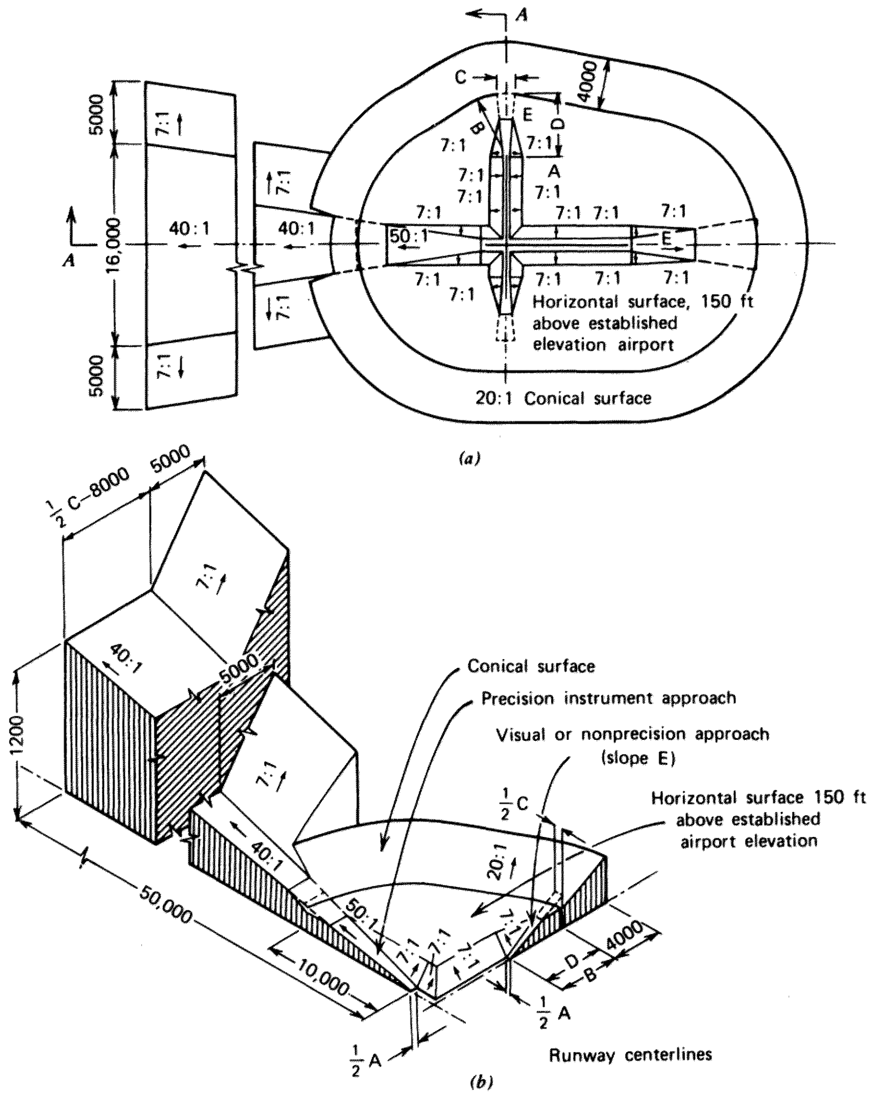


FIGURE 7.11 FAA imaginary surfaces for civil airports. (a) Plan view. (b) Isometric view of A-A. (*Source*: Reference 16)

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 7.12 is a schematic view of the

TABLE 7.5 Dimensions of FAA Imaginary Surfaces for Civil Airports

Dimensions[a]	Item	Dimensional Standards (ft): Visual Runway A	Visual Runway B	Nonprecision Instrument Runway A	Nonprecision Instrument Runway B: C	Nonprecision Instrument Runway B: D	Precision Instrument Runway
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
		Visual Approach A	Visual Approach B	Nonprecision Instrument Approach A	Nonprecision Instrument Approach B: C	Nonprecision Instrument Approach B: D	Precision Instrument Approach
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 ¾ mi.; D—Visibility minima as low as ¾ 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.

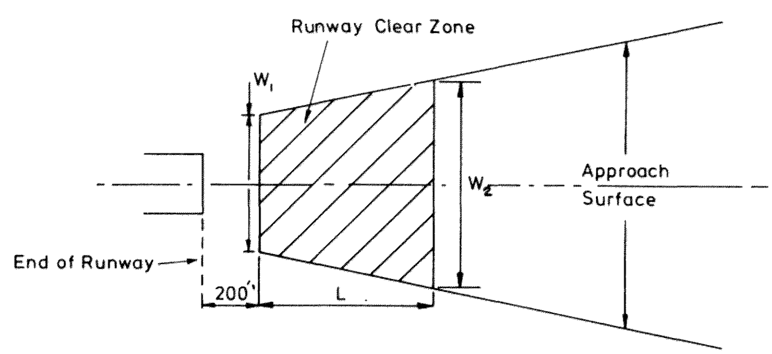


FIGURE 7.12 FAA clear zone proportions.

runway protection zone; the dimensions appear in Table 7.6. The airport owner must have positive control over development within the clear 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 ICAO are generally similar to those contained in FAR, Part 77; however, there are some significant differences.

TABLE 7.6 Runway Protection Zone (RPZ) Dimension

Facilities Expected to Serve	Runway End: Approach End	Runway End: Opposite End	Dimensions For Approach End: Length L feet	Inner Width W_1 feet	Outer Width W_2 feet	RPZ acres
Only Small Airplanes	V	V	1,000	250	450	8.035
		NP	1,000	500	650	13.200
		NP 3/4 P	1,000	1,000	1,050	23.542
	NP	V NP	1,000	500	800	14.922
		NP 3/4 P	1,000	1,000	1,200	25.252
Large Airplanes	V	V NP	1,000	500	700	13.770
		NP 3/4 P	1,000	1,000	1,100	24.105
	NP	V NP	1,700	500	1,010	29.465
		NP 3/4 P	1,700	1,000	1,425	47.320
Large or Only Small Airplanes	NP 3/4	V NP NP 3/4 P	1,700	1,000	1,510	48.978
	P	V NP NP 3/4 P	2,500	1,000	1,750	78.914

[a]1 ft = 0.3048 m.
V = visual approach
NP = nonprecision instrument approach with visibility minimums more than 3/4-statute mile
NP 3/4 = nonprecision instrument approach with visibility minimums as low as 3/4-statute mile
P = precision instrument approach

Source: Reference 15.

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.
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 approach surfaces are the same.

Tables 7.7 and 7.8 show the ICAO dimensions and slopes for obstacle limitation surfaces for approach and takeoff runways (16).

7.19 THE TAXIWAY SYSTEM

A key component in the airport layout is the taxiway system, which connects the runways to the terminal building and 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

TABLE 7.7 Takeoff Runways: Dimensions and Slopes of Obstacle Limitation Surfaces

	Code Number		
Surface and Dimensions[a]	1	2	3 or 4
(1)	(2)	(3)	(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 IMC, VMC by night.

Source: Aerodromes, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., Montreal: International Civil Aviation Organization, July 1990.

TABLE 7.8 Approach Runways: Dimensions and Slopes of Obstacle Limitation Surfaces

Runway Classification / Surface and Dimensions[a]	Noninstrument				Nonprecision Approach			Precision Approach		
								Category I		Category II or III
	Code Number				Code Number			Code number		Code number
	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%

continued

TABLE 7.8 *Continued*

Runway Classification	Noninstrument				Nonprecision Approach			Precision Approach Category I		Category II or III
	Code Number				Code Number			Code number		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)
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, Volume I, 1st Ed., Montreal: International Civil Aviation Organization, July 1990.

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.

At smaller airports, air traffic may not be sufficient to justify the construction of a parallel taxiway. In this case, taxiing is done on the runway itself, and a cul-de-sac or *turnaround* must be provided at the ends of the runway.

Consideration should be given to constructing a partial parallel taxiway when construction of a full parallel taxiway is not practicable.

Whenever possible, taxiways should be designed so that they do not cross active runways. Ideally, at busy airports, separate taxiway routes to and from the terminal area should be constructed, to provide one-way flow.

Specific criteria for the design of runways, taxiways, and aprons are given in Chapter 8.

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8

GEOMETRIC DESIGN OF THE AIR SIDE

8.1 INTRODUCTION

This chapter contains material of fundamental importance to the airport designer. It includes specific design standards and procedures that are required for the preparation of plans and specifications for an airport. Topics covered include determination of runway lengths, longitudinal grade design for runways, and geometric design of the runway and taxiway system.

The design criteria presented here have been prepared by the International Civil Aviation Organization, the U.S. Federal Aviation Administration, the U.S. Navy, and the U.S. Air Force. There is some variation in the rigidity of these criteria. Unless otherwise indicated, the ICAO criteria are *recommended practices,* as distinguished from compulsory standards. Although ICAO member countries endeavor to conform to these practices in the interests of air safety and efficiency, conformity is not mandatory. Similarly, the FAA criteria are recommended standards rather than absolute requirements. Design standards for military airports must accommodate the characteristics and peculiarities of high-performance aircraft and tend to be more rigidly enforced.

Because of local conditions and requirements, designers may find it necessary to deviate from a particular standard to improve another aspect or feature of the airport design. In such cases, they should be prepared to justify any decision to deviate from the recommended standards.

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 ICAO (1) relates the recommended runway dimensions and clearances to a "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. Section 8.4 further describes the ICAO reference code.

The FAA provides design criteria for six groups of transport airports, four classes of general aviation airports, and special criteria for heliports and STOL ports. Aircraft are grouped according to approach speed and wingspan width. Section 8.5 describes the FAA's airplane design group concept.

The U.S. Air Force employs a "use" category as an indication of the principal function of its bases: heavy bomber, fighter, trainer, and so on. However, most of the design criteria normally remain constant for airfields of all types, regardless of use categories (2). The U.S. Navy recognizes two classes of runways: A and B. Class A runways are primarily intended for small, light aircraft and do not have the potential for development to heavy aircraft use or for which no foreseeable requirement for such use exists. Class B runways are all other fixed-wing runways.

8.2 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 length of journey it can fly.

The runway must be long enough to allow safe landings and takeoffs by current equipment and by future aircraft expected to use the airport. It must accommodate differences in pilot skill and a variety of aircraft types and operational requirements.

The following factors most strongly influence required runway length:

1. Performance characteristics of aircraft using the airport (see Chapter 3).
2. Landing and takeoff gross weights of the aircraft.
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 (3) 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 FAA performance curves appearing in Figure 8.1 indicate the required runway lengths for the Boeing 727-00.

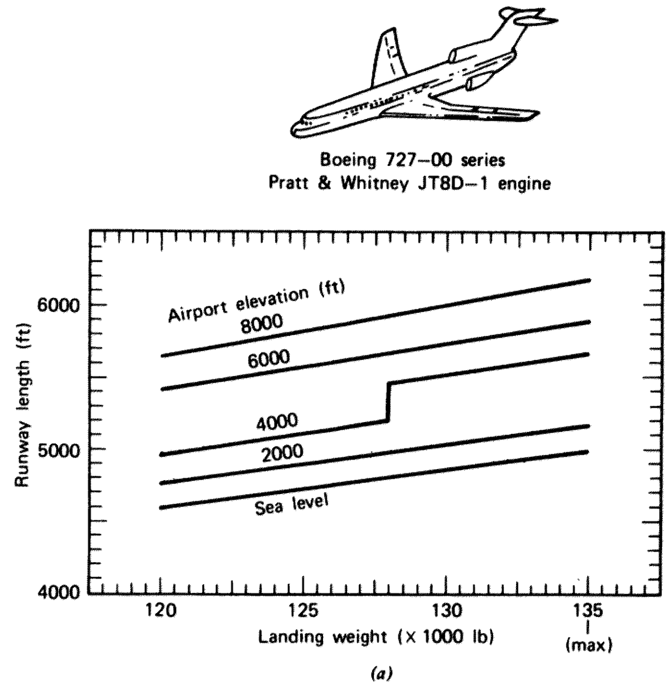


FIGURE 8.1 Aircraft performance curves for Boeing 727-00 series aircraft. (a) Landing.

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 landing length form 5.0 to 9.5%, depending on aircraft series (3). No correction is required for piston or turboprop airplanes.

Example 8.1 demonstrates the use of Figure 8.1.

EXAMPLE 8.1 RUNWAY LENGTH REQUIREMENT FOR A BOEING 727-00 SERIES AIRCRAFT

What length of runway is required for a Boeing 727-00 series aircraft, given the following conditions?

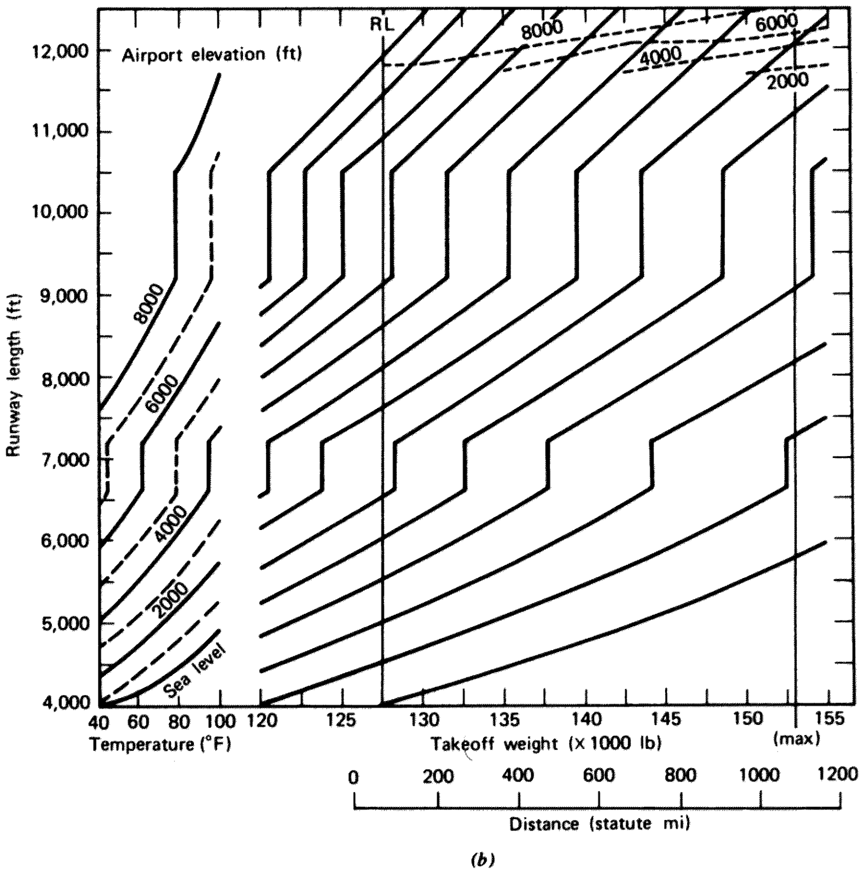


FIGURE 8.1 (continued) (b) Takeoff. (*Source*: Reference 3)

1. Maximum landing weight, 135,000 lb.
2. Allowance for slippery pavement, 7.0%.
3. Normal maximum temperature, 80°F.
4. Airport elevation, 4000 ft.
5. Flight distance, 1000 mi.
6. Takeoff weight, 147,500 lb.
7. Effective runway gradient, 0.5%.

Runway Length Required for Landing

Enter Figure 8.1a on the abscissa axis at the maximum landing weight (135,000 lb), and project this point vertically to intersect with the 4000 ft airport elevation line. Extend this point of intersection horizontally to the right ordinate scale, where a runway length required for landing of 5650 ft is read. If this figure is increased by 7.0% to allow for slippery pavement, the required runway length for landing is 6045 ft.

Runway Length Required for Takeoff

The following steps are required to determine from Figure 8.1b the runway length required for takeoff:

1. Enter the temperature scale on the abscissa axis at the given temperature (80°F).
2. Project this point vertically to the intersection, with the slanted line corresponding to the airport elevation (4000 ft).
3. Extend this point of intersection horizontally to the right until it coincides with the reference line (RL).
4. Proceed up and to the right or down and to the left, parallel to the slanted lines, to the intersection of the elevation limit line (in this case, 4000 ft), or until reaching a point directly above the aircraft's takeoff weight (e.g., 147,500 lb) or distance (e.g., 1000 mi), whichever occurs first.
5. Project this point horizontally to the right, and read the required runway length for takeoff at the right ordinate scale. In this example, a length of 9200 ft is required for takeoff.
6. Increase this runway length for effective gradient. The resulting runway length is 9660 ft, and this value, being the larger of the two, is taken as the design runway length.

Recently, the FAA has begun to publish airplane performance data in tables, from which planners and engineers can determine runway length by interpolation. In addition, a computer program is available from the FAA which may be used to determine the recommended runway length for airport design (4).

8.3 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 8.2). It increases the allowable airplane operating takeoff weight without increasing runway length (4).

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 8.3). 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 sel-

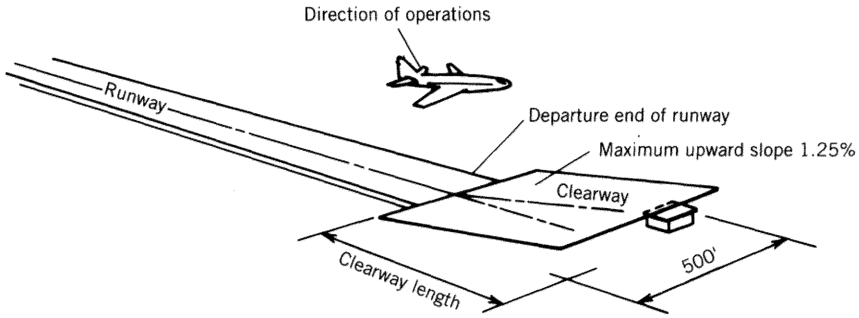


FIGURE 8.2 Clearway. (*Source*: Reference 4)

dom used, it is often more cost effective to construct a full-strength runway that would be useful in both directions rather than a stopway.

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 and on the operating characteristics of the airplanes expected to use it. The effects of aircraft characteristics on stopway, clearway, and runway lengths are discussed in Chapter 3.

8.4 ICAO REFERENCE CODE

Runway length, being the most important air side 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,

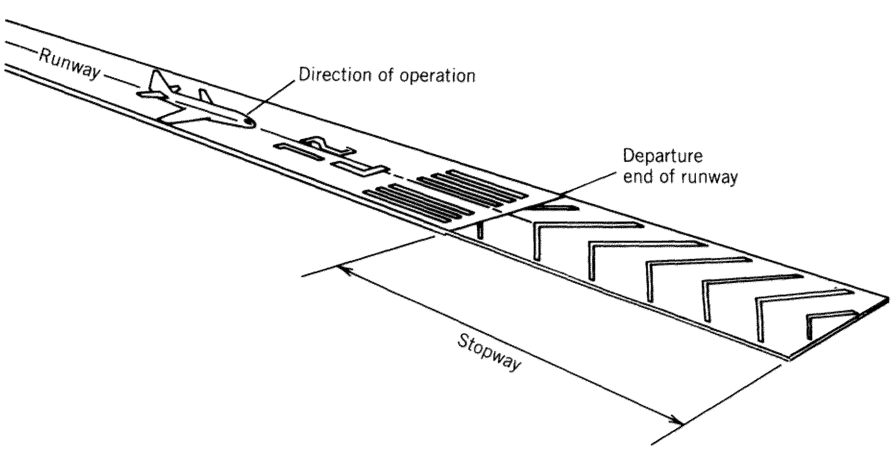


FIGURE 8.3 Stopway. (*Source*: Reference 4)

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.

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 Table 8.1 indicates, 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 (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

*The field length includes the runway length plus the stopway and/or clearway lengths, if provided.

TABLE 8.1 ICAO Reference Code

Code Element 1		Code Element 2		
Code Number	Aeroplane Reference Field Length	Code Letter	Wing Span	Outer Main Gear Wheel Span[a]
(1)	(2)	(3)	(4)	(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

[a] Distance between the outside edges of the main gear wheels.
[b] 1 m = 3.2808 ft.
Source: *Aerodromes*, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., Montreal: International Civil Aviation Organization, July 1990.

$$F_t = 0.01[T(°C) - (15 - 1.981E)] + 1$$

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

$$F_g = (0.10G + 1) \tag{8.4}$$

The relationships between planned and reference field lengths given in this section are generally applicable to military airports; however, the recommended corrections for nonstandard conditions are not the same as for civilian airports. Reference 5 and 6 give recommended corrections for nonstandard conditions of altitude, temperature, and effective gradient for military runways.

8.5 THE FAA AIRPORT REFERENCE CODE

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

TABLE 8.2 FAA Aircraft Approach Category Classification

Approach Category	Approach Speed, Knots	Airport Category
A	Less than 91	Utility Airport
B	91–120	Utility Airport
C	121–140	Transport Airport
D	141–165	Transport Airport
E	166 or greater	Transport Airport

Source: Airport Design, FAA Advisory Circular AC 150/5300-13, September 29, 1989.

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 certificated 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 1.3 V_{SO}. (V_{SO} is the aircraft stall speed at the maximum certificated landing weight.) See Table 8.2. 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.

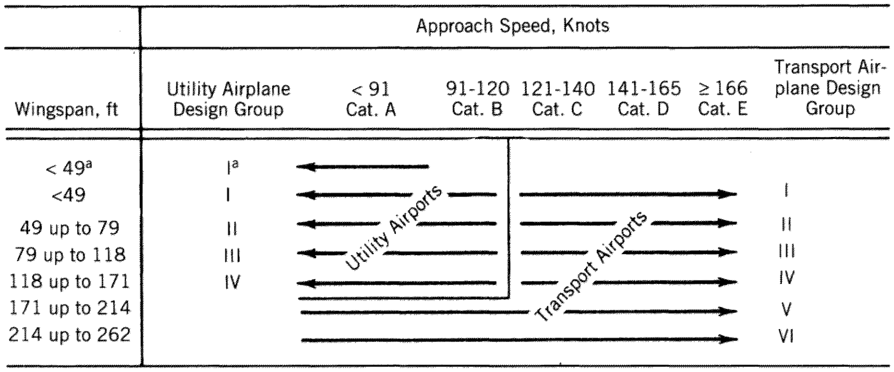
FAA geometric design standards are linked to the wingspan of the critical aircraft. Definitions of each Airplane Design Group are given in Table 8.3, along with a list of typical aircraft for each group. The chart shown in Figure 8.4 provides guidance in selecting the proper airplane design group and airport dimensional standards.

*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, nonprecision, and precision instrument runways).

TABLE 8.3 FAA Airplane Design Groups for Geometric Design of Airports

Airplane Design Group	Wingspan (ft)	Typical Aircraft
I	Less than 49	Beech Bonanza A36, Learjet 25
II	49 up to 79	DeHavilland DHC-6, Gulfstream II
III	79 up to 118	Boeing 737, Martin-404
IV	118 up to 171	Boeing 757, Lockheed 1011
V	171 up to 214	Boeing 747-400
VI	214 up to 262	Lockheed C5A

Source: Airport Design, FAA Advisory Circular AC 150/5300-13, September 29, 1989.



[a]Applies to airports that are to serve only small airplanes.

FIGURE 8.4 FAA airplane design group concept.

8.6 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 permits, for Code Number 1, parallel runway centerlines to be placed as close as 120 m (1). ICAO specifies a minimum separation for simultaneous visual operations of 150 m for Code Number 2 and 210 m for Code Numbers 3 and 4.

For simultaneous landings and takeoffs under visual flight rules, the FAA specifies a minimum separation between centerlines of parallel runways of 700 ft. However, the minimum centerline separation distance for Airplane Design Groups V and VI is 1200 ft.

The Navy (6) and Air Force (7) specify a minimum clearance of 1000 ft between the centerlines of parallel runways for simultaneous VFR operations. Where an intervening taxiway is to be provided, the Air Force recommends a clearance of 2000 ft. The U.S. Navy requires a minimum separation between parallel runway centerlines of 4300 ft where the runways are to operate with simultaneous IFR approaches.

Criteria for minimum separation of parallel instrument runways are 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 (8). Research in the 1960s indicated that a minimum separation of parallel runways of 5000 ft was required for simultaneous instrument approaches. However, the FAA (4) now specifies a minimum separation of 4300 ft for simultaneous precision instrument approaches, provided specific electronic navigational aids and monitoring equipment, air traffic control, and approach procedures are used. A minimum separation of 2500 ft is required for simultaneous departures and is also suitable for simultaneous arrivals and departures, provided radar air traffic control is exercised and the thresholds are not staggered (4). 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 4. It will be necessary to observe wake turbulence avoidance procedures when centerline spacings under 2500 ft are used. The Navy (6) specifies a minimum separation of parallel runways of 4300 ft for simultaneous instrument approaches.

8.7 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 (4) now refers to the entire graded area between the side slopes as the *runway safety area*, as Figures 8.5 and 8.6 illustrate. In its literature, the ICAO refers to a comparable area as the *runway strip*.

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 120 ft at the smallest utility airports to 500 ft or wider for all categories of transport airports (4). Similar widths of runway strips are recommended by the ICAO (1).

Runways and Shoulders

The runway is a paved load-bearing area that varies in width from about 60 ft at the smallest general aviation airports to 150 ft 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

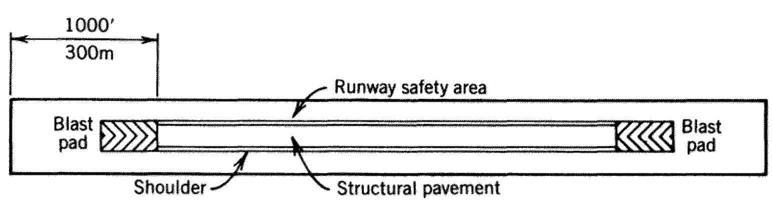


FIGURE 8.5 Plan view of runway elements. (*Source*: Reference 4)

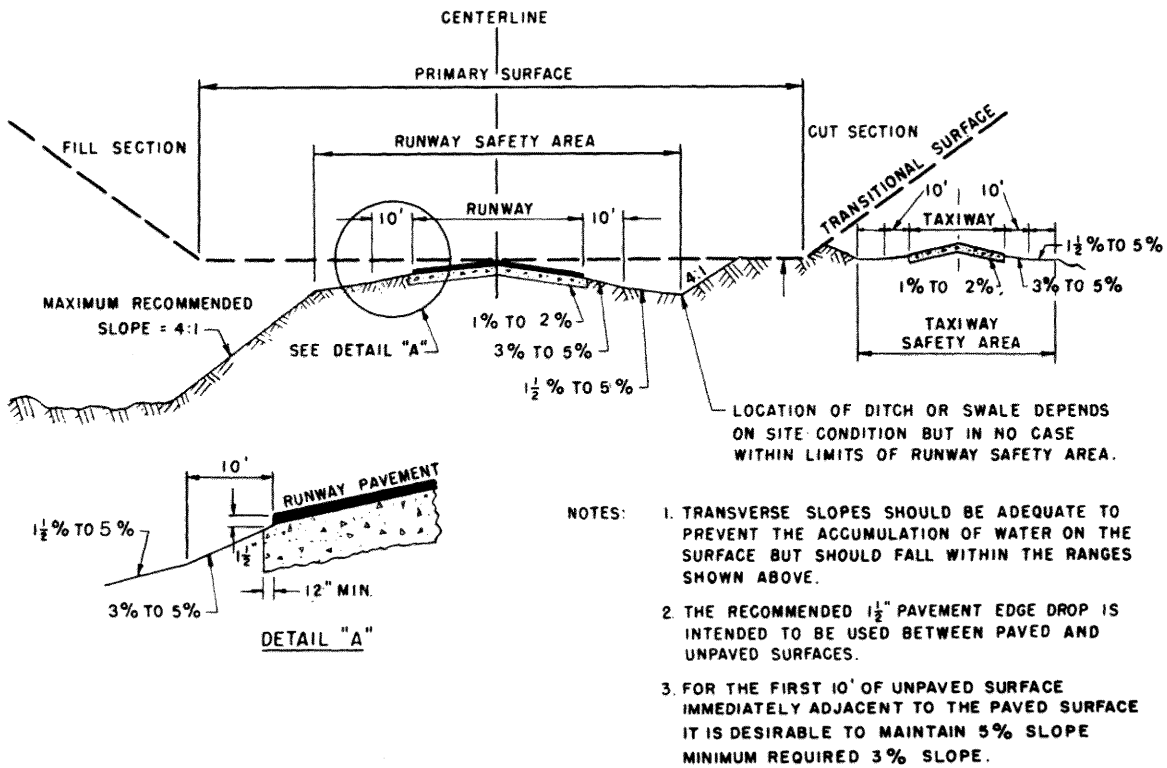


FIGURE 8.6 Transverse grade limitations for utility airports. (*Source*: Adapted from Reference 4)

distribution centered about the runway centerline. Virtually all the load applications are concentrated in a central width of about 100 ft. The additional 50 ft 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 form 10 ft to 40 ft for transport airports (4). The ICAO recommends that the overall width of the runway plus its shoulders be not less than 60 m or approximately 200 ft (1).

Airports serving military aircraft may require runways and runway safety areas wider than those provided at civilian airports. For example, the Air Force (5) requires a runway width of 150 ft for runways serving fighter and trainer aircraft but a width of 300 ft for those serving heavy bombers. A graded area bordering the runway 200 ft in width is uniformly specified for conventional aircraft. The Navy (6) specifies a 200 ft runway and a 500 ft runway safety area width.

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 civilian airports, shoulders are most commonly constructed of stabilized earth with a turf cover. The Air Force (5) recommends that the first 10 ft of shoulder beyond the runway edge be constructed with a select base material having a California bearing ratio (CBR) of 12 and paved with a double bituminous surface treatment, or with 6 in of soil cement topped with a single bituminous treatment.

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 nontraffic areas. Blast pads vary in length from 100 ft to 400 ft, 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 20 to 60 ft wide at general aviation airports and 50 to 125 ft wide at air carrier airports. Both the Air Force and the Navy specify a standard taxiway width of 75 ft.

In the interests of safety and good aircraft maneuverability, adequate separations must be provided between runways and taxiways, along with ample clearances to buildings and other obstacles. Tables 8.4 to 8.7 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 8.1.

FAA's dimensional standards for runways and taxiways at transport air-

TABLE 8.4a ICAO Minimum Dimensional Recommended Practices

	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.

Source: *Aerodromes*, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., International Civil Aviation Organization, July 1990.

TABLE 8.4b ICAO Recommended Practices—Width of Runways

	Code Letter				
Code Number	A	B	C	D	E
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

[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.

Source: *Aerodromes*, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., International Civil Aviation Organization, July 1990.

TABLE 8.4c ICAO Recommended Practices—Width of Taxiways

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

[a] 1 m = 3.2808 ft.

Source: *Aerodromes*, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., International Civil Aviation Organization, July 1990.

TABLE 8.4d ICAO Recommended Practices—Taxiway Minimum Separation Distances

Code Letter	Distance Between Taxiway Center Line and Runway Center Line (m)[a]								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)
	Instrument Runways				Non-instrument Runways						
	Code Number				Code Number						
	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			21	13.5	12
B	87	87			42	52			31.5	19.5	16.5
C			168				93		46.5	28.5	24.5
D			176	176			101	101	68.5	42.5	36
E				180				105	76.5	46.5	40

Note: The separation distances shown in columns 2 to 9 represent ordinary combinations of runways and taxiways. The basis for development of these distances is given in the Aerodrome Design Manual, Part 2.

[a] 1 m = 3.2808 ft.

Source: *Aerodromes*, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st July 1990.

TABLE 8.5 FAA Runway Dimensional Standards for Transport Airports (Aircraft Approach Categories C & D)

	Airplane Design Group					
Design Item	I	II	III	IV	V	VI
Runway safety area width (ft)[a,b]	500	500	500	500	500	500
Runway safety area length beyond runway end (ft)	1000	1000	1000	1000	1000	1000
Runway width (ft)	100	100	100[c]	150	150	200
Runway shoulder width (ft)	10	10	20[c]	25	35	40
Runway blast pad width (ft)	120	120	140[c]	200	220	280
Runway blast pad length (ft)	100	150	200	200	400	400
Runway object free area width (ft)	800	800	800	800	800	800
Runway object free area length beyond runway end (ft)	1000	1000	1000	1000	1000	1000
Nonprecision instrument and visual runway centerline to:						
Taxiway/taxilane centerline (ft)	300	300	400	400	Varies	600
Aircraft parking area (ft)	400	400	500	500	500	500
Precision instrument runway centerline to:						
Taxiway/taxilane centerline (ft)	400	400	400	400	Varies	600
Aircraft parking area (ft)	500	500	500	500	500	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.

Source: *Airport Design*, FAA Advisory Circular AC 150/5300-13, September 29, 1989.

TABLE 8.6 FAA Taxiway Dimensional Standards

Design Item	Airplane Design Group I	II	III	IV	V	VI
Taxiway safety area width (ft)[a]	49	79	118	171	214	262
Taxiway width (ft)	25	35	50[b]	75	75	100
Taxiway edge safety margin (ft)[c]	5	7.5	10[d]	15	15	20
Taxiway shoulder width (ft)	10	10	20	25	35	40
Taxiway object free area width (ft)	89	131	186	259	320	386
Taxilane object free area width (ft)	79	115	162	225	276	334
Taxiway centerline to:						
Parallel taxiway/taxilane centerline (ft)	69	105	152	215	267	324
Fixed or movable object (ft)	44.5	65.5	93	129.5	160	193
Taxilane centerline to:						
Parallel taxilane centerline (ft)	64	97	140	198	245	298
Fixed or movable object (ft)	39.5	57.5	81	112.5	138	167

[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.

[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.

Source: *Airport Design*, FAA Advisory Circular AC 150/5300-13, September 29, 1989.

TABLE 8.7a FAA Nonprecision Instrument and Visual Runway Design Standards for Utility Airports (Aircraft Approach Categories A & B)

Design Item	Airplane Design Group				
	I[b]	I	II	III	IV
Runway safety area width (ft)[a]	120	120	150	300	500
Runway safety area length beyond runway end (ft)	240	240	300	600	1000
Runway width (ft)	60	60	75	100	150
Runway shoulder width (ft)	10	10	10	20	25
Runway blast pad width (ft)	80	80	95	140	200
Runway blast pad length (ft)	60	100	150	200	200
Runway object free area width (ft)	250	400	500	800	800
Runway object free area length beyond runway end (ft)	300	500	600	1000	1000
Runway centerline to:					
Hold line (ft)	125	200	200	200	250
Taxiway/taxilane centerline (ft)	150	225	240	300	400
Aircraft parking area (ft)	125	200	250	400	500

[a] 1 ft = 0.3048 m.

[b] These dimensional standards are for facilities expected to serve only small airplanes.

Source: Airport Design, FAA Advisory Circular AC 150/5300-13, September 29, 1989.

TABLE 8.7b FAA Precision Instrument Runway Design Standards for Utility Airports (Aircraft Approach Categories A & B)

	Airplane Design Group				
Design Item	I[b]	I	II	III	IV
Runway safety area width (ft)[a]	300	300	300	400	500
Runway safety area length beyond runway end (ft)	600	600	600	800	1000
Runway width (ft)	75	100	100	100	150
Runway shoulder width (ft)	10	10	10	20	25
Runway blast pad width (ft)	95	120	120	140	200
Runway blast pad length (ft)	60	100	150	200	200
Runway object free area width (ft)	800	800	800	800	800
Runway object free area length beyond runway end (ft)	1000	1000	1000	1000	1000
Runway centerline to:					
Hold line (ft)	175	250	250	250	250
Taxiway/taxilane centerline (ft)	200	250	300	350	400
Aircraft parking area (ft)	400	400	400	400	500

[a] 1 ft = 0.3048 m.

[b] These dimensional standards are for facilities expected to serve only small airplanes.

Source: *Airport Design*, FAA Advisory Circular AC 150/5300-13, September 29, 1989.

ports are given in Table 8.5 and 8.6, respectively. These standards are given by Airplane Design Group. (Refer to Table 8.3 and Figure 8.4.) Similar standards are given in Table 8.7 for utility airports.

Transverse Grades

As shown in the typical section (Figure 8.6), 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; however, when rigid pavements are used, the Air Force (7) permits slopes as small as 0.5%. 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 to 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.

8.8 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 8.5, 8.6 and 8.7.

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 (4). Dimensions of object-free areas are set forth in Tables 8.5, 8.6 and 8.7.

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 8.7.

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" (4). 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 8.7 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.

8.9 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 flat as 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 8.8 and Figure 8.8 indicate, a maximum longitudinal grade of 1.25 to 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 (4) 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 (1).

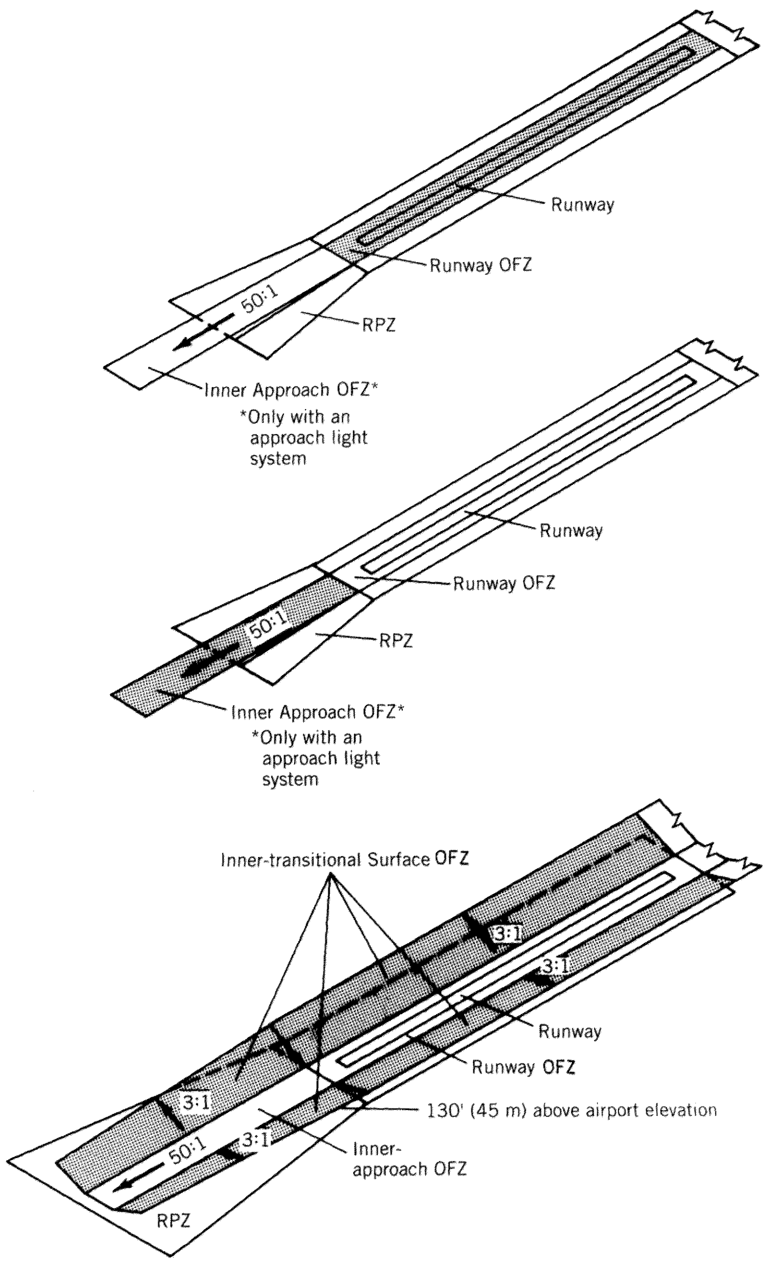


FIGURE 8.7 FAA Components of Obstacle-Free Zone (OFZ).

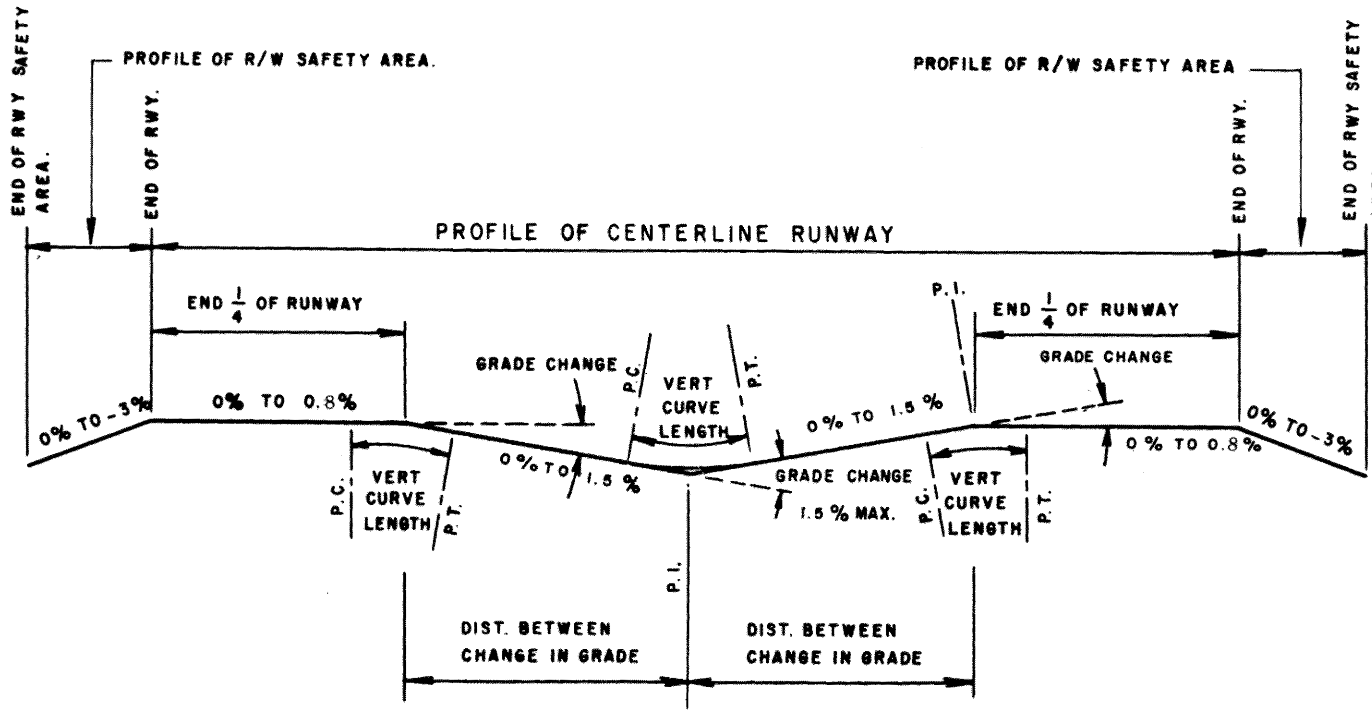
Note from Tables 8.8 and 8.9 that agencies specify the minimum distance between the points of intersection of two successive grade changes. This distance is based on the sum of the absolute values of corresponding grade changes.

TABLE 8.8 Runway Longitudinal Grade Design Criteria for Civilian Airports[a]

	Maximum Longitudinal Grade (%)	Maximum Grade, First and Last Quarter (%)	Maximum Effective Grade (%)	Maximum Change (%)	Distance Between Points of Intersection (ft)[d]	Length of Vertical Curve[b] (ft/1% grade change)
FAA						
Transport airports	1.5	0.8	1.0	1.5	1000(A + B)	1000
Utility airports	2.0	—	—	2.0	250(A + B)	300
ICAO						
Code number 4	1.25	0.8	1.0	1.5	984(A + B)	984
Code number 3	1.5	0.8[c]	1.0	1.5	492(A + B)	492
Code number 2	2.0	—	1.0	2.0	164(A + B)	246
Code number 1	2.0	—	2.0	2.0	164(A + B)	246

[a]Runway grade changes shall also conform to sight distance criteria described in Section 8.9.
[b]No vertical curve is required when grade change is less than 0.4%.
[c]For precision approach runway category II or III.
[d]1 ft = 0.3048 m.

Sources: *Airport Design*, FAA Advisory Circular AC 150/5300-13, September 29, 1989; *Aerodromes*, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., Montreal: International Civil Aviation Organization, July 1990.



MINIMUM DISTANCE BETWEEN CHANGE IN GRADE = 1000' (300m) x SUM OF GRADE CHANGES (IN PERCENT).

MINIMUM LENGTH OF VERTICAL CURVES = 1000' (300m) x GRADE CHANGE (IN PERCENT).

FIGURE 8.8 Longitudinal grade criteria for transport airports: P.I. = point of intersection; P.C. = point of curvature; P.T. = point of tangency. (*Source*: Reference 4)

TABLE 8.9 Runway Longitudinal Grade Design Criteria for U.S. Navy and Air Force Airports

Design Item	Value
1. Maximum longitudinal grade (%)	1.0
2. Minimum distance between points of intersection (ft)[a]	1000[b]
3. Minimum length of vertical curve (ft/1% change)	600
4. Maximum grade change criteria near runway ends	No grade change within 3000 ft of ends

[a] 1 ft = 0.3048 m.
[b] The Navy specifies that no two successive distances between points of intersection shall be the same.

Sources: *Airfield Geometric Design*, NAVFAC DM-21.1, Naval Facilities Engineering Command, November, 1984, and *Airfield and Airspace Criteria*, Air Force Manual 86-8B, May 3, 1967.

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

$$A = -0.5\% - (-1.2\%) = 0.7\%$$

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,

$$D = 492(A + B) = 492(0.7 + 1.5) = 1082 \text{ ft}$$

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, the FAA, the U.S. Navy and the U.S. Air Force are given in Tables 8.8 and 8.9.

Sight distance along runways should be as unrestrictive as possible and

TABLE 8.10 Runway Sight Distance Requirements

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* (ft)[a]	*X* (ft)
Utility airport	5	Entire runway length[b]
Transport airport	5	Entire runway length
ICAO code letter A	5	Half runway length
ICAO code letter B	7	Half runway length
ICAO code letter C, D, E	10	Half runway length
U.S. Air Force	10	5000 ft
U.S. Navy, Class B	8	5000 ft
U.S. Navy, Class A	5	3000 ft

[a] 1 ft = 0.3046 m.
[b] If full-length parallel taxiway is provided, X = half the runway length.
Sources: Airport Design, FAA Advisory Circular AC 150/5300-13, September 13, 1989; *Aerodromes*, Annex 14 to the Convention on International Civil Aviation, Volume I, 1st Ed., International Civil Aviation Organization, July 1990.

must adhere to the applicable requirements given in Table 8.10. The FAA (4) 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 sandards 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 (4) 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 (4).

8.10 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, ICAO code letters C, D, and E, and military jet bomber bases. 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 and for Air Force bases other than jet bomber bases.

Agencies generally agree that taxiway vertical curves should be at least 100 ft long for each 1% grade change. The ICAO permits taxiway vertical curves as short as 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 Air Force recommends a minimum taxiway sight distance of 1000 ft, measured from any two points 10 ft above the pavement. The ICAO recommendations (1) 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, or E.
> 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. 1.5 m 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.

8.11 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 (8) and the FAA (4) 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 to 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 8.6 shows recommended

TABLE 8.11 Taxiway Fillet Dimensions

		Airplane Design Group					
Design Item	Dimension[b]	I	II	III[c]	IV	V	VI
Radius of taxiway turn (ft)[a]	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] 1 ft = 0.3048 m.
[b] Letters are keyed to those shown as dimension on Figure 8.9.
[c] Airplane Design Group III with a wheelbase equal to or greater than 60 ft, should use a fillet radius of 50 ft

Source: *Airport Design*, FAA Advisory Circular AC 150/5300-13, September 29, 1989.

taxiway edge safety margins, the minimum distance between the outside of the airplane wheels and the pavement edge. The dimensions given in Table 8.11 are suitable for the design of 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 8.9. 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 4.

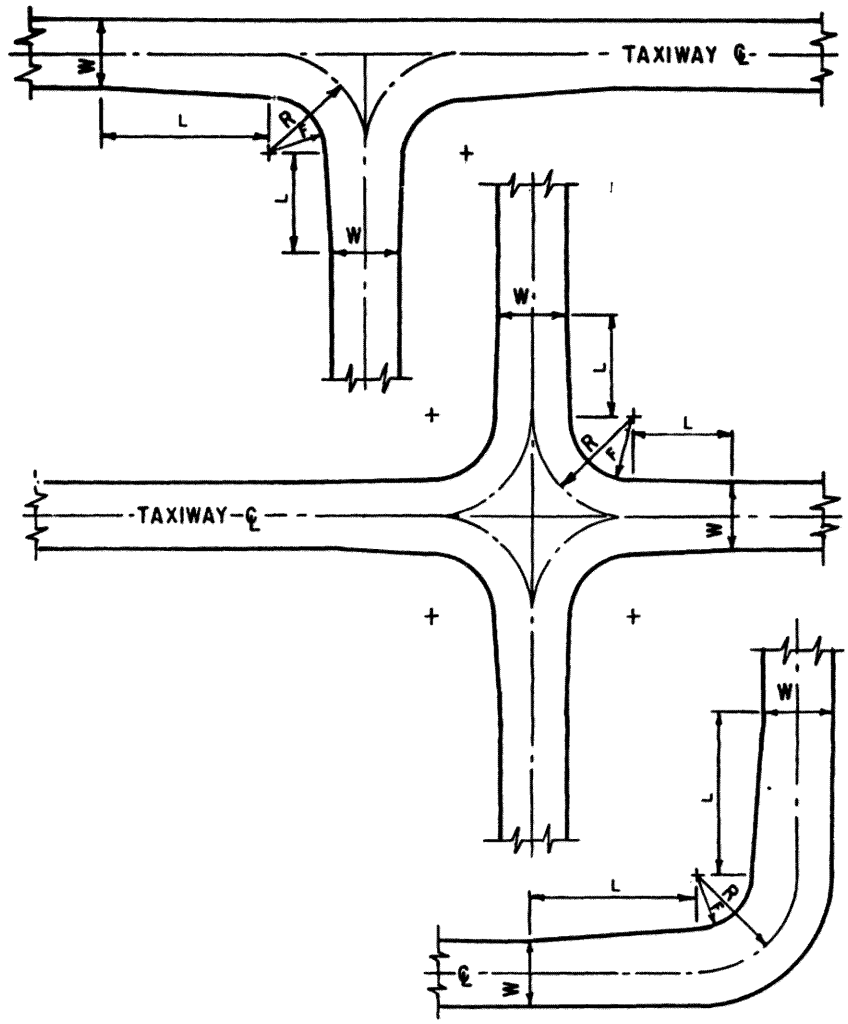


FIGURE 8.9 Typical taxiway intersection details. (*Source*: Reference 4)

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. The same wing-tip clearance is recommended for taxiway to obstacle separation (4). In the immediate terminal area, where taxiing is 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	$1.2\ W + 10$
Taxiway centerline to obstacle	$0.7\ W + 10$
Taxiway centerline to obstacle in terminal area	$0.6\ W + 10$

where W = wingspan of the most demanding aircraft, ft.

In most instances, the clearance and separation distances given in Table 8.6 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.

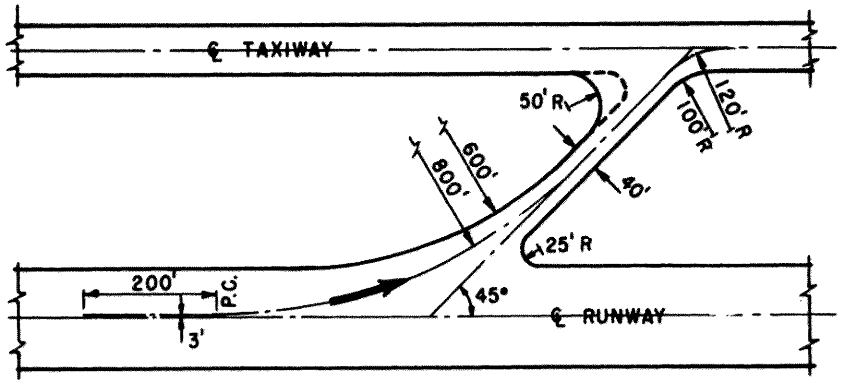
Figure 8.10 illustrates three common types of exit taxiways. Perpendicualr exit taxiways may be used when the design peak hour traffic is less than 30 operations per hour. To expedite the movement of landing aircraft from the runway, most modern air carrier airports provide exit taxiways that are oriented to 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 Figure 8.10c (30° angle of intersection) permits runway turnoff speeds up to 60 mph.

The number and location of exit taxiways depends 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.

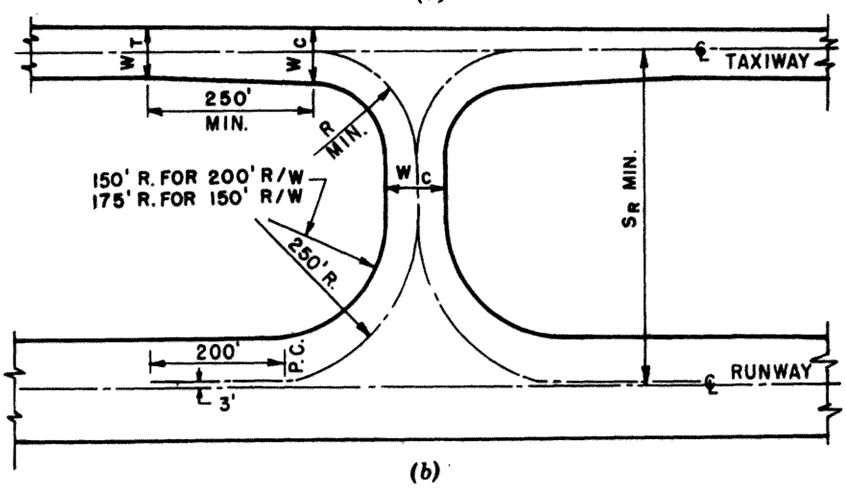
For a given class of aircraft, the desired location of a high-speed exit taxiway can be calculated, based on the following factors.

1. Distance from the threshold to touchdown.
2. Touchdown speed.
3. Initial exit speed (turnoff speed at the point of curvature) (P.C.).
4. Rate of deceleration.

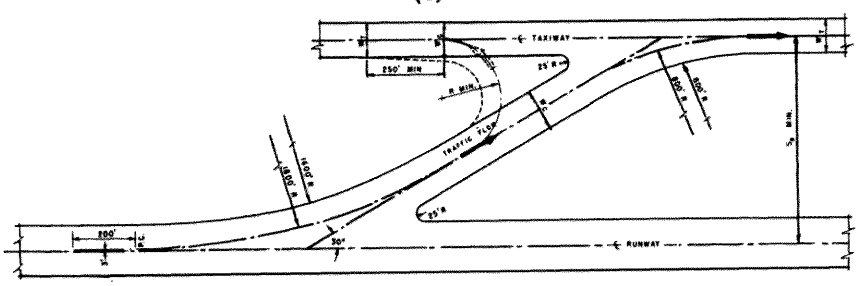
The distance from the threshold to touchdown averages about 1500 ft for tur-



(a)



(b)



(c)

FIGURE 8.10 Common types of exit taxiways. (a) Angled exit taxiway for small airplanes. (b) 90° exit taxiway. (c) Angled exit taxiway for large airplanes. (*Source*: Reference 4)

bojet 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

*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 max-taken to be 40 mph (59 ft/sec) for small aircraft and 60 mph (88 ft/sec) for large aircraft. The ICAO (8) recommends a deceleration rate of 1.25 m/sec^2 (4.1 ft/sec^2), and the FAA has utilized 5 ft/sec^2.

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 P.C. 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.

8.12 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 aiports, the FAA (4) 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.

> 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 (9).

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imum landing weight, should not be confused with those mentioned in Sec. 6-4 for the ICAO categories designated by the same letters.

8.13 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 (10) has published guidelines for the sizing and clearances required for aircraft gate design in terms of four aircraft gate types:

Gate Type A serves aircraft in Airplane Design Group III which have a wingspan of between 79 ft 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 ft 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 ft to 196 ft. These aircraft operate over long-range routes and carry a high volume of passengers.

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 (10) has published the following clearance recommendations for planning purposes.

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
For Gate Types B, C	20 ft
For Gate Type D	10 ft

Nose-to-Tail Clearances

When taxi-in/taxi-out operations are used, separation is required to acommodate the adverse effects of jet blast as well as separation for maneuvering. Typical nose-to-tail clearances required are:

For Gate Types A, B	120 ft
For Gate Type C	370 ft
For Gate Type D	490 ft

These distances may be reduced by providing jet blast fences and low breakaway thrust operating procedures.

Wing-tip to Wing-tip Clearances

In the aircraft gate area, the following wing-tip clearances are recommended:

For Gate Type A	15 ft
For Gate Types B, C, and D	25 ft

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 should be allowed.

Aircraft Extremity to Building Clearances

The FAA (10) recommends a 45 ft clearance from aircraft extremity to building for inboard pier gates and otherwise at least a 20 ft clearance.

The area required for an airplane negotiating a turn is governed by the size of nosewheel angle that is used. Thus, under turn and taxi-out conditions, the minimum size of gate position is determined by the maximum nosewheel angle. The geometry of minimum aircraft parking turns is illustrated by Figure 8.11. To locate an aircraft's turning center, a line is extended along the nosewheel 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.

The FAA (9) has 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°. The FAA recommended that clearances allow 10 ft forward roll for nosewheel alignment prior to turn for taxiing out and another 10 ft forward roll prior to stopping. A design procedure for determining the separation of aircraft parking stands that utilizes polar coordinate graph paper has been described by the ICAO (8).

One method of designing stand spacing and depth is to obtain accurate scaled outlines or silhouettes of all aircraft that may use the stand and a similarly scaled outline of the apron area (8). The outline of each aircraft that is to use the gate position is traced on the sketch, with the main wheels on a common stop line and the line through the undercarriage passing through the turning center. The sketches are drawn so that the aircraft turning centers are located at a common stand turning center. From these outlines, the maximum wing-tip radius for that particular group of aircraft becomes readily apparent, as do the nosewheel paths. Nosewheel guidelines painted on the pavement are commonly used to aid pilots in terminal apron maneuvers. These lines must be designed to accommodate all the aircraft that will use the apron. The sketches also reveal the angle of parking that will give the most economical use of the space in both width and depth of the gate position. A slight variation of

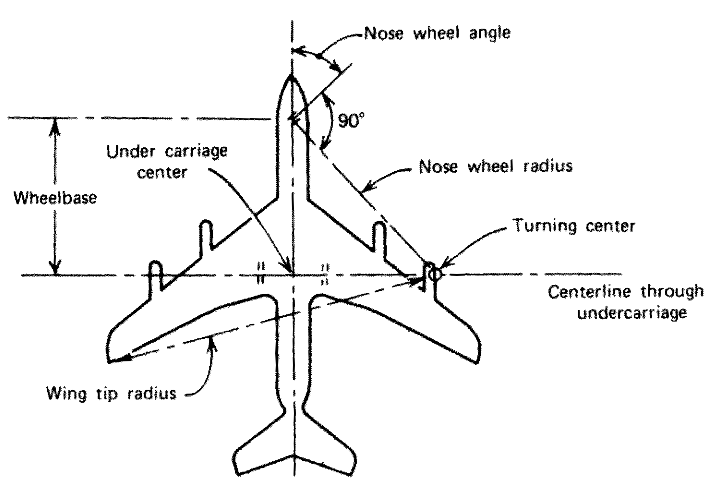


FIGURE 8.11 Geometry of minimum aircraft parking turns. (*Source*: Reference 8)

this procedure involves the use of plastic models or templates of the various aircraft in plan view.

An apron and terminal planning report (1) 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 com-

TABLE 8.12 Ground Servicing Equipment Summary: Dimensions of Ground Equipment

Item	Width (ft,in.)[a]	Length (ft,in.)	Height (ft,in.)
Passenger Stairs			
Self-propelled	7,6	20,3	13,0
Truck mounted	8 to 14,10	25 to 35,0	12,8 to 21,3
Baggage Equipment			
Containers (wide body)	5,0	6,7	5,4
Containers (narrow body)	3,6	7,10	3,4
Dolly (self-propelled)	7,2	10,2½ to 13,7½	1,8
Dolly (truck-mounted)	4,0	8,6 to 12,9	1,11
Small tug	4,8	8,6	6,10
Typical cart	4,10	10 to 14,0	6,9
Transporter (single container)	9,3	13,8½	5,10½
Transporter (double container)	8,3	19,7	5,10
Container loader (wide body)	8,0	24,6	9,9 to 11,0
Container loader (narrow body)	6,0	14,9	7,11
Loading conveyor	7,0	10,8	10,0 to 13,0
Cabin Service			
High-lift catering	8,0	26,0	11 to 18,0
Lavatory service	7,11	23,6	5,10 to 13,8
Cabin service	8,0	31,8	12,7 to 25,10
Typical Aircraft Tugs			
Wide body	10,0	30,0	5,2
Narrow body	8,0	20,0	7,4
Fuel Trucks			
Tanker	10,0	41,8	9,0
Hydrant truck	7,5	20,6	8,6 to 22,2
Miscellaneous			
Ground power (truck-mounted)	8,0	21,3	11,1
Ground power (dolly-mounted)	4,10	10 to 14,0	7,0
Pneumatic power	8,0	21,9	8,4
De-icing unit	8,0	28,4	12,0
Reel cart for fixed utilities	3,0	4,6	6,0

[a] 1 ft = 0.3048 m.

Source: *The Apron and Terminal Building Planning Report*, prepared for the FAA by Ralph M. Parsons Company, Report FAA-RD-75-191, July 1975 (rev. March 1976).

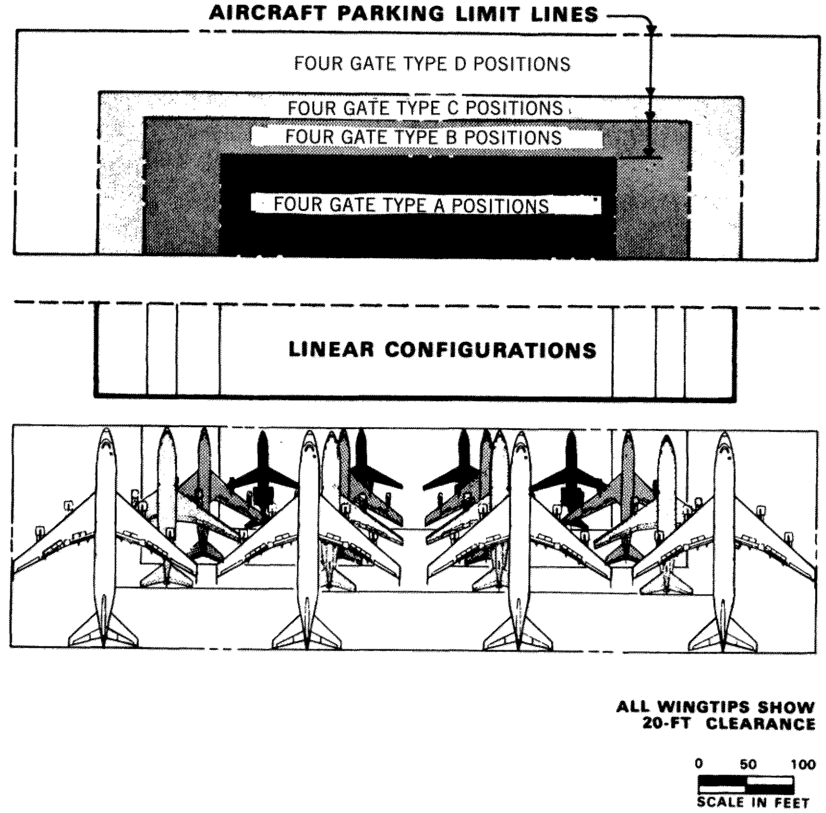


FIGURE 8.12 Scaled sketches showing apron space requirements for six groups of aircraft. (*Source*: Adapted from References 10 and 11)

plexes. It includes scaled 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 in Advisory Circular AC 150/5360-13 (10) showing scaled typical gate position layouts for selected aircraft and gate types. Figure 8.12 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 8.13 illustrates. Table 8.12 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. Table 8.13 shows recommended parking envelopes for six aircraft groups for push-out and taxi-out conditions.

A service road, typically 20 to 30 ft wide, must be provided either adjacent to

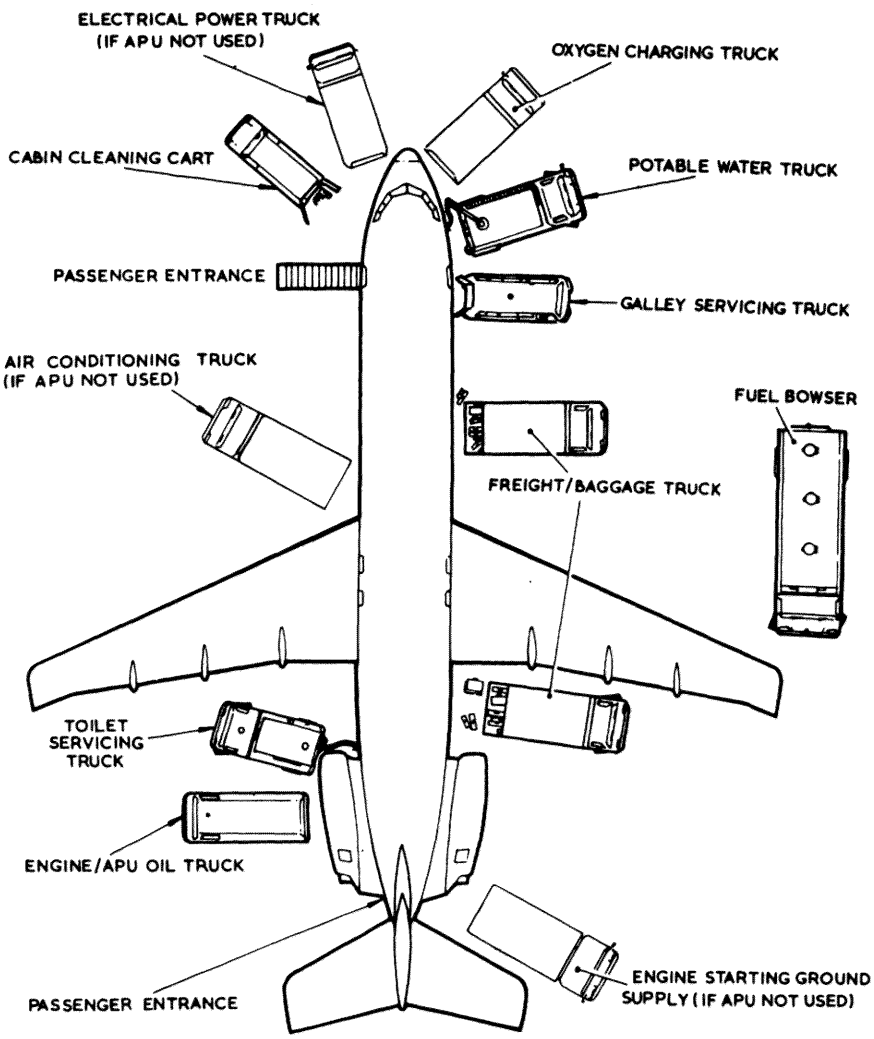


FIGURE 8.13 Ground servicing arrangement for model BAC 111 series aircraft. (*Source*: Reference 11)

the terminal or on the air side of the gate positions. If the road is placed next to the terminal 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 air side of the parked aircraft, special precautions may need to be taken to minimize conflicts between ground vehicles and aircraft and to prevent collisions.

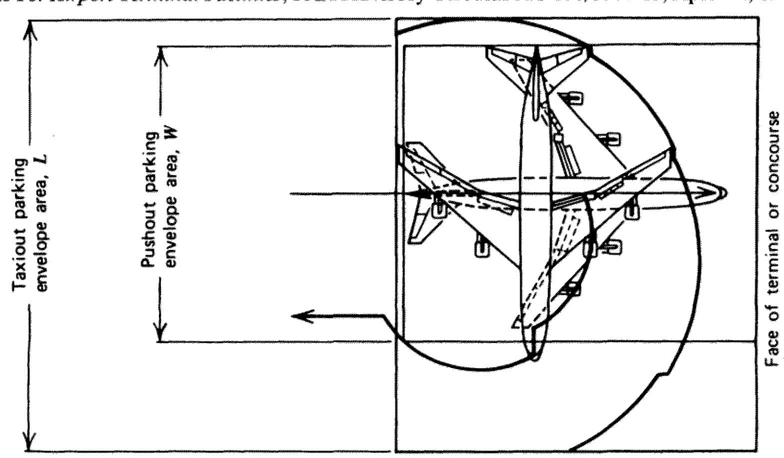
The effects of jet blast should also be considered in determining gate position size and location (4). It is sometimes necessary to install jet blast deflector screens or fences to protect workers and possibly passengers.

TABLE 8.13 Comparative Parking Envelopes: Push-out[a] Versus Taxi-out[b]

Aircraft Group	Push-out (ft,in.)[c] L^d	W^d	Area (yd²)	Taxi-out (ft,in.) L^d	W^d	Area (yd²)
A						
FH-227	103,1	115,2	1319	148,10	140,2	2318
YS-11B	106,3	124,11	1474	171,0	149,11	2850
BAC-111	123,6	113,6	1557	130,0	138,6	2001
DC-9-10	134,5	109,5	1634	149,2	134,5	2228
B						
DC-9-21,30	149,4	113,4	1880	149,0	138,4	2290
727 (all)	173,2	128,0	2463	194,0	153,0	3298
737 (all)	120,0	113,0	1507	145,4	138,0	2228
C						
B-707 (all)	172,11	165,9	3188	258,0	190,9	5468
B-720	156,9	150,10	2627	228,0	175,10	4454
DC-8-43,51	170,9	162,5	3081	211,10	187,5	4411
D						
DC-8-61,63	207,5	168,5	3882	252,4	193,5	5423
E						
L-1011	188,8	175,4	3676	263,6	200,4	5865
DC-10	192,3	185,4	3959	291,0	210,4	6801
F						
B-747	241,10	215,8	5795	328,0	240,8	8771

[a]Including clearances of 20 ft wing tip to wing tip; nose to building: 30 ft, groups A and B; 20 ft, groups C and D; 10 ft, groups E and F.
[b]Including clearances of 20 ft to other aircraft and GSE, 45 ft.
[c]1 ft = 0.3048 m.
[d]Length and width are based on the largest dimension in the group of aircraft.

Source: *The Apron and Terminal Building Planning Report*, prepared for the FAA by Ralph M. Parsons Company, Report FAA-RD-75-191, July 1975 (rev. March 1976); and *Planning and Design Guidelines For Airport Terminal Facilities*, FAA Advisory Circular AC 150/5360-13, April 22, 1988.



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.

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9

AIRPORT SAFETY*

9.1 INTRODUCTION

In spite of the best efforts of pilots, air traffic controllers, aircraft manufacturers, and airport designers, aircraft accidents continue to occur. Humans and machines are not perfect. It is not surprising, therefore, that even with the advances in modern technology, there has been little change in the aircraft accident rate in recent years. It is, therefore, necessary that more emphasis be placed on reducing the severity of accidents by improving the chances of survival for those involved in an accident and any subsequent fire. It is in this area that airport design can play a very important role. The following suggestions are made to supplement the regulations and recommendations of the responsible authorities and are based on the experiences of accident investigators and line experience of airline pilots.

9.2 THE NATURE OF AIRCRAFT ACCIDENTS

It is helpful for airport engineers to know where, when, and how the majority of aircraft accidents have occurred in the past. Surveys taken during the last 25 years by the Airline Pilots Association indicate that only 5% of accidents occur en route. These are usually caused by structural fatigue failure, violent weather, or hitting mountains or other high obstructions. There are few survivors from these accidents, and they are of little concern to the airport engineer.

Fifteen percent of all accidents occur in the airport approach areas, usually within 15 mi of the airport. While some of these are weather related, most of them involve engine failure, mid-air collisions in the traffic pattern, or premature descent into high terrain. These accidents are of primary concern to community emergency services; however, due to the fact that most community

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structural fire equipment is not very effective on a large fuel fire, the airport's rescue and fire fighting personnel will usually respond under a mutual aid agreement.

The remaining 80% of recent accidents take place on the active runway or its overrun areas and clear zones. A plot of accident locations shows that almost all of these accidents occur withing 500 ft of the active runway centerline and 3000 ft of the runway thresholds (see Figure 9.1). For airport emergency crews, this is called "the Critical Rescue and Fire Fighting Response Area." This is where many lives and aircraft are lost due to unnecesary obstructions and where improved airport design can be most effective. In past years, there has been little effort to remove obstructions from runway approach areas other than those which violate height restrictions. These hazards not only severely damage an aircraft in the event of any deviation from normal flight operations but also impede the response of emergency services.

Airport accidents can be divided into three categories: *undershoots, veeroffs,* and *overruns.* The *undershoot* is a landing accident that occurs when the aircraft contacts the ground or some elevated obstruction prior to the aircraft reaching the runway. Due to the relatively high speed of the approach, the aircraft frequently continues its momentum and comes to rest on or about the first part of the runway area. Severe structural damage usually occurs in this type of accident.

The main causes of these accidents are wind shear and pilot judgment. Wind shear instrumentation is now being installed at many major airports;

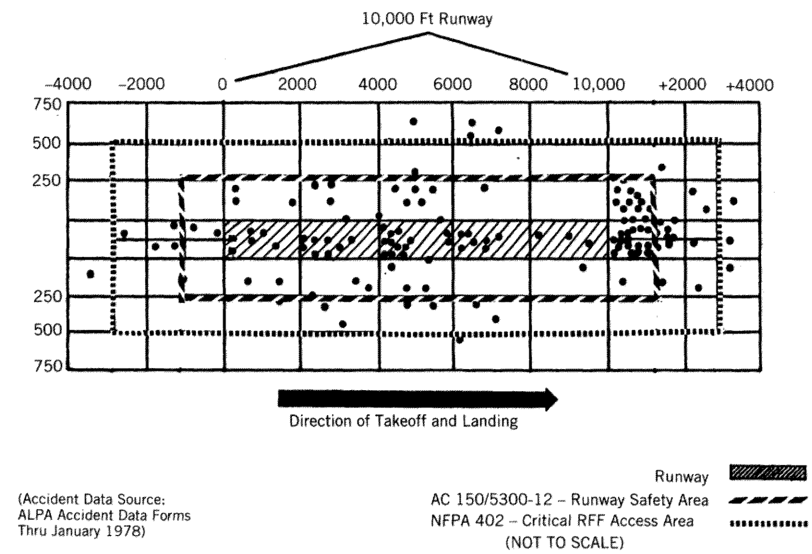


FIGURE 9.1 Accident site distribution within the critical rescue and fire fighting access area and the runway safety area. (Accidental Data Source: ALPA Accident Data Forms through January 1978.)

however, the microburst so far has been impossible to predict. It is a vertical burst of wind that suddenly erupts from the base of a thunderstorm. Its effect is similar to a tornado without the twisting motion. An aircraft flying through such an area can lose airspeed and stall into the ground. This may occur during a landing or takeoff.

The runway *veeroff* occurs when the pilot loses directional control on either landing or takeoff due to tire or brake failure or skidding on an icy runway, especially in crosswind conditions.

The *overrun* is the most common airport accident. It may occur on landing due to hydroplaning on a wet runway, skidding on ice or snow, or excess landing speed. Most of the overruns, however, occur during a rejected takeoff. This may occur due to a mechanical failure prior to lift-off or a blown tire. This latter cause has been responsible for half of the accidents involving fire in the last 10 years. When aircraft are certificated by the FAA, takeoff runway length requirements are based on tests conducted on a clean, dry runway as well as new brakes and tires and an instant pilot reaction time. In actual flight operations, this is never the case. These overrun accidents usually involve relatively slow speeds and should be survivable.

In 1989, the Airline Pilots Association conducted a survey of 1146 turboprop and turbojet aircraft accidents occurring at airports for the years 1959-1989. The accident locations are as follows:

No. of Accidents	Accident Location
466	The overrun areas
402	Veered off the runway
278	Undershot the runway

Most of these accidents involved fatalities that could have been avoided if the aircraft had not come in contact with some form of obstruction that could, with a little foresight, have been reduced or eliminated.

A survey of 50 overrun accidents conducted by the National Transportation Safety Board (NTSB) shows aircraft hitting the following obstructions in the overrun areas.

No. of Accidents	Obstruction
10	Lights, stanchions
7	Embankments, dikes
6	Fences
6	Ditches
4	Trees, stumps
3	Boulders, rocks
2	Hills, mounds
2	Navigation facilities
2	Other aircraft

2	Autos
1	Buildings
1	Roadways

9.3 RUNWAY BORDER AREAS

It was previously noted that most airport accidents occur within 500 ft of the runway centerline and within 3000 ft of the end of the runway. This is the critical response area for emergency services. It is also the area where the airport engineer can reduce or eliminate hazards and, therefore, prevent an incident from becoming an accident. It can, at the same time, provide a more rapid access for the emergency vehicles.

In order to process a safe obstruction-free approach area, national and international regulations limit the height of obstructions along the sides of runways and in the approach areas and clear zones. However, there are not requirements for depressions or surface obstructions in these areas. Neither is there any regulation limiting the type of building or obstruction in the approach zone as long as it does not violate the glide slope limitations.

FAA advisory circulars only require 1000 ft of overrun area (the runway end safety area) cleared of obstructions, and this applies only to new construction. Because of "grandfathering" provisions in the regulations, there is no requirement for cleaning up the clear zone, despite the fact that it is in this area where most fatal accidents occur.

At present, there is no requirement for a smooth transition area between the overrun area and the clear zone. Many runway end safety areas terminate with a steep embankment with a grade that is impossible to negotiate by either the aircraft or the emergency vehicles. In other runway clear zones, it is not uncommon to find a ditch, river, ravine, railroad, highway, or other major obstruction that even at slow speeds would cause major structural damage to the aircraft and severe injury to its occupants.

The following suggestions will serve to reduce hazards in the overrun areas and clear zones.

Extended Runway Safety Areas and Clear Zones

Where sufficient land is available, the runway end safety area should be extended to 3000 ft in length, 1000 ft in width at the threshold, and extend to 2000 ft in width at the boundary. This area should be cleared of all obstructions except for navigational facilities. All rocks, tree stumps, earth mounds, and depressions, or any object which could damage a transgressing aircraft should be removed (see Figure 9.2).

Regardless of its size, there must be a smooth transition area between the safety areas and the surrounding terrain. This should consist of a gentle slope, with the elimination of sharp angles between the surfaces. Forty-five degree embankments between the safety area and the clear zone cannot be safely

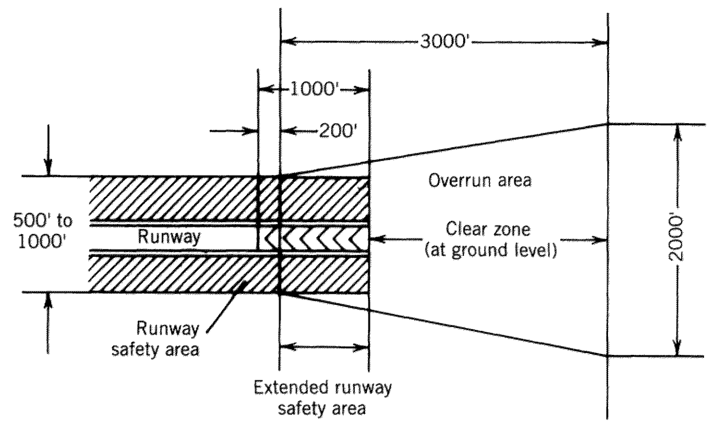


FIGURE 9.2 Preferred dimensions of extended runway safety area and clear zone.

traversed by either the aircraft or the airport emergency equipment. If the area can be transited by emergency equipment at high speed, it is assumed that the aircraft can do likewise (see Figure 9.3).

Drainage Ditches

Ditches through the runway end safety area have been responsible for minor accidents, from breaking off the landing gear to major accidents which result in the complete disintegration of the fuselage. Most of these depressions can be rerouted or replaced with drainage structures and covered. Construction ditches opened up for the installation of electrical wiring have also caused loss of life when the aircraft has veered off the runway.

At those airports where large ditches or small streams exist that cannot be moved or rerouted, the hazard can be changed to a safety factor. If the banks of the stream are graded to a gentle slope and the stream bed hard surfaced, the

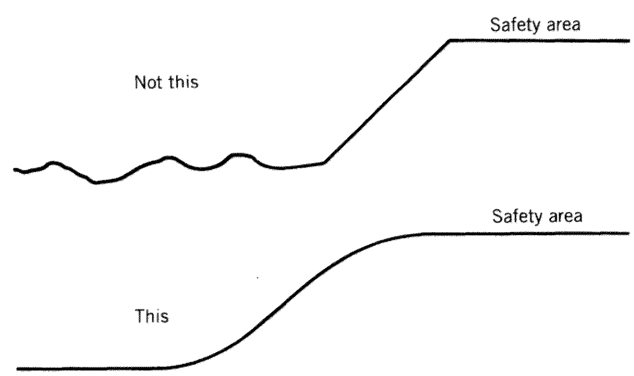


FIGURE 9.3 Preferred treatment of transition slopes in vicinity of runway ends.

aircraft will be able to pass through the water without damage. The water depth must be reduced to a maximum of 2 ft, which is the maximum wading depth of the emergency equipment. There are two advantages with this proposal: first, the decelerating effect of the water acts as an arresting device and quickly slows the aircraft; second, the emergency equipment can reach the scene without having to make a detour.

Runways Terminating at the Edge of Large Bodies of Water

Many airports are located adjacent to large bodies of water, such as lakes and tidal shorelines. The runway end safety area usually has at its boundary, a concrete sea wall which will severely damage an aircraft. This obstruction should be eliminated and the runway end safety area graded off into the water; construction should be similar to that of a boat loading ramp. This will enable an overrunning aircraft to slide into the water without structural damage and, therefore, be able to remain afloat for an extended time or at least until the occupants have escaped. This ramp would also minimize the damage to an undershooting aircraft which, without the ramp, would tear its landing gear off on the concrete wall. Where runways are adjacent to water areas subject to large tidal variations, the safety area should extend at least 3000 ft from the runway to provide for frangible approach light installations and to provide a stabilized surface for radar altimetry during low-visibility approaches.

Roadways

Roadways of various types are one of the most common obstructions found in the runway clear zones. They consist of anything from small airport service roads to major four-lane interstate highways. In order to meet the FAA approach slope clearance requirements, many of these roads and highways are depressed so that transitting vehicles will not interfere with the landing aircraft or the navigation aids. While this is supposed to be a safety factor, it is, in fact, a hazard, since the depression forms a tank trap for any overrunning or undershooting aircraft.

Airport service roads and emergency vehicle access roads should be of all-weather construction but must be level with the surrounding terrain, with no drainage depressions or gullies that would damage the aircraft landing gear.

Major highways within the 3000 ft extended safety area should be depressed and bridged with a structure that will support the weight of the largest aircraft using the airport. Where this is impractical or the highway is located at the end of the 3000 ft clear zone, any steep embankment should be replaced with a gradual slope, and all surface obstructions, such as light poles, any signage, or other objects that would damage the aircraft, should be removed. Where these highways are located outside the airport boundary, a strong position should be taken with the local highway authority, explaining the dangers involved, together with the litigation possibilities following fatalities caused by these obstructions.

Railroads

For many of the same reasons, railways also provide a problem when they run through the extended runway safety area. Since the railroads were often built before the airport, communication with the railway authorities is often difficult. They should, however, be contacted, and the possiblity of the tracks causing damage to the aircraft resulting in serious injury or fatalities should be explained. This hazard can be reduced by grading the embankments and paving the tracks the width of the safety area to make a grade crossing similar to those found crossing a highway. This will enable the aircraft to cross the tracks without breaking up, and also the emergency equipment can follow without slowing down or going some circuitous route, thereby reducing response time and improving the survival factor. From the railroad's viewpoint, this will keep the accident from occurring on the tracks and stopping rail traffic.

In summary, the overrun area and clear zones should be constructed so that a person could drive an automobile over the area at a reasonable speed without danger or damage.

9.4 RUNWAY DESIGN FOR SAFETY

Many pilots and air safety experts believe that runways should be designed and built to stricter standards than currently promulgated by the ICAO and FAA. For example, they recommend that, in order to reduce false visual reference, the runway should be level throughout its length, with the longitudinal gradient not exceeding 1%. If a gradient change is unavoidable, it should be limited to 1%. A runway crown of 1% to 1.5% should be provided in order to provide adequate drainage under adverse weather conditions, prevent ponding and subsequent loss of braking and hydroplaning.

Where parallel runways are constructed, the distance between the runway centerlines should be a minimum of 5000 ft in order to prevent mid-air conflict in the approach areas.

9.5 WIND SOCKS

It is very important for a pilot making a landing or takeoff to have an accurate knowledge of the true wind direction and velocity at all times. Frequently, at large airports, there is quite a difference between the data recorded in the control tower and that experienced on the runway. This is most evident during a thunderstorm or a frontal passage. Frangible-mounted and lighted wind socks should be installed near the approach end of each runway, preferably opposite the 1000 ft mark and 150 ft off the left side of the runway.

9.6 PAVING

Where runway, taxiway, and ramp areas are paved with asphalt, they should not be sealed with a sealer that would provide a slick surface when wet. Lack of braking action could result in the taxiing aircraft being unable to stop, resulting in collisions with other aircraft, sliding off the taxiway, or even hitting the terminal building. This problem is enhanced with a tail wind. If the sealer is used, the pavement should be grooved.

9.7 LANDSCAPING

One item that is seldom considered by the airport engineer is the landscaping of the area. Trees should not be planted in the clear zones. Instead, small bushes that will not damage an aircraft are acceptable. They should be of a type that will not attract birds either for cover or bear berries that attract migrating flocks, which are especially dangerous. Aircraft flying through a flock of birds have experienced engine flame outs, some resulting in fatal accidents.

9.8 FIRE AND RESCUE OPERATIONS

Commercial aircraft carry large numbers of occupants, together with large quantities of fuel. Of the 21 major aircraft crash fires that occurred between 1979 and 1989, over 650 of the occupants lost their lives due to thermal exposure. It is essential that adequate, well-equipped, and well-trained fire departments be maintained at all airports, especially those engaged in commercial transportation.

Survival time in an aircraft crash fire is very limited. Even if the fuselage is intact, the fire will often penetrate the wall and windows in less than 3 min. This makes a rapid response to the accident site one of the prime requirements of an airport crash rescue service. Since almost all of the survivable aircraft accidents occur on the runway or in the overrun areas, the location of the firehouse becomes a matter of major importance.

Response time in the United States is now a matter of regulation. The FAA requires a response to the mid-part of the farthest runway in 3 min or less. The ICAO recommendation requires response to any part of the movement area in 3 min or less. The National Fire Protection Association (NFPA) Standard 403 requires a response to any part of the runway in 2 min or less and the overrun area in 2 1/2 min. As previously stated, the reason for this rapid response is obvious; a fire can burn through the aluminum skin of the aircraft in 30-50 sec, and it can penetrate the insulation and inner fuselage wall in an additional 2-3 min under optimum conditions. If there is any break in the fuselage, these times are greatly reduced.

Airport crash trucks are designed and built to very exacting standards, which include acceleration rates and top speeds. NFPA 414 requires an acceleration rate of 0-50 mph for large major vehicles in 45 sec and for smaller vehicles, 0-50 mph in 25 sec. Such rapid acceleration is wasted if the airport engineer sites the fire station in the wrong location.

Since the advent of the jet aircraft, there have been very few fires occurring on the ramp areas. There are, in fact, only three recorded cases of a ramp fire to a large jet: one to a DC 8 in Canada, one to a Boeing 747 in Barbados, and one to a Boeing 737 in Salt Lake City in 1990. When such a fire does occur, the occupants can rapidly evacuate the aircraft in the required demonstration time of 30 sec. This is because they have not been subjected to the trauma of an accident, they are all mobile, and they usually leave through the jetway they used to board the aircraft. This means that the aircraft will be evacuated prior to the arrival of the emergency equipment and, therefore, the response is secondary to that of a crash fire.

When the occupants have been involved in a crash, they are disoriented, injured, or trapped, and often cannot escape without assistance from the emergency services. For this reason, response to a crash site is the primary responsibility of the aircraft rescue and fire fighting personnel.

9.9 SITING OF AIRPORT RESCUE AND FIRE FIGHTING FACILITIES

It has already been noted that 80% of all accidents occur on the operational strip within 500 ft of the centerline and within 3000 ft of a threshold. In order to obtain the most rapid response, the fire station should be located adjacent to the mid-point of the runway. Where more than one runway exists, consideration must be given to providing multiple fire stations if required to meet the response time criteria.

The FAA's Advisory Circular 150/5210-15 (1) provides a checklist of factors that should be considered in choosing sites for aircraft rescue and fire fighting facilities (ARFF). For example, the site should allow for

1. Immediate, straight, and safe access toward the air side.
2. Unimpeded access routes, with a minimum of turns to runways, taxiways, and aircraft parking areas.
3. Direct access to the terminal aprons without crossing active runways, taxiways, or difficult terrain.
4. Noninterference with the air traffic control tower's (ATCT) line of sight.
5. Maximum surveillance of the air operations area.
6. Shortest response time to the most probable aircraft accident areas.

7. Compliance with building restriction lines (BRL).
8. Future additions or expansion of the station without
   a. Limiting or reducing airport surveillance.
   b. Blocking fire traffic lanes.
   c. Intruding on adjacent roads, buildings, aprons, runway or taxiway clearances, and air traffic control tower's line of sight.
9. Airport expansion, such as new runways or extensions that will not jeopardize its emergency service areas by creating emergency response runs of excessive length.
10. Noninterference by aircraft ARFF vehicle or station's telecommunications equipment with airport navigational facilities.
11. Minimum obstructions or interference from existing facilities or uses, such as access roads, fueling areas, and aircraft taxiing operations or parking areas.

The size of the lot for the rescue and fire fighting facility should allow for the accommodation of the present station as well as any future additions or expansions of the structure to accommodate increases in rescue and fire fighting equipment or personnel. Space must also be provided for employee parking and for servicing of ARFF vehicles.

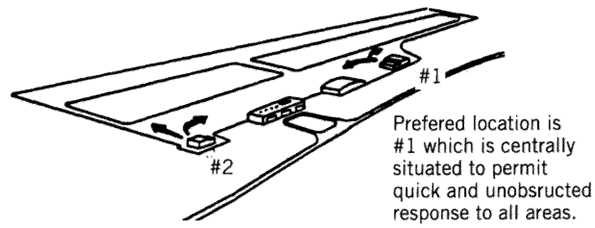
The site should offer reasonable access to existing airport service roads and to needed utilities: electrical power, telephone, water supply, and, if available, sewer hookups.

Some airports staff their ARFF vehicles with volunteers or auxiliary personnel employed by either the airport or the airlines. If this is the case, the ARFF vehicles should be easily accessible to the drivers and other personnel in meeting any required emergency response times (1).

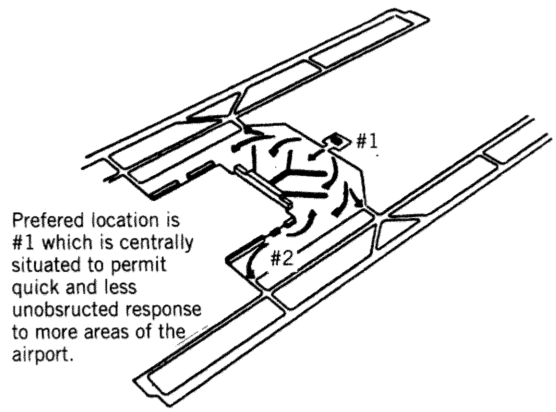
When locating ARFF buildings, planners must take care to ensure that rapid egress cannot be blocked by taxiing aircraft. Direct access to the runway is necessary with straight access roads that lead from the vehicle bay to the runway. The high center of gravity of most emergency vehicles makes high-speed turns very hazardous. Figure 9.4 shows examples of functional single and multiple-site locations for rescue and fire fighting stations.

9.10 AIRPORT RESCUE AND FIRE FIGHTING STATION BUILDING DESIGN

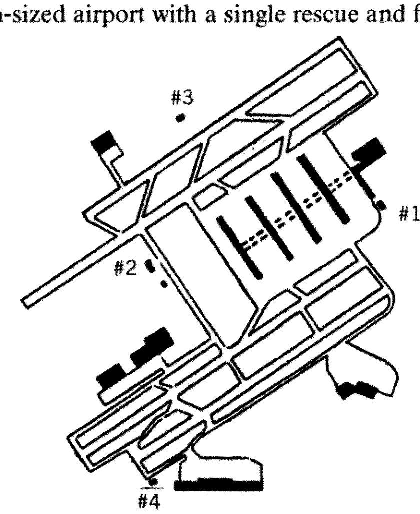
Fire stations should be constructed according to government and local regulations. Extra attention should be given to providing a visual electronic alarm system and/or an elevated watch office on top of the building. This is a vital part of the rapid response capability. Several valuable seconds can be saved if



a. Small-sized airport with a single rescue and fire fighting station.



b. Medium-sized airport with a single rescue and fire fighting station.



c. Large-sized airport with a main station, for example, #1, and three airport rescue and fire fighting satellite stations.

FIGURE 9.4 Examples of site locations for rescue and fire fighting stations. (*Source*: Reference 1)

the fire fighters know exactly where they have to respond without waiting for notification from the tower. Fire house doors linked to the alarm system should be capable of rapidly opening, especially in the event of a power outage. Doors should be located at both ends of the vehicle bays to provide a drive through capability for recharging the vehicles. An elevated reserve foam tank should be built into the ceiling of the vehile bay to provide for this capability. Extra height should be allowed for the construction of firehouse vehicle doors. Many new crash trucks are being fitted with elevated platforms or booms which increase the height of the vehicle by up to 6 ft. An extra bay should be provided for mobile disaster vans, which should have refrigeration capability for the preservation of emergency drug supplies.

FAA regulations now require that each certificated airport have an airport emergency plan and test it by conducting airport emergency drills (2,3). Each airport is required to have at least one fire fighter per shift trained as an emergency medical technician. It is recommended that adequate first aid facilities and equipment be provided for the maximum number of passengers on the largest aircraft scheduled into the airport. It is, therefore, desirable to make the airport fire stations the primary first aid holding points until transportation to hospitals can be arranged. Design of the fire station should include provison of storage facilities for first aid equipment and drugs. Fire fighter sleeping quarters should be capable of being turned into an emergency first aid room and should be located for easy access of stretchers and wheelchairs. At least one adjacent ambulance bay should be provided.

For additional information on airport rescue and fire fighting station building design, the reader is referred to FAA Advisory Circular 150/5210-15 (1), which provides detailed design criteria for station elements and systems.

9.11 THE AIRCRAFT RESCUE AND FIRE FIGHTING TRAINING FACILITY

Aircraft rescue and fire fighting personnel must be properly trained in the application of extinguishing agents to fires that simulate actual emergency conditions. ARFF training is best accomplished at a special training facility that is carefully selected and designed to exacting standards. The FAA has published an advisory circular (4) that sets forth standards, specifications, and recommendations for training facility design on which much of this section is based.

As Figure 9.5 illustrates, an ARFF training facility consists of a burn area, a vehicle maneuvering area that surrounds the structure, as well as fuel and water distribution systems and other support systems.

The burn area normally consists of an aircraft mock-up equipped with strategically placed fuel nozzles and other devices to simulate a variety of aircraft fires. As Figure 9.6 shows, the mock-up rests on a bed of aggregate, which serves as a quick drainage medium and a level walking and training surface. It also serves as a heat shield for a double layer of flexible membrane placed under the burn area to contain and drain off fuel, water, and other fluids used in training exercises. The various components that comprise the burn area system are commonly supported by a concrete floor. Normally, the burn area

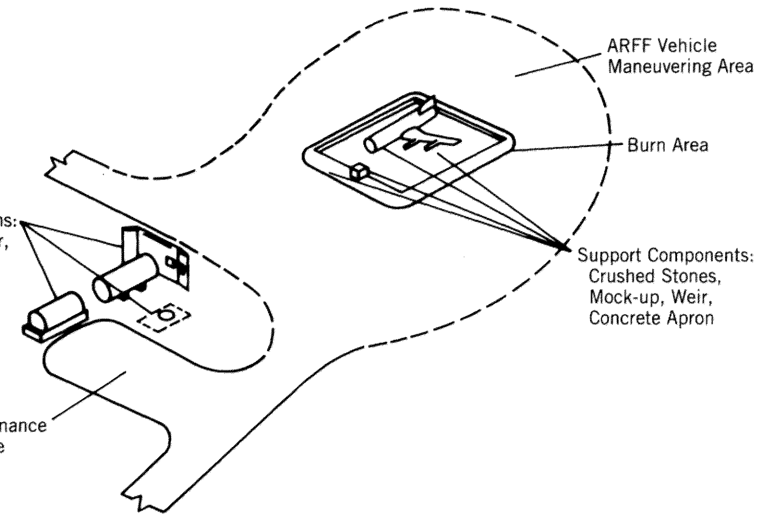


FIGURE 9.5 Elements of an aircraft rescue and fire fighting training facility. (*Source*: Reference 4)

is surrounded by a concrete curb which contains fluids within the burn area and a concrete apron which collects and disposes of any training fluids washed over the curb. The burn area is surrounded by an earth berm that contains the fluids and separates the burn area from the ARFF vehicle maneuvering area.

Size of Burn Structure Area

The FAA recommends the use of an ARFF index to establish the size of the burn structure area.* The ARFF index is determined by the aircraft size, specifically the lengths and fuselage widths of the aircraft in each group. Seven ARFF indices have been established: two for general aviation and five for commercial aircraft.

For each ARFF index, a *theoretical critical fire area* has been determined based on research and experimental work done by the FAA. The theoretical critical fire area is defined as "the area adjacent to the fuselage extending outward in all directions to those points beyond which a large fuel fire would not melt an aluminum fuselage regardless of the fire exposure time" (5). In other words, it is that area adjacent to the aircraft in which fire must be controlled in order to ensure temporary fuselage integrity and provide an escape area for the occupants of the aircraft.

*Where available land is limited, the FAA permits the use of an alternative sizing method which depends on the type of extinguishing agent and the discharge rate of the applicator(s) to be used in the training (4).

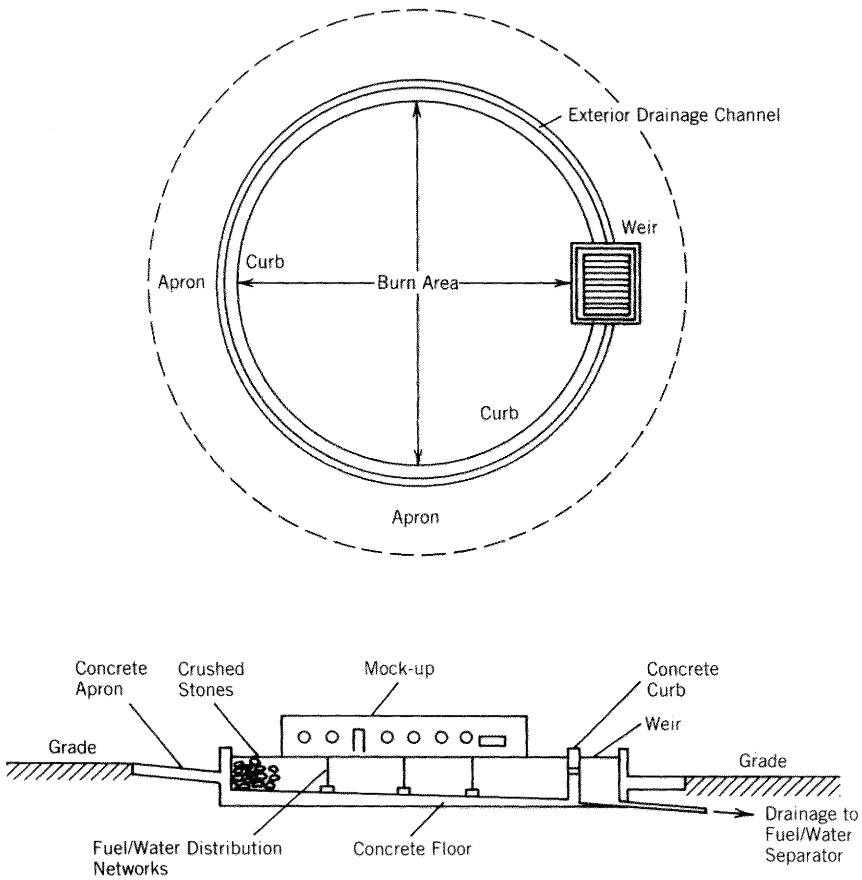


FIGURE 9.6 A concrete burn area structure. (*Source*: Reference 4)

For each ARFF index, the theoretical critical area, *TC*, is calculated by the following formulas:

$$TC = L \times (100 \text{ ft} + w) \text{ for } L > 65 \text{ ft} \tag{9.1}$$

$$TC = L \times (40 \text{ ft} + w) \text{ for } L < 65 \text{ ft} \tag{9.2}$$

where

L = the average length of the aircraft (ft)
w = the average width of the aircraft fuselage (ft)

Research conducted for the FAA by an independent engineering firm determined that, in survivable aircraft crashes, a *practical fire area* should be considered which is smaller than the theoretical critical area. After further study of extinguishing agent quantities used on previous fires, both actual and

TABLE 9.1 Burn Area Structures as a Function of Airport ARFF Index

Airport ARFF Index[a]	Overall Aircraft Lengths (feet) Lower Limit	Average	Upper Limit	Average Fuselage Width (ft)	Practical Critical Fire Area (PCA) (square ft)	Rect. Burn Area (L/W = 4/3) (ft)	Circular Burn Area Diameter (ft)
GA-1	30	38	45	6	1,171	40 × 30	39
GA-2	45	53	60	10	1,775	49 × 36	48
A	60	75	90	10	5,527	86 × 64	84
B	90	108	126	10	7,959	103 × 77	101
C	126	143	160	10	10,539	118 × 89	116
D	160	180	200	20	14,475	139 × 104	136
E	200	225		20	18,090	155 × 116	152

[a] Airport ARFF index dimensions are defined in AC 150/5210-6B, Aircraft Fire and Rescue Facilities and Extinguishing Agents.

Source: *Design Standards for an Aircraft Rescue and Fire Fighting Training Facility*. FAA Advisory Circular AC 150/5220-17, April 1, 1988.

training, the ICAO Rescue and Fire Fighting Panel indicated that a practical fire area approximately two-thirds of the theoretical area could be used (5). On this basis, the sizes of recommended burn area structures have been specified, as shown in Table 9.1

It should be noted, however, that recent experience with the quantities of extinguishing agents used in actual fires raises questions as to the validity of using a practical fire area rather than a theoretical fire area. A survey of 42 aircraft crash fires in the 12-year period 1978-1990 revealed that, in most cases, over four times the amount of extinguishing agent was used than required by the FAA of the ICAO. Only in three cases was less agent used. In the early 1990s, this matter was under further evaluation.

Size of ARFF Maneuvering Area

The maneuvering area must be large enough for the ARFF vehicle to park, back up, maneuver into position, and allow other ARFF vehicles to pass. The size of the maneuvering area is also affected by the maximum and minimum distances the equipment can discharge foam in both straight and dispersed stream patterns and under both stationary and "pump and roll" operations. The layout of the maneuvering area should provide more than one vehicle approach path and allow room for future expansion for additional and more demanding ARFF vehicles (4).

Siting of ARFF Training Facility

An ARFF training facility must satisfy all federal, state and local environmental and fire regulations. A first step in selecting a site for a training facility should, therefore, be to review and comply with all such regulations. Generally speaking, the site should be on relatively flat land in a remote area. It should be located where generated smoke will neither become a hazard to aircraft operations nor interfere with or cause physical damage to navigational aids. Recommended minimum distances from the burn area perimeter to various objects and activities are given in Table 9.2.

TABLE 9.2 Clearances for Burn Area Structures

Recommended Minimum Distances from Burn Area Perimeter to	
Aircraft parking and/or movement area	500 ft[a]
Airport building	300 ft
Automobile parking lots	300 ft
Occupied residential areas	1000 ft
Trees and large shrubbery	300 ft

[a] 1 ft = 0.3048 m.

Source: *Design Standards for an Aircraft Rescue and Fire Fighting Training Facility*, FAA Advisory Circular AC 150/5220-17, April 1, 1988.

To minimize any environmental impact from ARFF training activities, the facility should be located above the 100-yr flood plain and as far as possible from any water supply wells. A layer of a low permeability soil, such as clay or silt may need to be constructed beneath the burn area structure to inhibit downward migration of contaminants. Strict regulations in the use of the facility should be observed to reduce the amount of fuel remaining in the burn area and to contain and treat or recycle effluent from training exercises.

Finally, the availability of water, electric utilities, and sewer services should be considered in the selection of a training facility site. Good utilities improve safety, reduce facility operating costs, and enhance the quality of training (4).

9.12 OTHER SAFETY CONSIDERATIONS

Major ARFF vehicles are designed to carry a large quantity of water and a double quantity of foam solution allowing for one refill. It is, therefore, essential that the vehicles can be refilled with water as soon as possible. A water hydrant system should be installed around the CFR critical response area for this purpose.

When an aircraft accident occurs off the end of a runway but outside the airport perimeter, a problem of rapid access for the fire trucks exists. Even with the increased emphasis on airport security access, roads and gates must still be available at the end of each overrun area. These gates should have frangible mountings in order not to waste valuable seconds if the emergency crews have to stop their vehicles and open the gates with a bolt cutter or keys. Even in the event of the accident being inside the boundary, it is important that responding ambulance services be able to enter the site as soon as possible.

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10

PASSENGER TERMINAL

10.1 THE FUNCTION OF THE 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

 Airport Engineering, Third Edition. Norman Ashford and Paul H. Wright

passengers continuously and processes them in batches. On the arrivals side, the pattern is reverse. 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 should be 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 THE TERMINAL USER

The successfully designed air terminal facility must perform satisfactorily to meet the needs of those who can be expected to use it. The passenger terminal has three principal user classes: the passenger and those who accompany him or her, 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 passenger is seen as a major source of airport income during the time that he or she spends 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 THE PASSENGER TERMINAL

The airport terminal acts as the transfer point between the land side and air side 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 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 level of service for passengers and visitors, the airlines, and the airport operator (1).

The facilities can be categorized as follows: access (including the land side interface), passenger processing areas, passenger holding areas, internal circulation and air side interface, and airline and support areas.

Access and the Land Side Interface (2)

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, shuttle services to parking lots and other terminals, and loading and unloading areas for buses, taxis, limousines, and rapid surface modes.

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.

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 care for the level of service supplied by these necessary facilities warrants careful design of holding areas. The following are among the facilities that may be required:

1. *Passenger Lounges.* General, departure, and gate lounges.
2. *Passenger Service Areas.* Wash rooms, public telephone, nurseries, post office, information, first aid, shoeshine, valet service, storage, barber shop, beauty parlor.
3. *Concessions.* Bar, restaurants, newsstands, novelties, tax and duty-free shops, hotel reservations, banks and currency exchange, insurance, car rental, automatic dispensing machines.
4. *Observation Decks and Visitors' Lobbies.* Including VIP and CIP* facilities.

*CIP: Commercially Important Persons.

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 easy to negotiate. The air side interface is designed for secure and easy boarding of the aircraft.

Internal circulation is handled by corridors, walkways, people movers, and moving belts, ramps, and tramways.

Air side interface requirements include loading facilities such as jetways, stairs, air bridges, and mobile lounges. At international facilities, transit passenger lounges may be necessary.

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):

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 and offices for security staff.
4. Governmental office and support areas for staff working in customs, immigration, health, and air traffic control; bonded storage and personal detention facilities.
5. Public address systems, signs, indicators, flight information.
6. Maintenance personnel offices and support areas, 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, no longer encumbered by baggage, the passengers move into the general departure lounge and finally into the gate

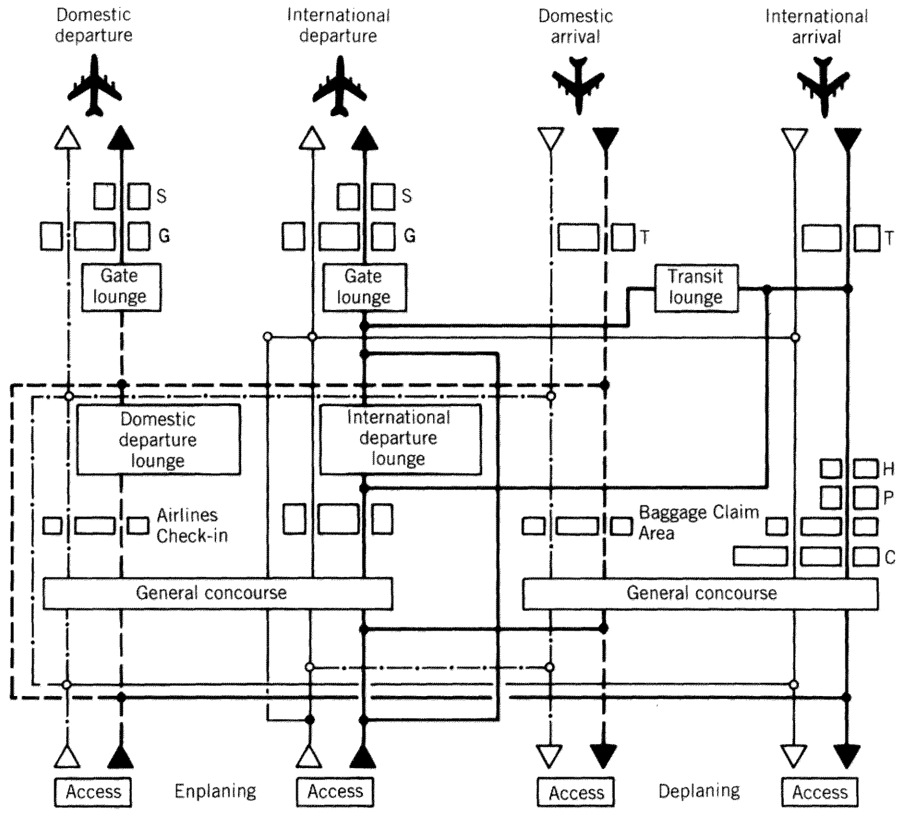


FIGURE 10.1 Passenger/baggage flow system. (*Source*: Adapted from Reference 4)

lounge. On international flights, entry into the departure lounge may be preceded by customs control. (In many countries, airports must have customs 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 await 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.

Deplaning domestic passengers proceed directly to the baggage claim and pass immediately into the general departures concourse; international arrivals must first pass through health and immigration controls and proceed through customs inspection before entering the general concourse. In many European airports, those who have goods to declare and those who have nothing to declare pass along red and green channels, respectively. This innovation has significantly speeded flow through the customs area, with no apparent increase in serious smuggling offenses.

International deplaning passengers en route to yet a third country normally pass into a holding transit lounge without officially entering the country of transit. Therefore, they 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, 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 between connections. Since departing customs controls are usually far less stringent, the domestic/international passenger usually does not face the same problem.

10.5 SECURITY CONSIDERATIONS IN PASSENGER TERMINAL DESIGN AND LAYOUT (2)

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 airport passengers. Countermeasures against terrorism and other illegal acts against civil aviation are now virtually universal. Theoretically, all passengers on international flights have been through security checks for weapons detection, and the aircraft and its load have been subject to security procedures which ensure that it has been kept safe from interference. Different countries have adopted different degrees of security which can even differ depending on the type of airport (e.g., local domestic or international) within an airport. In the United States, FAA regulations define security procedures. In most countries, this is the responsibility of the central civil aviation agency, although the state, provincial, and local police authorities may be involved. 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 passenger terminal space:

1. Physical separation of arriving and departing passengers on the air side. 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 space and equipment, decentralized at the individual gate lounges.
3. Prohibition of visitors into the secure air side parts of the terminal. In some 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 air side, 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 when this activity is carried out.
6. Provision of extra space at check-in for very high security flights to allow passenger interviewing and search.
7. Division of terminal into a "clean air side—dirty land side" arrangement. This is a by-product of the decision to centralize or decentralize security combs. The provision of a "clean air side" may significantly reduce the market potential of commercial concessions on the air side.
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.
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 the use of extensive areas of glass, which

in the past have caused considerable injuries to passengers attacked in the terminals 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 simply "bus-stop" type of operation may be infeasible.

Many existing terminals were designed prior to the need to provide aviation security. 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 will 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 (4)

The design of a terminal depends on the nature of the air traffic to be handled at an airport. 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 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 concept embraces the range of possibilities, from using independent terminals for various airlines (the unit terminal concept) to simply providing 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

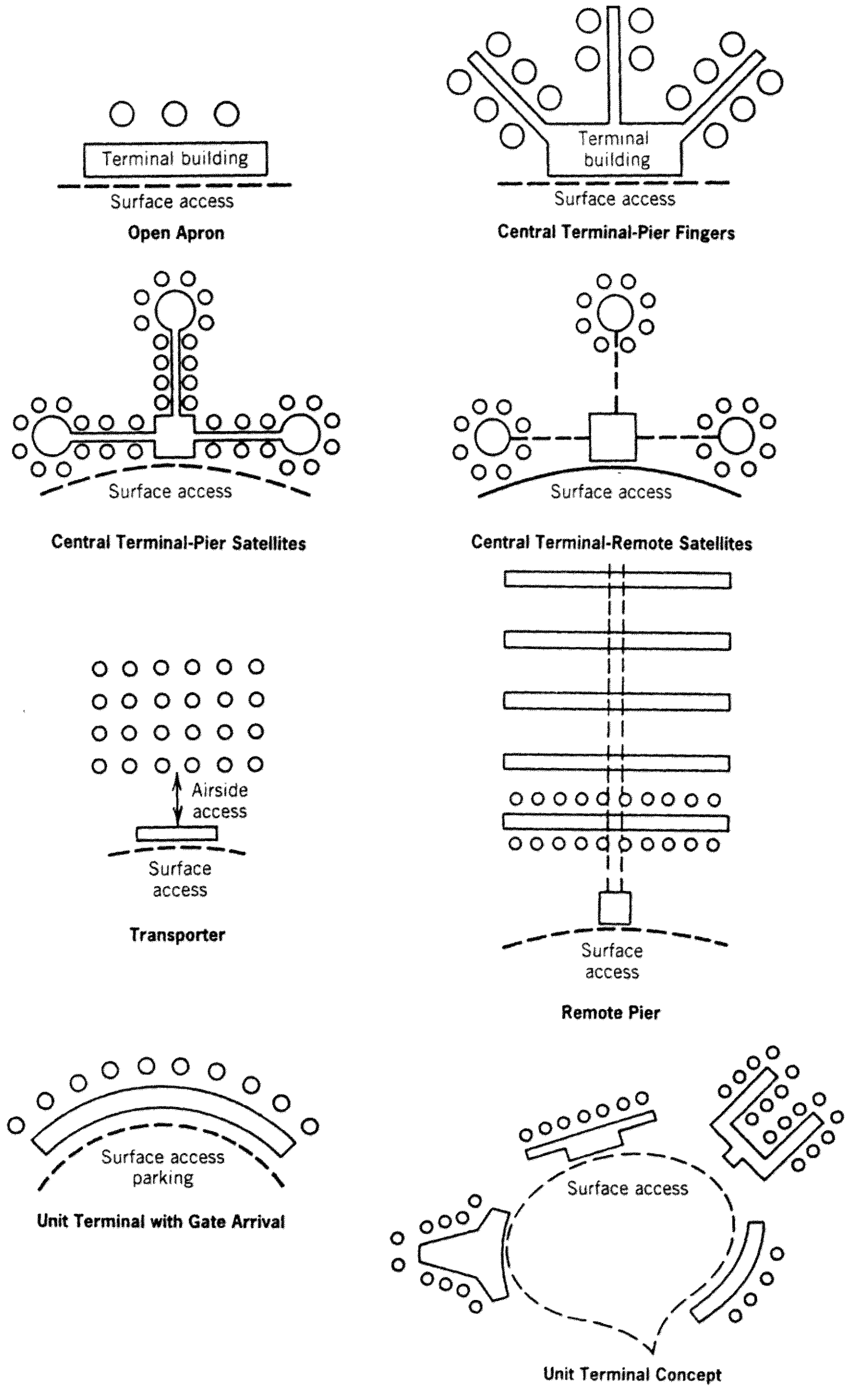


FIGURE 10.2 Terminal configurations.

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 air side 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 departure gate, thereby minimizing walking distances. Part of the Seattle terminal operates on the open apron concept, and the new Munich II facility 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. The longitudinal passenger flows along the axis of the terminal conflict with the concept of transverse flows in the gate arrival terminal with conveniently narrow terminals.

Central Terminal with Pier Fingers

Centralized terminal operation can be achieved with a large gate requirement by effectively increasing the air side 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 assembly facilities, and possibly even gate check-in facilities. 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 the Denver and Amsterdam airports are examples, can be very economic to build; however, 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.

Pier finger terminals can be very efficient for annual passenger volumes up to approximately 35 million for domestic operations and 25 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 tiimes 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 Tullamarine in Melbourne and at 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 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., Tampa, Orlando, London Gatwick) or below the apron (e.g., 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, 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

Perhaps the most significant example of the remote apron type of design is Mirabel International Airport, in Montreal. The servicing of remote stands by buses is common, both in the United States and Europe, for example, Kennedy, 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. The principal advantages accrue from the separation of the aircraft servicing apron from the terminal, giving greater flexibility on the air side to changes in the size and maneuvering characteristics in aircraft; in addition, less time is required for taxiing on the ground. The principal disadvantages seem to be the poor level of service 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. Tranporter terminals are extremely unpopular with airlines because of long ground turnaround times and poor passenger service.

Central Terminal with Remote Piers

A fairly recent innovation in terminal layout is the central terminal linked under the apron to remote piers. This is a good 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. Parallel alignment of the piers assures efficient use of apron space. The subapron corridor connecting the terminals and piers is suited to automated movement of both passengers and baggage. Atlanta Hartsfield Airport and London Stansted are examples of this form of design.

Unit Terminal

The unit terminal concept is defined by 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's 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. More modern designs have attempted to provide a high level of interline connection service by surface connection systems (e.g., Dallas-Fort Worth International Airport). Unit terminal systems can be designed to operate gate check-in facilities, which was the conceptual design of the Kansas City airport.

10.7 VERTICAL DISTRIBUTION OF ACTIVITIES

In small airport terminals, for example, 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, unilevel terminals can be most difficult to extend in the face of growing passenger demand, and the intermingling of growing enplaning, deplaning, and transfer flows presents significant problems. Figure 10.3 shows the various ways of distributing activities vertically in the terminal.

The most common solution adopted to 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 land side access with two levels of bus and car curbside pickup and set down; design solutions in the past have used single-level access at the land side 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 land side access interface.

The one-and-a-half-level arrangement works well at lower volume airports,

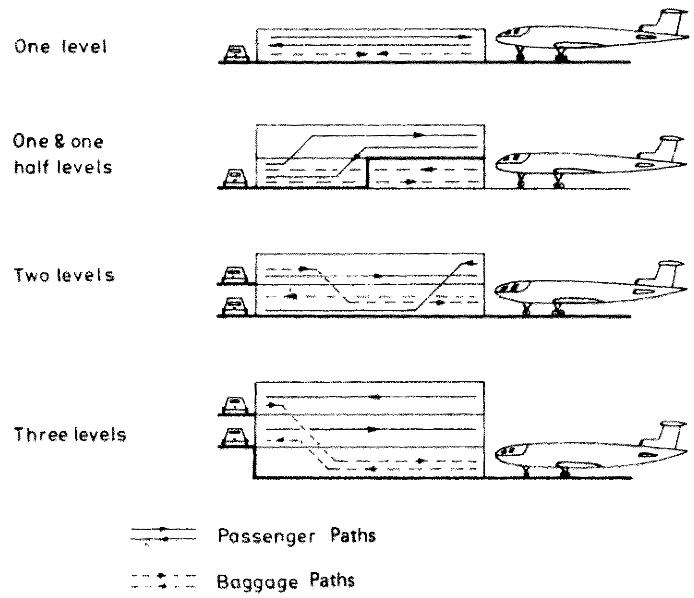


FIGURE 10.3 Typical vertical separation arrangements of passenger and baggage flows.

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.

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 must be provided in the piers. This requires 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.

10.8 PASSENGER BEHAVIOR IN THE TERMINAL (2,5,6)

Air passengers consider time spent in the terminal 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. It is therefore essential that airports convey the same image of being part of the premier mode that is presented by airlines in their efforts to market air travel. This being the case, airport terminals have been constructed in a more lavish manner than bus or railway stations. This is especially true in the United States; European air terminals tend to be less spacious and more utilitarian than those in the United States.

Terminal design is customarily constrained by the needs of passengers, workers, and visitors, as discussed in Section 10.2. 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).

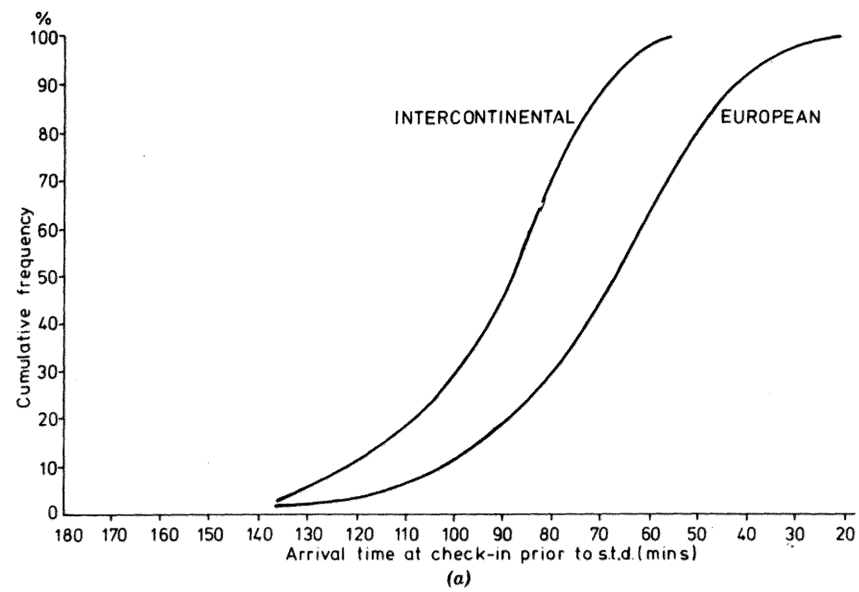
It has been stated that terminal design should reflect awareness of passenger needs and behavior. However, passenger behavior varies according to the purpose of the trip, the flight logistics, and the type of flight. *Air travel purpose* is normally divided into leisure and business categories. Business 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.

It is a general rule that the longer the distance traveled, the greater the time allowed by passengers prior to time of scheduled departure. Figure 10.4a 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 scheduled flight or charter. 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. Figure 10.4b shows the cumulative distribution for chartered and scheduled passengers at a typical European airport.

Since the introduction of advanced purchase excursion tickets (APEX) and standby fares, the development of charter operations has been inhibited. However, the terminal dwell times of all these types of "nonstandard" passengers tends to be much greater than for passengers holding transferable tickets on scheduled flights.

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 and leisure traffic, operating on a mixture of chartered and scheduled flights,



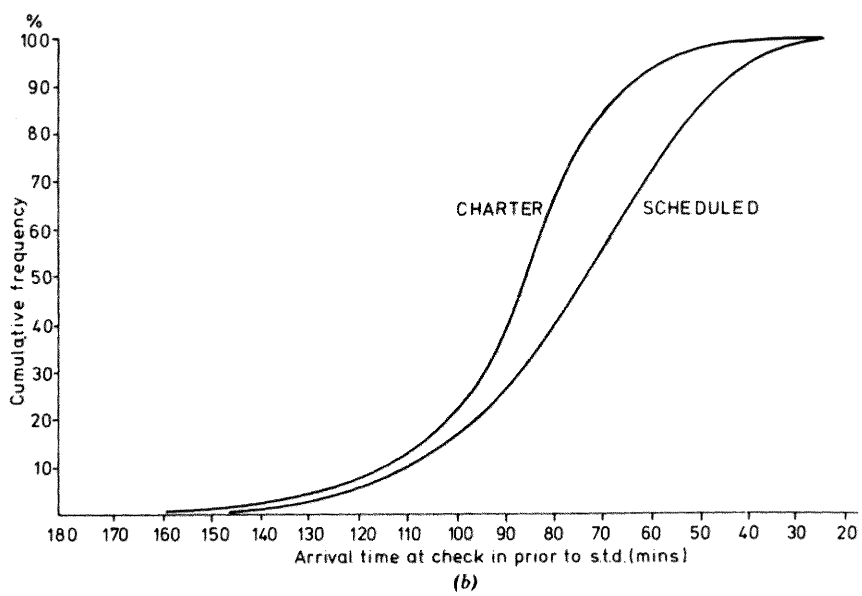


FIGURE 10.4 Relationship of arrival time for enplaning passengers and type of flight. (a) short and long haul, international. (b) charter and scheduled. (*Source*: Reference 5)

traveling over domestic, short-haul international, and intercontinental distances. Modifications and extensions to the terminals take into account variations in traffic mix across these variables.

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 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 (Table 1.3), with increasing airport size, terminal revenues supplant landing fees as the principal source of operational revenues, which normally account for approximately 95% of total 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 with the growing trend of privatizing 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, Amsterdam, 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.

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 thirtieth highest hour used in the design of highways. Some European designers still use the Standard Busy Rate (SBR), which is, in fact, the thirtieth highest hour of the year.(2)

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, intercontinental or short haul, and by access mode.

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 space requirement criteria used for the design of air terminals have varied capriciously. However, the FAA and other bodies have set down

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

The above values apply separately to domestic and international passengers at any given location.

guidelines that, if related to the design peak figures, will give adequate and comfortable space provision to the terminal user. Table 10.2 indicates these FAA standards. Others have attempted to approach the provision of space from an ergonomic viewpoint (5,6), suggesting a differentiation of area provided, depending on whether the passenger is in a processing circulation or a holding area (7). More recent approaches to design have reflected stated preferences of passengers to determine good, adequate, and poor levels of service provision (8). Most airports which have set their own design standards recognize that provision of space is correlated with the amount of time spent in a facility. Consequently, many published space design standards are stated in parameters of both space provision and maximum processing times (9).

IATA has published a set of space design standards based on the level of service concept, where level A is excellent, level D is desirably the lowest level achieved in peak operations, and level F is the point of system breakdown or congestion. These standards are shown in Table 10.3 (10,11).

TABLE 10.2 FAA Terminal Space Design Standards (7)

Domestic Terminal Space Facility	Space Required per 100 TPHP, (1000 ft^2)	(100 m^2)
Ticket lobby	1.0	0.95
Airline operational	4.8	4.57
Baggage claim	1.0	0.95
Waiting rooms	1.8	1.70
Eating facilities	1.6	1.52
Kitchen and storage	1.6	1.52
Other concessions	0.5	0.48
Toilets	0.3	0.28
Circulation, mechanical, and maintenance, walls	11.6	11.05
Total	24.2	23.02

International Terminal Space Facility	Additional Space Required per 100 TPHP (1000 ft^2)	(100 m^2)
Public health	1.5	1.42
Immigration	1.0	0.95
Customs	3.3	3.14
Agriculture	0.2	0.19
Visitor waiting rooms	1.5	1.42
Total	7.5	7.12
Circulation, baggage assembly, utilities, walls partitions	7.5	7.12
Total	15.0	14.24

TABLE 10.3 IATA Level of Service Space Standards for Airport Passenger Terminals

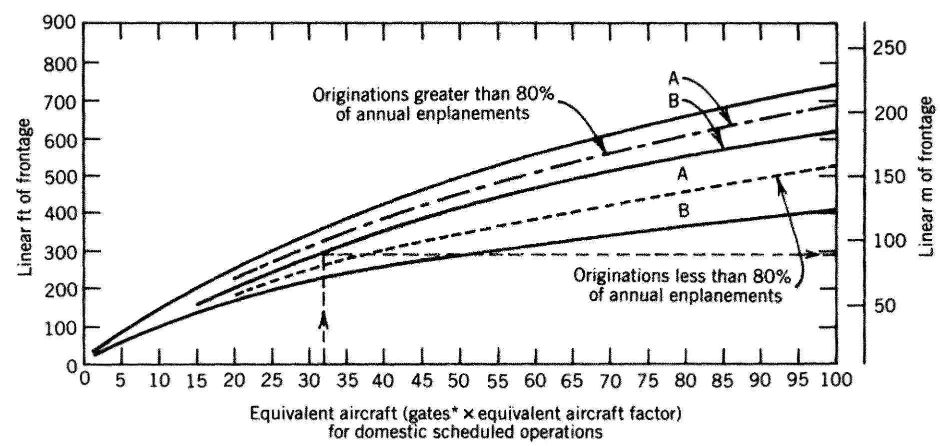
	Level of Service Standards (m^2 per occupant)					
	A	B	C	D	E	F
Check-in queue area	1.8	1.6	1.4	1.2	1.0	
Wait/circulate	2.7	2,3	1.9	1.5	1.0	
Hold room	1.4	1.2	1.0	0.8	0.6	
Bag claim area (excluding claim device)	2.0	1.8	1.6	1.4	1.2	
Government inspection	1.4	1.2	1.0	0.8	0.6	

In attempting to estimate the overall gross area requirements for terminals, it has been found that, for domestic operations, $14m^2$ or $150ft^2$ per peak hour passenger is a reasonable guideline. For international operations, this should be increased to $24m^2$ or $250ft^2$. 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%.

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 planning purposes, however, the FAA has developed a set of more specific recommendations on spatial provision for the various functions and facilities accommodated at the airport passenger terminal. Figure 10.5a–j shows relationships between passenger volumes and the requisite areas for



(a)

FIGURE 10.5(a) Terminal counter frontage.

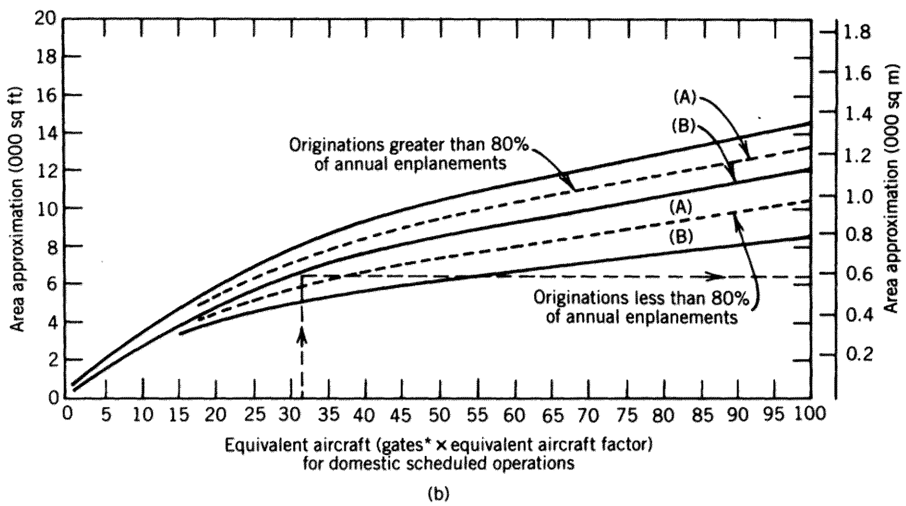


FIGURE 10.5(b) ATO office and support space.

the ticket lobby, the waiting lobby, departure lounges, the outbound baggage hall, the baggage claim area, food and beverage services, and the concessions and building services. Example 10.1 indicates how these charts may be used in the design of a domestic terminal.

EXAMPLE 10.1 DESIGN OF DOMESTIC TERMINAL USING FAA CHARTS (3)

Assumptions

1. Annual passenger throughput in design year = 4 million. This is assumed to equate with 2000 design hour passengers; 60% of arrivals or departures maximum imbalance of flow, 80% passengers terminate.
2. Aircraft mix in peak hour is as in the following tabulation:

Type of Aircraft	No. of Aircraft	Seat Range	Equivalent Aircraft Factor	Column 2 × Column 4
A	—	Up to 80	0.6	—
B	10	81–110	1.0	10.0
C	3	111–160	1.4	4.2
D	2	161–210	1.9	3.8
E	1	211–280	2.4	2.4
F	2	281–420	3.5	7.0
G	1	421–500	4.6	4.6

Total Equivalent Aircraft Factor = 32

Computation of Overall Areas

Overall gross area:

2000 passengers/peak hr × 14 m²/peak hr passenger = 28,000 m²

Estimated Breakdown by Functional Areas (Gross)

Airline	Other	Public	Services
ATO	Concessions	Circulation	Mechanical
Administration	Food and beverage	Waiting areas	Shafts
Operations	Airport administration	Restrooms	Tunnels
Baggage	Miscellaneous	Exits	Stairs
			Shops
			Electrical
			Communication
38% × 28,000 = 10,640	17% × 28,000 = 4760	30% × 28,000 = 8400	15% × 28,000 = 4200

Rentable and airport adminstration: 55% × 28,000 = 15,400

Nonrentable: 45% × 28,000 = 12,600

Computation of Individual Areas

1. *Airline Ticket Counters* (see Figure 10.5a):
   Linear meters of counter = 87
   Assuming depth of area = 3 m, Area = 87 × 3 = 261 m²
2. *Airline Ticket Offices and Support* (see Figure 10.5b):
   Area required = 590 m²
3. *Outbound Baggage Room* (see Figure 10.5c):
   Area required = 1300 m²
4. *Bag Claim*:
   Assume 60% arrivals: 32 EQA × 0.6
   = 19.2 EQA
   Assume 50% occur in peak 20 minutes = 9.6 EQA
   With 80% terminating passengers, Figure 10.5d gives 107 lineal meters of claiming frontage
   Assuming oval sloping bed devices (Type D), from Figure 10.5e, area = 1000 m²
5. *Airline Operations and Support Areas*:
   Use 2 × ATO/Support area = 2 × 590 m² = 1180 m²
6. *Departure Lounges* (see Figure 10.5f):

Type of Aircraft	No. of Gates	Area/Gate	Area
A	0	60 m^2	0
B	10	100 m^2	1000
C	3	140 m^2	420
D	2	190 m^2	380
E	1	250 m^2	250
F	2	360 m^2	720
G	1	460 m^2	460

= 3230 m^2

7. *Other Airline Space*:
Use 20% of item 5 = 236 m^2

8. *Lobby & Ticketing* (see Figure 10.5g):
Area from graph = 2300 m^2
less ticket counters (item 1) = 261 m^2
= 2039 m^2

9. *Lobby Waiting Area (Departure)* (see Figure 10.5h):
Assume seating for 25% design peak flow. Remainder in concessions, and so on, and departure lounges.
Seating for 500 pass/hr. = 1000 m^2

10. *Lobby Bag Claim*:
Estimated two greeters/passenger plus one passenger. Assume average waiting time 30 minutes, space requirement of 1.5 m^2/person and 60% of design peak flow arriving.
$3 \times 1.5 \text{ m}^2 \times 0.5 \text{ hr} \times 0.60 \times 2000$ = 2700 m^2

11. *Food and Beverage* (see Figure 10.5i):
Assume 40% usage factor = 2700 m^2

12. *Other Concessions and Terminal Services* (See Figure 10.5j):
Area from graph = 3000 m^2

13. *Other Rental Areas*:
Assume 50% item 12 = 1500 m^2

14. *Other Circulation Areas*:
Assume 0.7 × (total items 1 through 7) = 5458 m^2

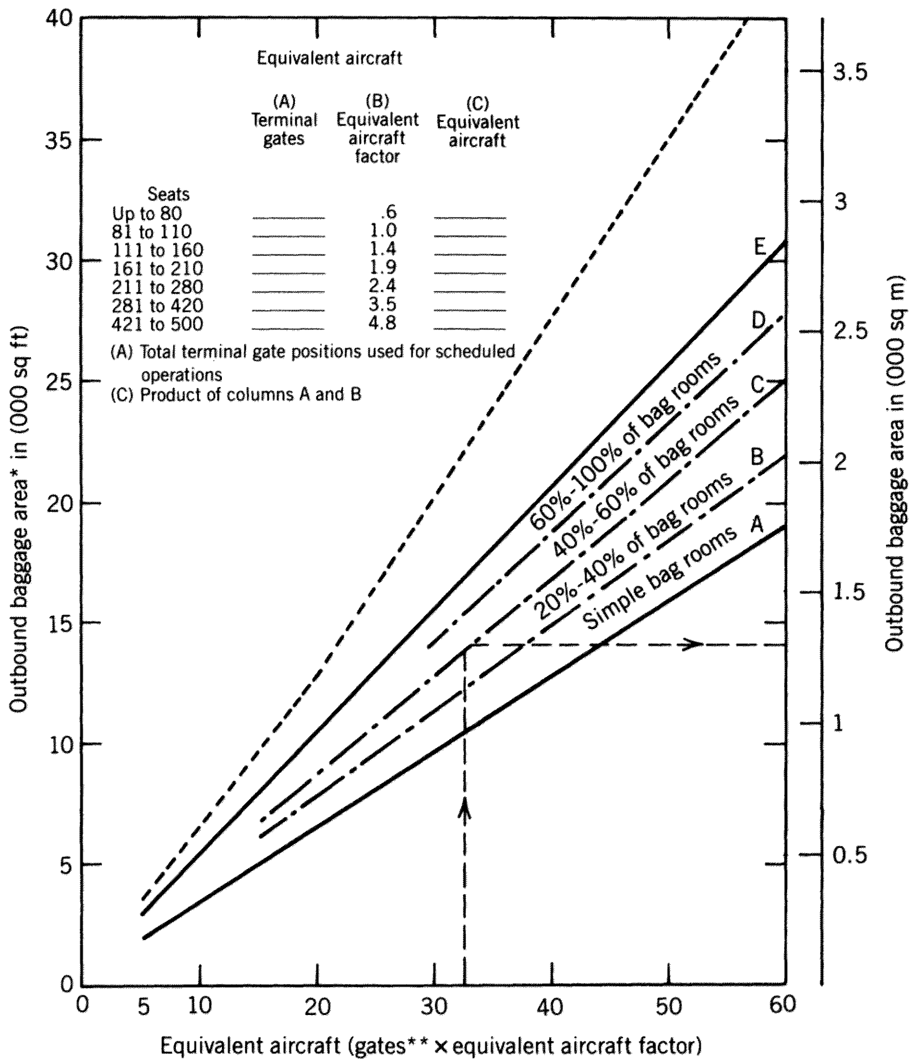
15.
Subtotal 26,198 m^2

16. *Heating, Ventilating, Air Conditioning and Other Mechanical Areas*:
15% × item 15 3,929 m^2

17.
Subtotal 30,127 m^2

18. *Structure*:
5% × item 17 1,506 m^2

This amounts to 15.8 m^2/peak hr passenger. Total = 31,633 m^2



(c)

FIGURE 10.5(c) Outbound baggage area.

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

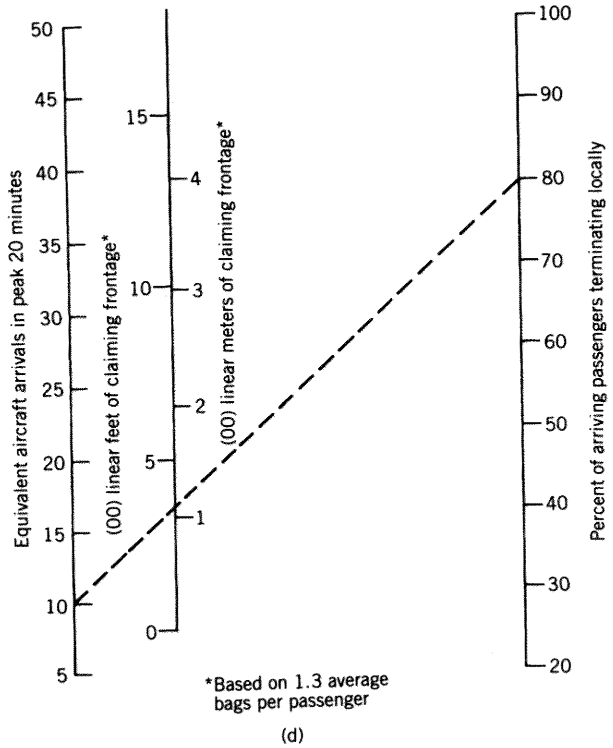


FIGURE 10.5(d) Inbound baggage claim area.

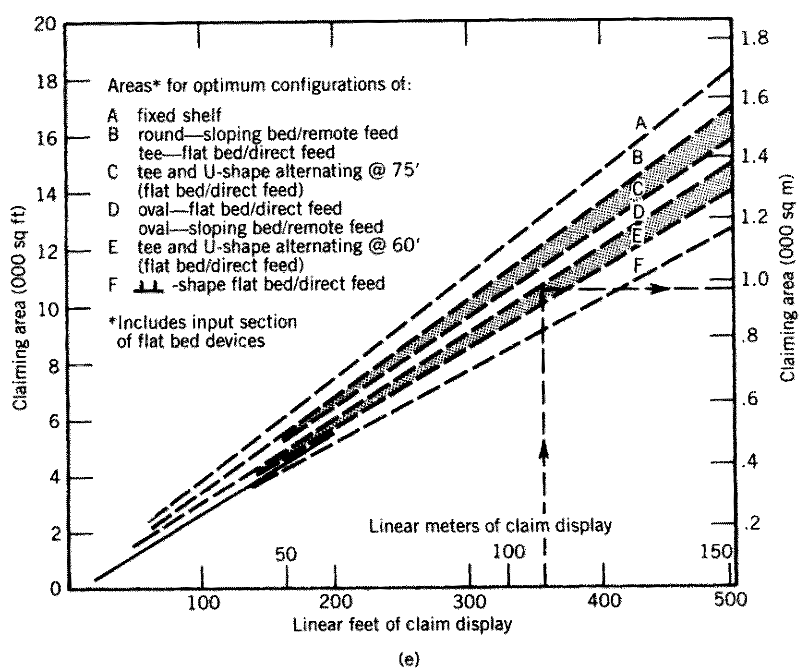
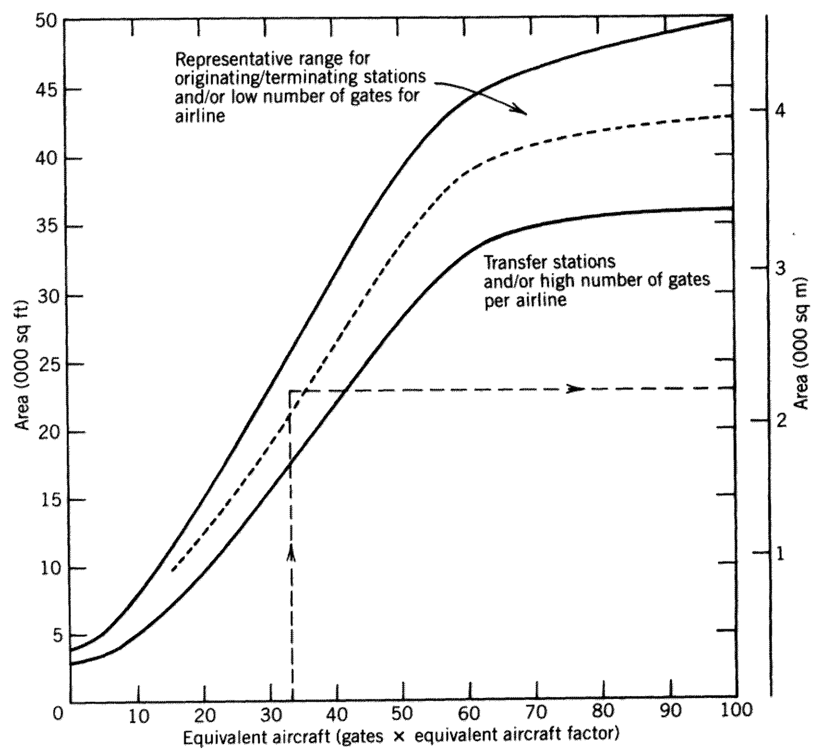


FIGURE 10.5(e) Baggage claim area.

Aircraft Type Model	Seat Capacity Range	Average Departure Lounge Size
CV-580: DC-9 -10; BAC-111; YS-11-B; M-404; F-227B	40–80 Av. 60	640 sq ft 60 sq m
B-737; B-727 -100; DC-9 -30; CV-880	90–110 Av. 100	1080 sq ft 100 sq m
DC-8 -50; DC-8 -62; B-727 -200; B-727 -300; B-707 (all); B-720	120–160 Av. 140	1500 sq ft 140 sq m
DC-8 -61, B-757	170–210 Av. 190	2050 sq ft 190 sq m
DC-10, L-1011, A300, B-767, MD11	220–280 Av. 250	2690 sq ft 250 sq m
B-747	300–420 Av. 360	3870 sq ft 360 sq m
High capacity Wide body	420–500 Av. 460	4950 sq ft 460 sq m

(f)

FIGURE 10.5(f) Departure lounge area by type of aircraft served.



(g)

FIGURE 10.5(g) Ticket lobby and counter area.

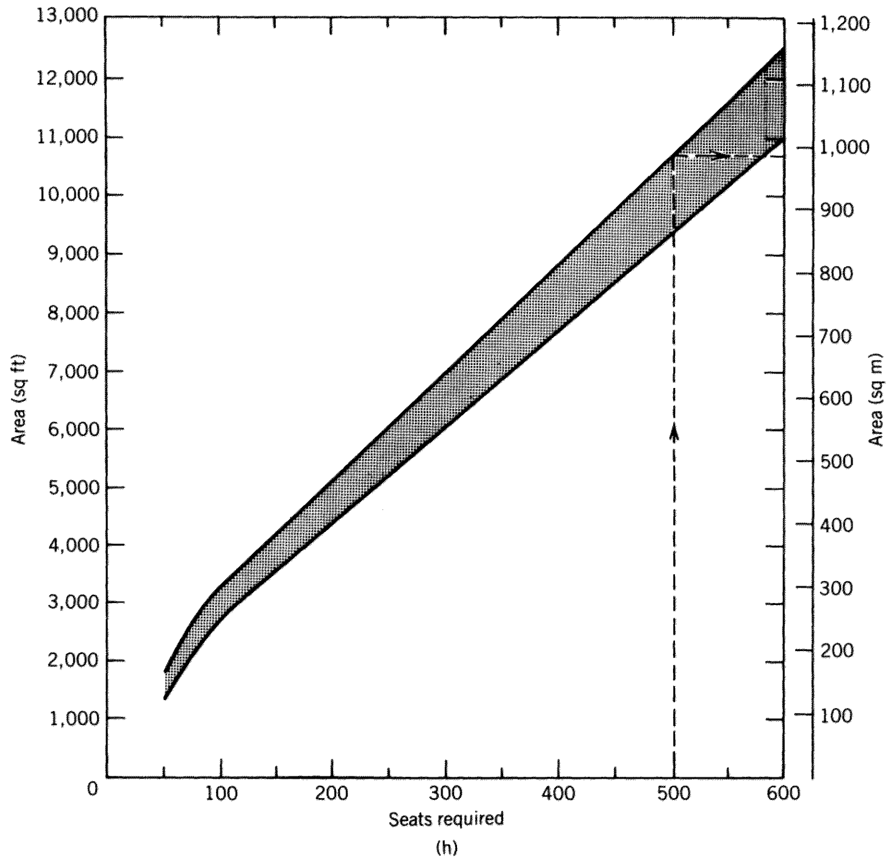


FIGURE 10.5(h) Waiting lobby area. (Note: For requirements of over 600 seats, use multiples of 200 or more. Graph includes primary circulation areas from counters to concessions, connectors, etc.)

efficiency and at an extremely high level of reliability. Figure 10.6 diagrams the possible baggage flows from pickup and check-in through 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, all or some of these facilities will be present (1).

Sorting for the individual flights in the baggage sortation 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.

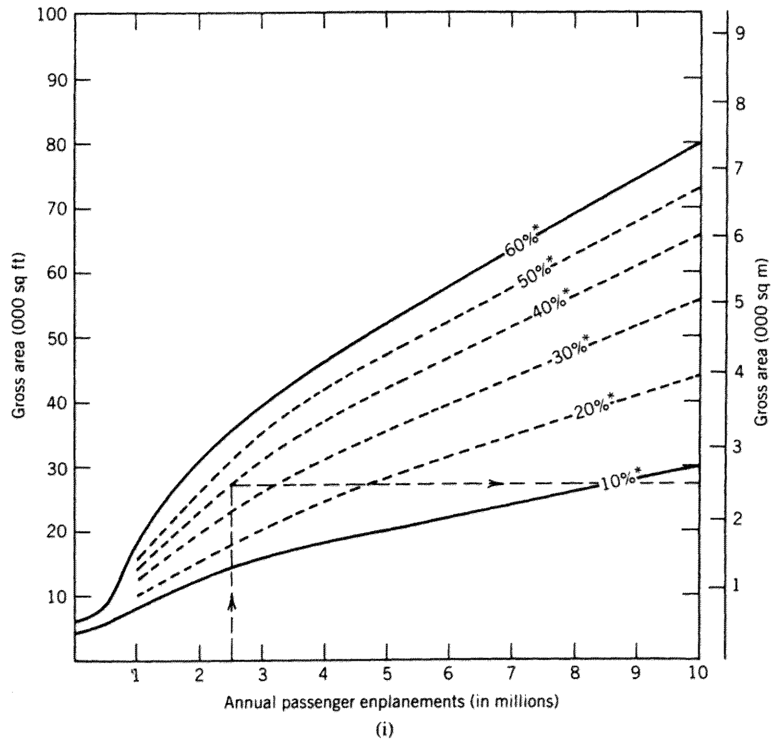


FIGURE 10.5(i) Food and beverage services.

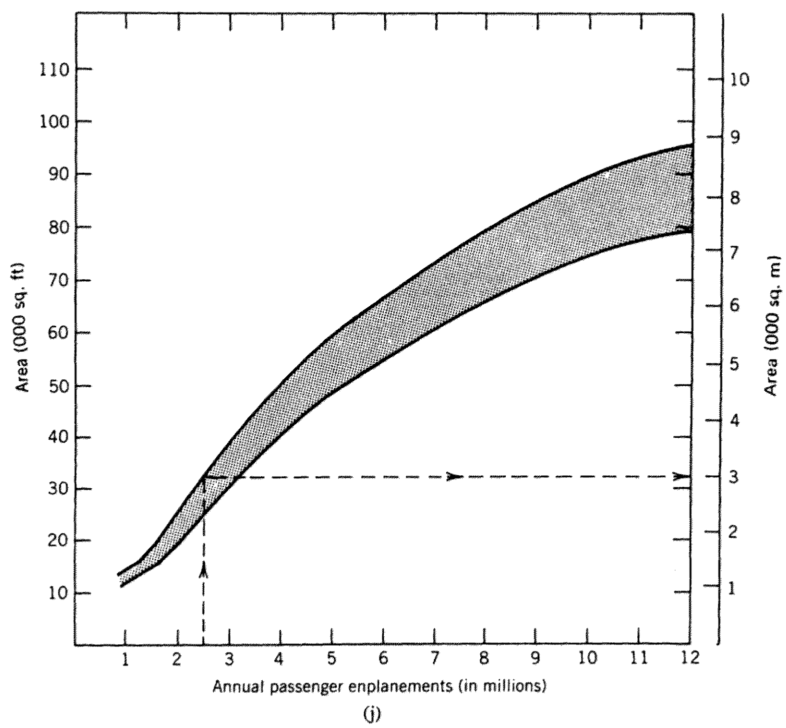


FIGURE 10.5(j) Concessions and building services.

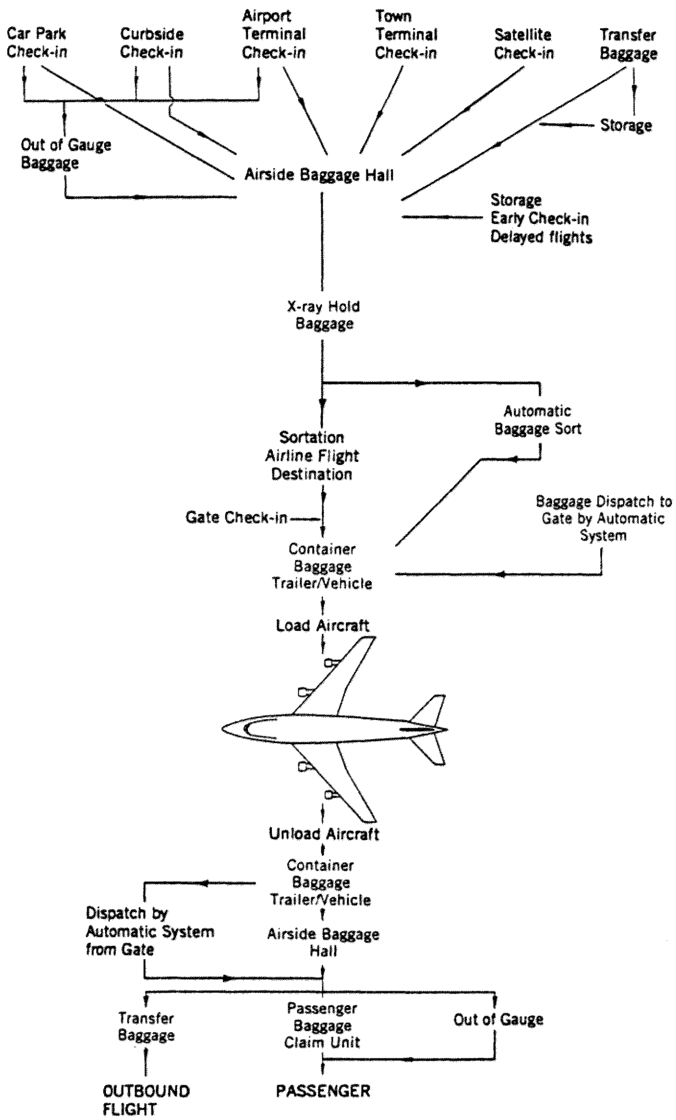


FIGURE 10.6 Baggage loading and unloading sequence.

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 sortation area, its destination is encoded into the automatic system. This is 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.

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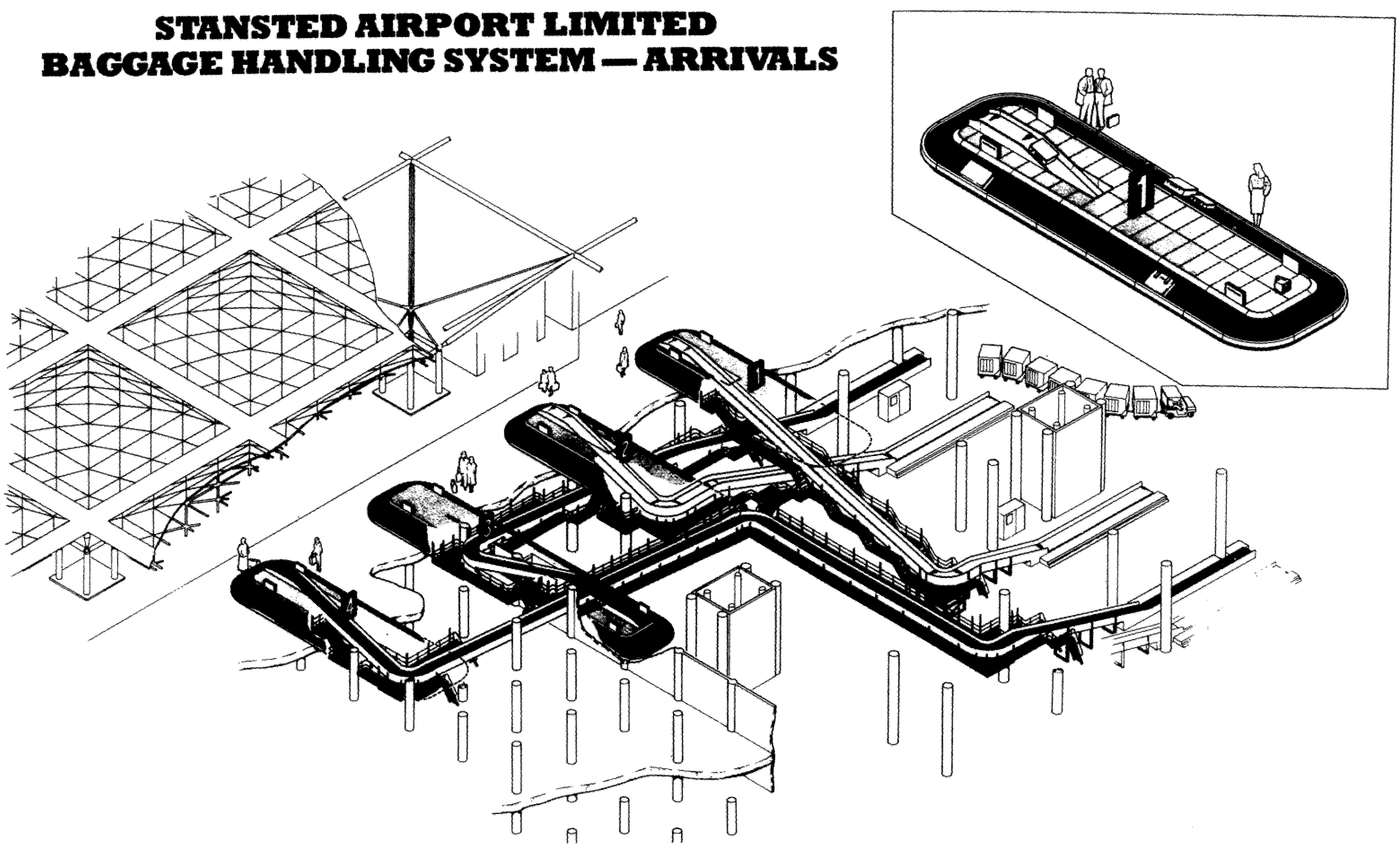
BAGGAGE HANDLING SYSTEM — ARRIVALS



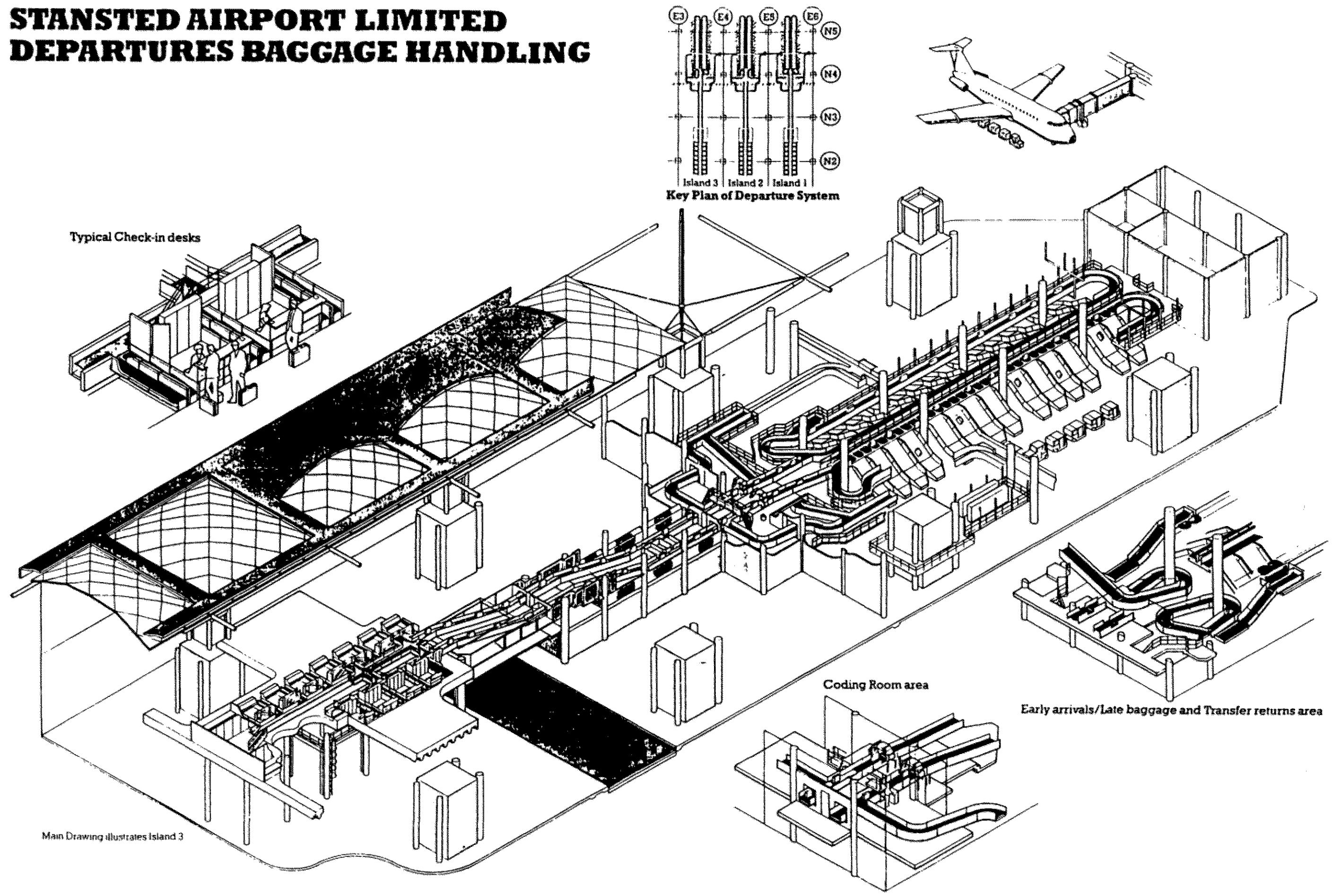


FIGURE 10.7 An automated outbound baggage system. (Courtesy: BAA plc)

Depending on the system used, the bag is then automatically directed to a point in the sortation 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 10.7 shows the layout of an automated outbound baggage system.

It is important to ensure, in the design of the inbound baggage claim hall, that not only is the overall size of the facility 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, if container pods are used, semimechanically. The baggage is brought to the air side 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 10.8 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 carousel and racetrack designs are necessary to handle the volume of baggage delivered by the large, wide-bodied aircraft.

10.12 ANALYSIS OF FLOWS THROUGH TERMINALS

As Figure 10.1 indicates, the pattern of flows through airports can be extremely complex. A knowledge of daily and even hourly flows is insufficient for detailed design of some facilities, since flows are of a varying and stochastic nature rather than uniform, even during peak design periods. To be able to examine the detailed behavior of passenger and baggage flows, the interaction of the design of one facility on another, three principal methods of analysis are used:

1. Network analysis.
2. Queueing theory.
3. Simulation.

Network Analysis

In network analysis, the time sequence of various activities is examined and structured to establish patterns of temporal interrelationships. Figure 10.9 is a very simplified critical path network, showing the interrelationships of the various activities associated with the enplanement of a domestic air pas-

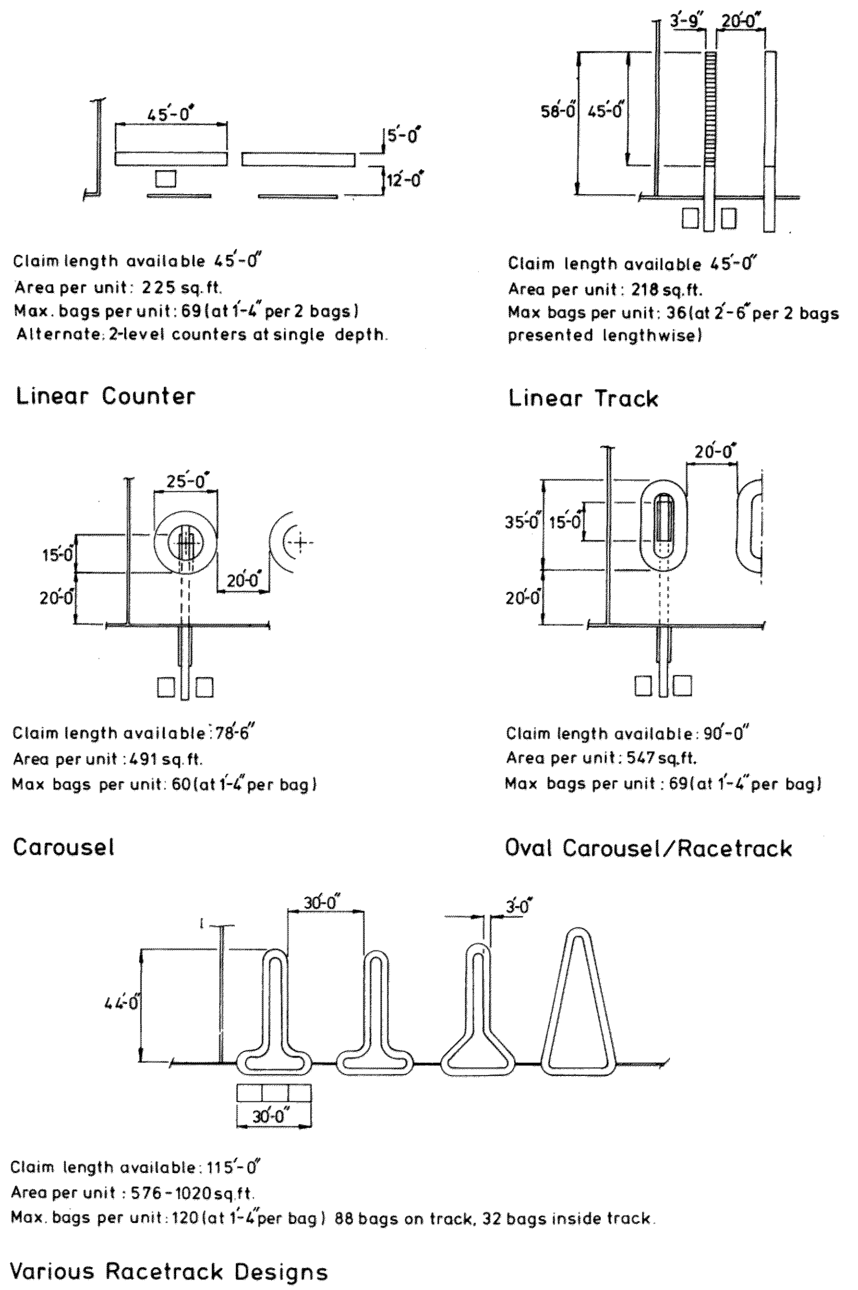


FIGURE 10.8 Examples of five different baggage delivery systems. (*Source*: Reference 4)

senger. This systems analysis technique can be used to identify the critical path of time through a network by assigning duration times to each activity. Applied to terminal planning, the analysis is a tool for scheduling terminal

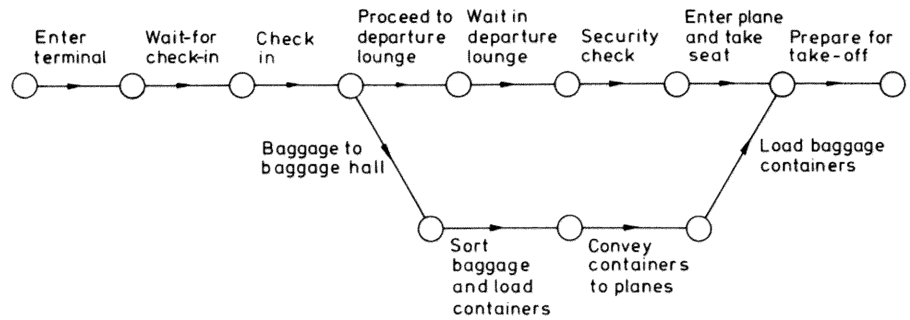


FIGURE 10.9 Simple network analysis of the enplanement of a domestic passenger. (*Source*: Reference 6)

activities, hence for determining equipment and labor requirements within the terminal and on the apron. Airport designers also make use of PERT (program evaluation and review technique) in arriving at such decisions.

Queueing Theory

In a system composed of one or more processes that can be described in terms of the patterns of the arrivals of the individuals undergoing processing and the service times during processing, queueing theory can be applied to predict delays. Typically, queueing theory analysis gives outputs of overall system delays, delays at individual facilities, time in the system, and average numbers of passengers in the system or in any facility. Figure 10.10 shows the structure of a chain of probabilistic queueing models that has been used to model flow at an international airport. The average queueing time for the network can be shown to be equal to the weighted contributions from the activities comprising each route through the network:

$$\text{Prob(delay} > \tau)_{1234567} = pr \times \text{Prob(delay} > \tau)_{14725} + ps \times \text{Prob(delay} > \tau)_{14726} + qr \times \text{Prob(delay} > \tau)_{14735} + qs \times \text{Prob(delay} > \tau)_{14736}$$

Although useful and reasonably accurate for modeling single facilities or single processes, this approach has considerable limitations in more general applications.

Chief among the many difficulties associated with the use of analytical models when they are linked in chains, as required by airport terminal networks, is the need to incorporate random arrivals and exponential servicing in all models, if the mathematics is not to become intractable (13). The great advantage of queueing model analysis is that, once the difficult mathematics has been handled, the amount of computing time required for general sizing of facilities may be quite small.

Node	Description	Model Used
1	Disembarkation	Dummy node
2	Immigration - Domestic	Random arrivals/exponential service/ n channels
3	Immigration - Alien	Random arrivals/exponential service/ m channels
4	Baggage Reclaim	Random arrivals/exponential service/ ∞ channels
5	Customs-Red Channel	Random arrivals/ exponential service/ k channels
6	Customs- Green Channel	Random arrivals/ exponential service/ ∞ channels
7	Leaving terminal	Dummy node

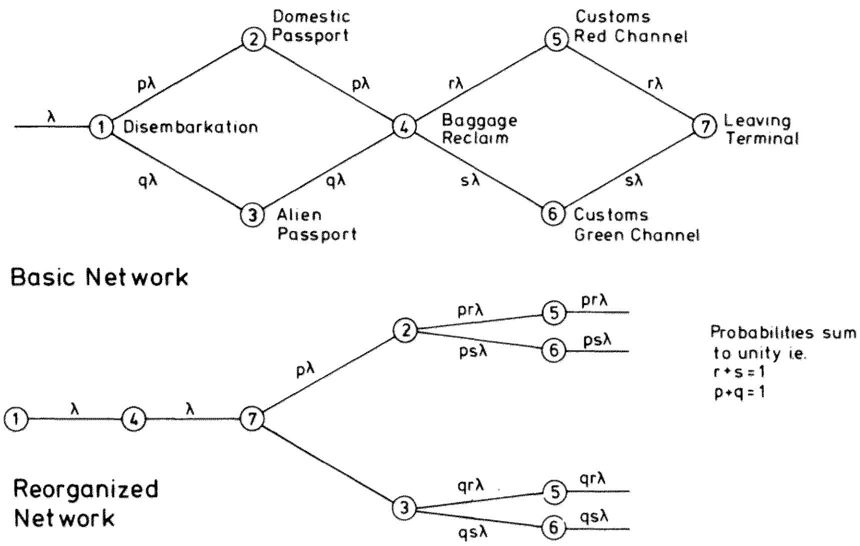


FIGURE 10.10 Queueing theory model for disembarkation with red and green channel customs operation. (*Source*: Reference 6)

Simulation Procedures

Current practice now routinely uses simulation procedures in the planning, design, and operation of airport passenger terminals, and there are a number of available simulation programs available for these purposes. Many are commercially available through consultants and operators; others are in the public domain. Very significant advances in the use of simulation procedures for use in conjunction with air passenger terminals occurred in the 1980s with the introduction of fast high-capacity microcomputers. Previously, simulation programs were of use only to those with ready access to mainframe computers. Even then, the large amounts of computing time which were required for simulation limited the use of the procedure. The general availability of relatively inexpensive high-capacity microcomputers led to the development of readily available software such that no major facility should now be planned or designed without considerable use of simulation.

In practice there are three types of models:

- Models for preliminary design.
- Models for detail design.
- Decision support models for operation.

Models for Preliminary Design. These models are primarily for use by airport policymakers, airport or airline executives, or senior consultants. They are used for the selection of the design concept and major configuration decisions, as well as for approximate sizing.

Ideally, these models should be:

- Easy to reconfigure for different designs.
- Able to give approximate estimates of flows and performance.
- Able to emphasize the relative merits of the options examined.
- Capable of fast turnaround times.
- Easily transportable.
- Based on analytic approaches.

Models for Detailed Design. Such models are for use in the design of individual authorities and as such are mainly used by architects and engineers. Their outputs are useful for determining detailed space allocation, for determining the number and arrangement of services, and for the evaluation of facility performance. Current practice uses these models in a disaggregate mode for individual facilities. Ideally, detailed design simulators will provide models for:

- *Processing facilities:* Using capacity analysis and queueing analysis, output is in the form of number of service stations, linear frontage, area for servers, area for queues.
- *Holding facilities:* From an analysis of occupancy statistics, output is related to space requirements, geometry,and configuration.
- *Flow facilities:* Analysis of flows and walking distances gives information related to corridor widths, capacity, geometry, and configuration.

ALSIM, the FAA model available through the National Transportation Information Service (NTIS), is an example of a detail design simulation model (14). Such models typically deal with:

Well wisher and passenger flows.
Passenger queues at each processing facility.
Walking distances.
Allocation of discretionary time.
Occupancy in each part of the terminal.
Occupancy of gates by aircraft.

Baggage flow analysis.
Passenger/baggage/aircraft interaction.

Decision Support Models for Operation. Decision Support Systems (DSS) models are used by airport operators and airlines managing airport facilities. These are usually real time systems. They must be highly interactive and user friendly. In the early 1990s, a number of these models have become available, although many are limited to the gate areas and their proximities (compare American Airlines and United Airlines at O'Hare and Denver). In the next few years, such models will be generally available and will encompass the entire terminal.

For a more complete discussion of the use of simulation models for airport passenger terminal design, the reader is referred to other published works (References 15a and 15b).

10.13 EXPANDABILITY, MODULARITY, AND FLEXIBILITY

Because air transport continues to grow at a steady rate exceeding 6% 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 must face a doubling of volume over a 10-year period and a quadrupling over 20 years. Designers must therefore take 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 proposed facility for the new airport for Oslo, shown in Figure 10.11, is an example of a mid-field terminal designed to operate on commissioning with 51 gates on two piers, one of which is remote. The ultimate design is for 120–140 gates on three expanded length piers, two of which are remote. This design is reached in at least three expansion phases. The third pier is 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, 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. Figure 10.12, which shows Houston International Airport, exemplifies this well.

In the original master plan, Terminals C and D were planned to replicate

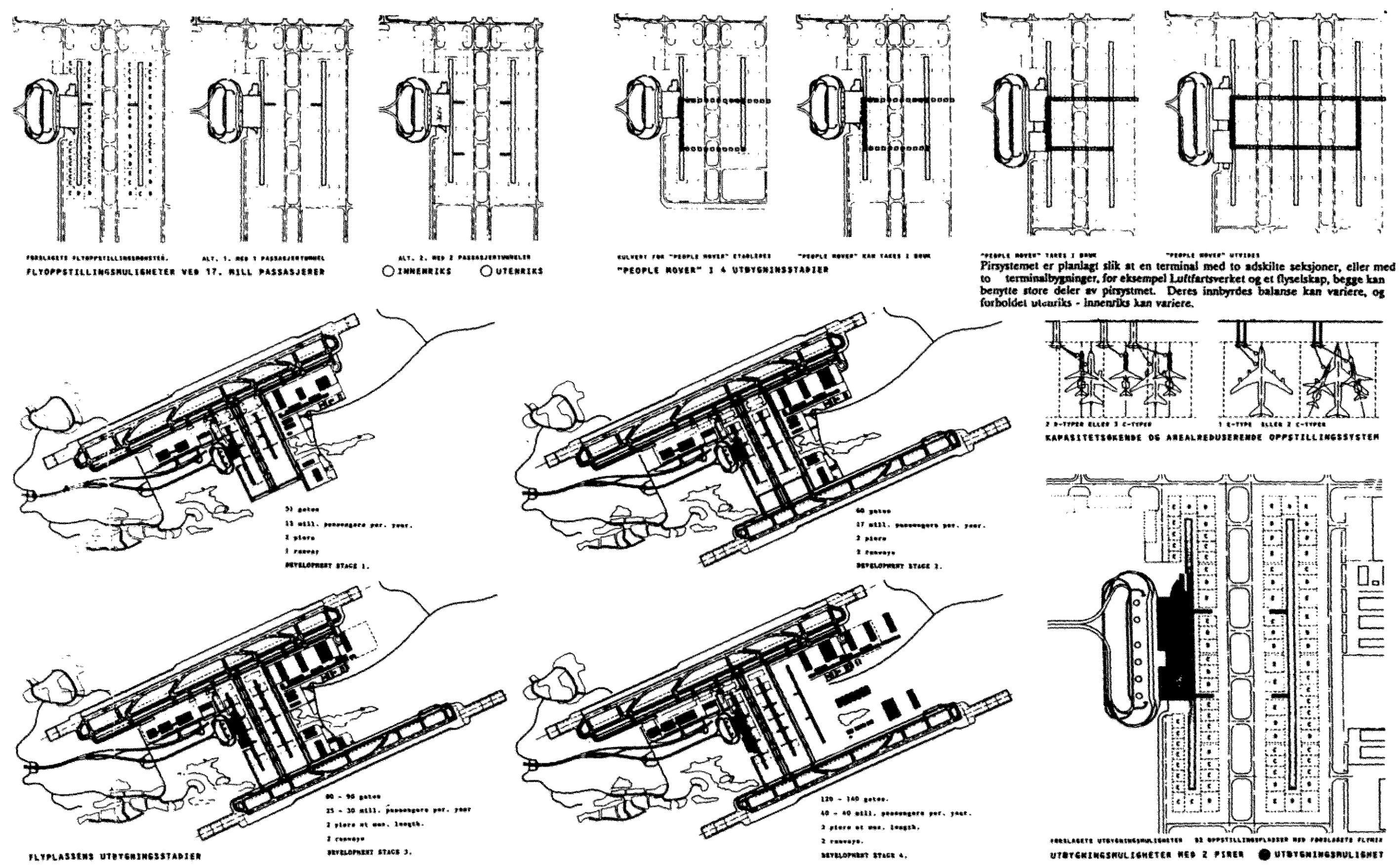


FIGURE 10.11 Example of an expandable terminal: New Oslo Airport competition entry 1990. Courtesy: as Hjellnes, Oslo.

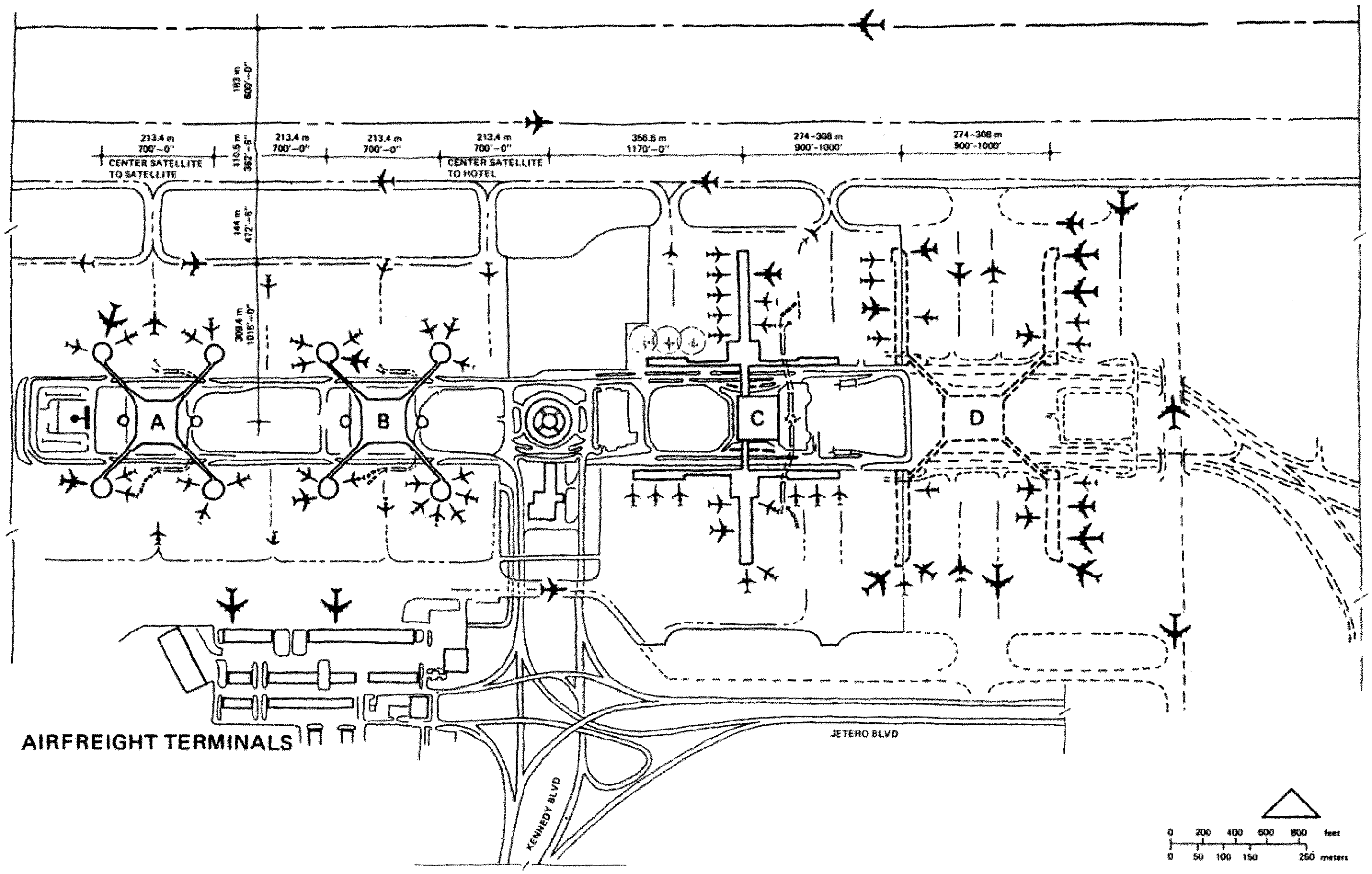


FIGURE 10.12 Apron-terminal complex at Houston Intercontinental Airport. (*Source*: Hart W., *The Airport Passenger Terminal*, Wiley Interscience, 1985)

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 planned format 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 expecially 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.

Figure 10.13 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 required 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.

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 THE NUMBER OF AIRCRAFT GATES

The final configuration of the air side 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 impossibility of filling all gates for 100% of the peak time, because of maneuvering and taxiing.

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 apron practice most closely approximating that for which he or she is designing.

Horonjeff (United States) (16)

$$n = \frac{vt}{u}$$

where

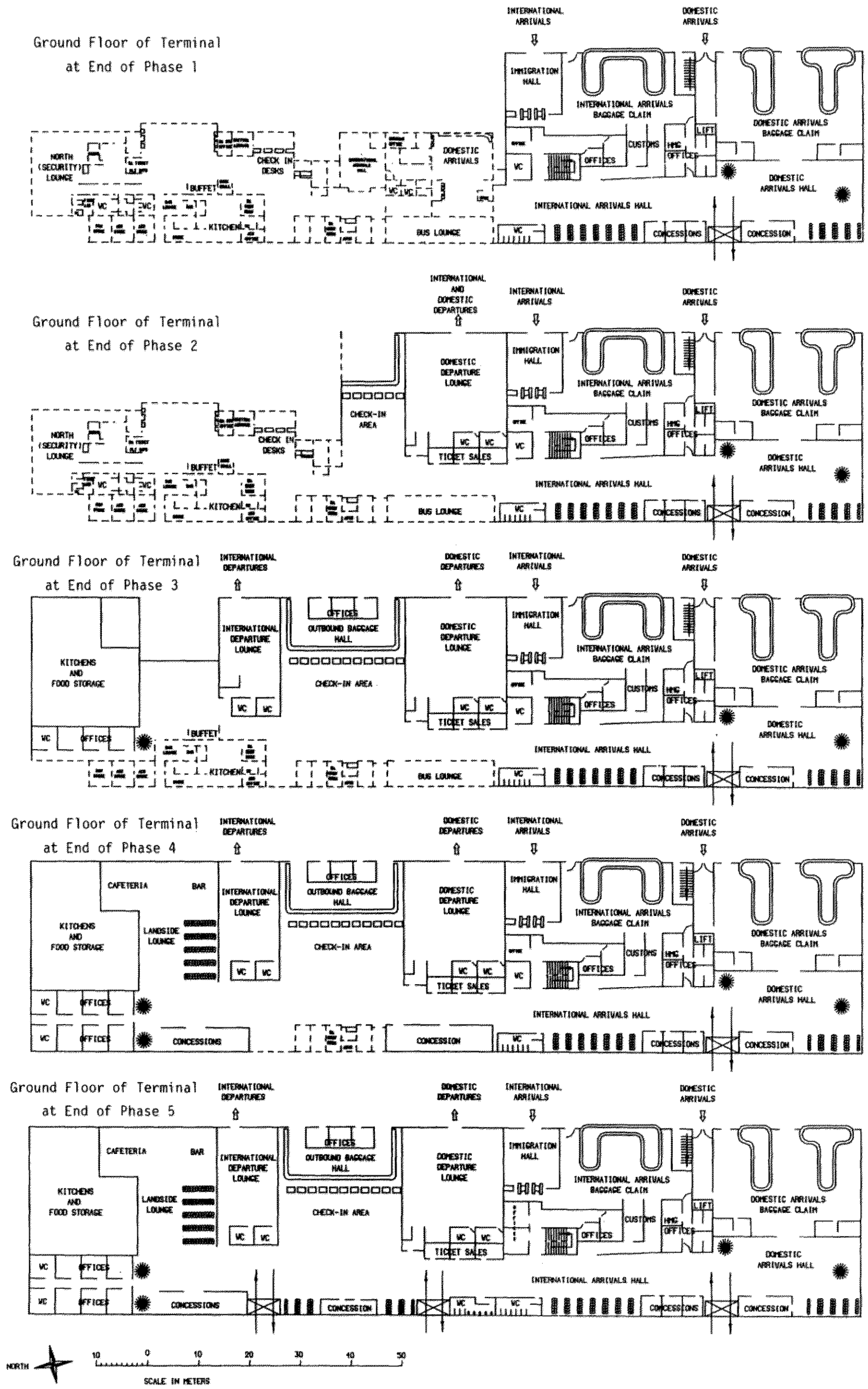


FIGURE 10.13 Phased expansion of Inverness, Airport passenger terminal, Scotland. Expansion to be carried out at a small airport while maintaining operations. (*Source*: Norman Ashford (Consultant Engineers) Ltd.)

v = design hour volume for arrivals or departures (aircraft/hr)
t = weighted mean stand occupancy (hr)
u = utilization factor, suggested to be 0.6 to 0.8 where gates are shared

Piper (West Germany) (17)

$$n = mqt$$

where

m = design hour volume for arrivals and departures (aircraft/hr)
q = proportion of arrivals (total movements)
t = mean stand occupancy (hr)

Sir Frederick Snow and Partners (United Kingdom)

$$n = 1.1m$$

where

m = design hour volume for arrivals and departures (aircraft/hr)

Loughborough Method (United Kingdom)

$$\mathrm{n} = \mathrm{vt}$$

where

v = design hour volume for arrivals or departures (aircraft per hour)
t = weighted mean stand occupancy time according to route type
= 0.90 hours for domestic
= 1.1 hours for short-haul international
= 3.8 hours for long-haul international.

Three different methods have been used by U.S. airlines (1):

Hart Method I (Hourly Method) (United States)

$$n = \frac{m}{2r}$$

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 Parson's report and FAA).
   Divide future enplanements by enplanements per gate.

The calculation of apron gate requirements is also amenable to simulation; software for modeling these requirements, compatible with microcomputers is now widely available (18,19). A variety of calculation methods is contained in Reference 2.

10.15 PARKING CONFIGURATIONS

The form of the air side 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 towed out by tractors. The two principal advantages to this design are that passenger loading can be carried out by loading bridges, thereby protecting passengers from the elements, and that 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. Many airports, however, do not favor this because of the effect of jet blast on the terminal; similarly, most airlines reject this type of maneuver, fearing there will be engine damage from foreign objects and dirt on the apron.

Power-in, power-out designs have five basic configurations (Figure 10.14).

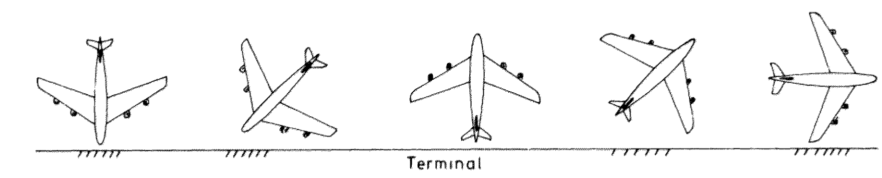


FIGURE 10.14 Five basic aircraft parking configurations.

Usually the choice of any of these configurations 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

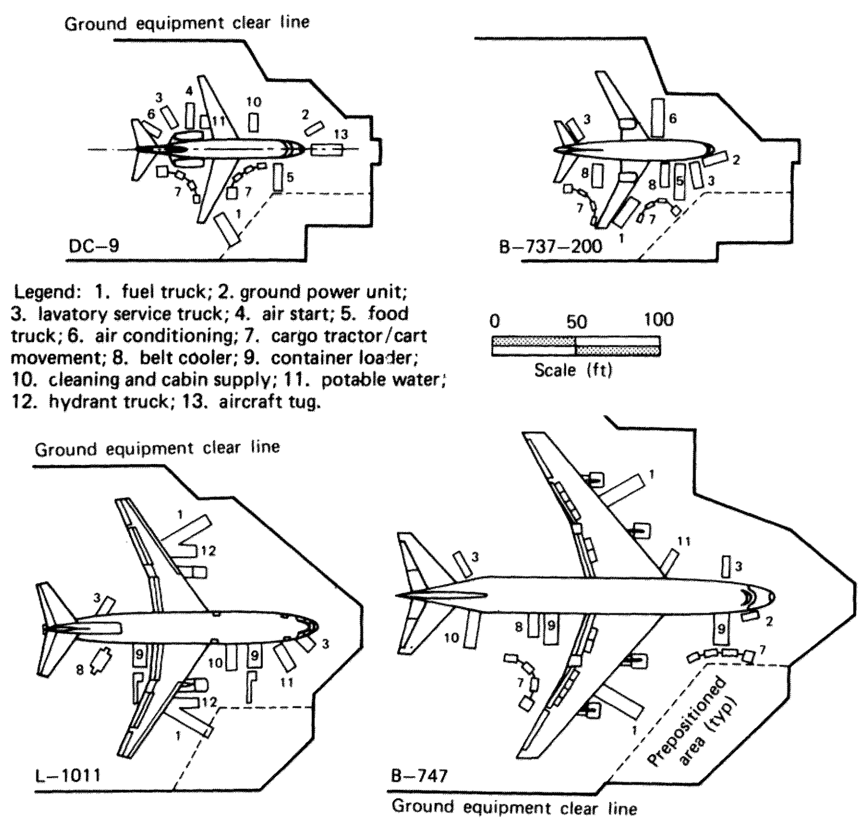
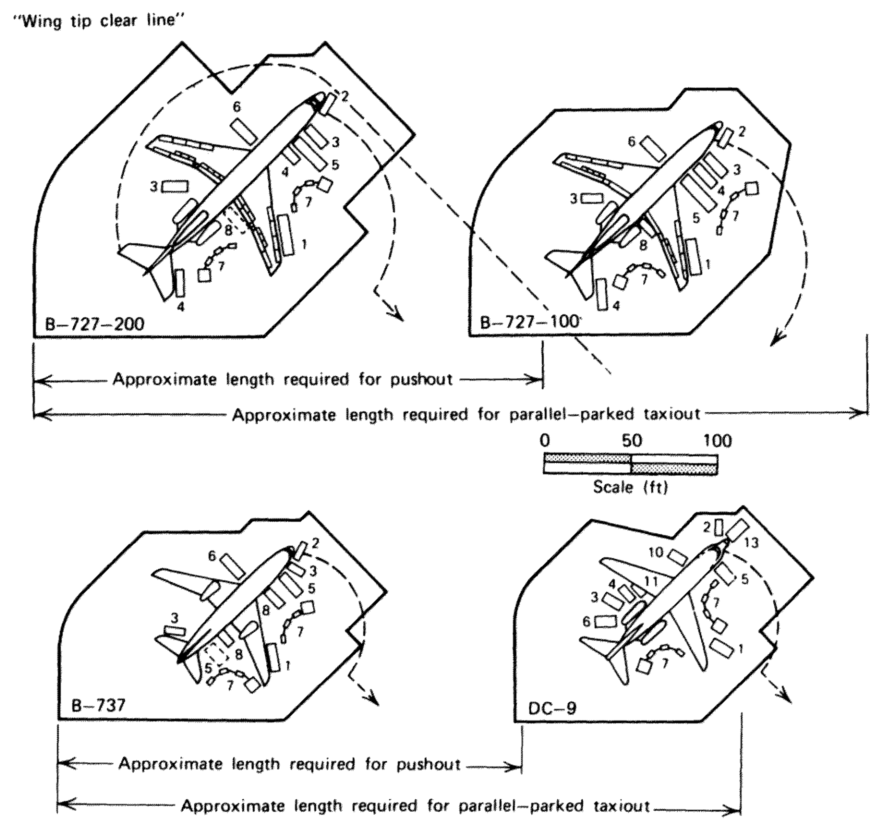


FIGURE 10.15 Examples of aircraft and ground servicing equipment maneuvering for push-out and taxi-out angle configurations. The parking angle, normally 30° and 60° or 45°, will be at the discretion of the airline unless physical or other constraints dic-

aircraft is lighter and has more momentum when turning immediately after taxiing. Often the latter configurations have less overall apron area requirements. 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 breakway.

10.16 APRON LAYOUT

The aircraft is unloaded, loaded, and serviced in the terminal apron, which is usually in close proximity to the passenger air side gates. The spacing of aircraft on the apron, 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.



tate otherwise. Note that the illustrations of the B-747 shows equipment staging before aircraft positioning. (*Source*: Reference 20)

Aircraft can either move into and out of parking postions under their own engine power ("power-in, power-out") or use the "power-in, push-out" configuration just discussed. The former method, 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 jetways. Because jetways are needed only at the largest facilities, most airports are still designed without them; their aprons and gate positions must have dimensions that permit the aircraft to maneuver with adequate clearances (20).

The apron dimensions are determined on the basis of the aircraft parking configuration. Figure 10.15 gives examples of the maneuvering requirements for push-out and taxi-out angle configurations of parking. Angle parking is normally used at apron stations where traffic is relatively light and manpower is to be conserved. Less ramp frontage is required than for the parallel parked arrangement but more than for push-out parking. Figure 10.15 indicates the comparative length requirements for the three arrangements.

For design purposes, commercial passenger transport aircraft may be designated as belonging to one of six categories (20). Table 8.13 gave the required dimension ranges of their parking envelopes, indicating the extreme requirements of push-out and parallel taxi-out parking configurations. For detailed discussion of apron design dimensions, see Section 8.12 and 8.13 and other standard references (20,21). When detailed geometrics are not necessary—in master planning, for example—the following apron areas are suggested for various aircraft classes (7):

Wide-bodied, four-engine jet aircraft and SST	15,000 m^2
Four-engine, narrow-bodied jet aircraft	6,000 m^2
Three-engine, narrow-bodied jet aircraft	4,000 m^2
Two-engine, narrow-bodied jet aircraft	3,000 m^2

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. The guideline, usually yellow, 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.

10.17 APRON FACILITIES AND REQUIREMENTS

The apron serves two functions: it is an area 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. 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 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.

Air Side Roadways

Air side 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 air side 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 THE IMPORTANCE OF AIR CARGO

In order to prevent unnecessary and undesirable interference between surface access passenger traffic and land side freight movements, cargo operations are ideally well separated from the passenger terminal area. Therefore, even the frequent air traveler tends to regard the passenger terminal as the hub of all important comings and goings in the daily activities of the airport. The airport designer, however, cannot overlook air cargo, for this is an important and steadily increasing area of civil aviation. During the period 1960–1969, overall growth rates in tonne km carried averaged 19%, which consistently exceeded passenger growth rates. By 1982, these very high growth rates had disappeared, and Figure 11.1 shows that the rate of increase fell to 8.8% for the period 1970–1990 and is predicted to increase in the foreseeable future at 6.5% per annum, which is close to estimates of world passenger traffic growth (1). There is strong evidence that the freight market has stabilized to a predictable share of the overall market for air transport and that the very dramatic growth of the 1960s is unlikely to reappear in the absence of dramatic technological innovations. However, while air freight represents only about 1%, in tonne km, of all freight transported by all modes, its importance to civil aviation should not be underrated. Accounting for approximately 26% of the total combined scheduled passenger and freight tonne km carried by air, the revenue generated is approximately 12% of total revenues. These revenues however generally far outweigh even allocated costs, and freight operations are seen by operators to be highly profitable when examined on a marginal cost basis.

The air cargo area of civil aviation is an area which during the 1970s and 1980s underwent fast technological change. This is due to a multiplicity of influences:

1. The freight industry itself underwent a conversion to the use of unitized loads (containerization).

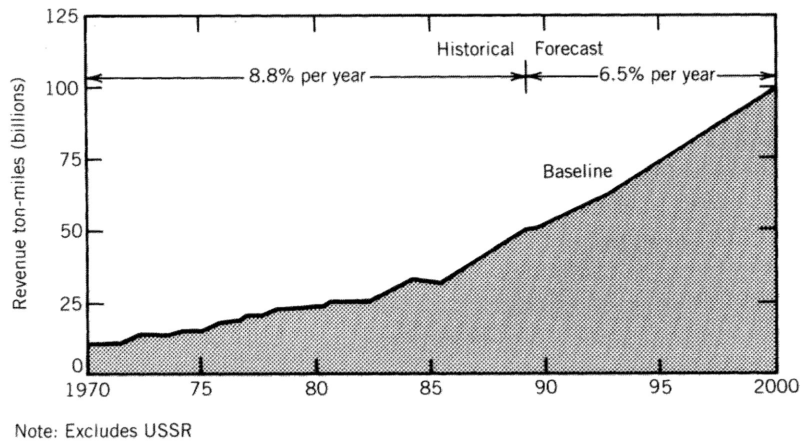


FIGURE 11.1 World air cargo forecast. (*Source*: Reference 1)

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 settling 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.

11.2 THE FUNCTIONS OF THE 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 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 air side. A conversion also almost certainly takes place in flow patterns. The land side 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, combining them, and forming aircraft loads for individual destinations.

Storage is necessary to permit load assembly by conversion and sorting, since flow rates and patterns on the land side and air side are quite dissimilar.

Finally, *facilitation and documentation* is 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 THE SIZE AND FORM OF THE 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:

The mix and flow characteristics of the cargo.
The characteristics of the surface and air vehicles.
Materials handling, documentation, and communication techniques.
Degree of mechanization.

The Mix and Flow Characteristics of the 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. In the mid-1960s, the containerization revolution was underestimated by many involved in air cargo planning. Until that time, air cargo had been composed of a large number of heterogeneous consignments that required significant handling in the air cargo terminal.

Some of the major cargo terminals being planned at that time (1965) were designed around the assumption that the nature of the traffic would remain relatively unchanged. Therefore, these terminals 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. Figure 11.2 shows how air freight has become increasingly containerized since 1965. This figure also speculates on the future share of the freight market to be carried in intermodal containers if technological development can produce sufficiently robust devices with light tare weights. Intermodal container transport

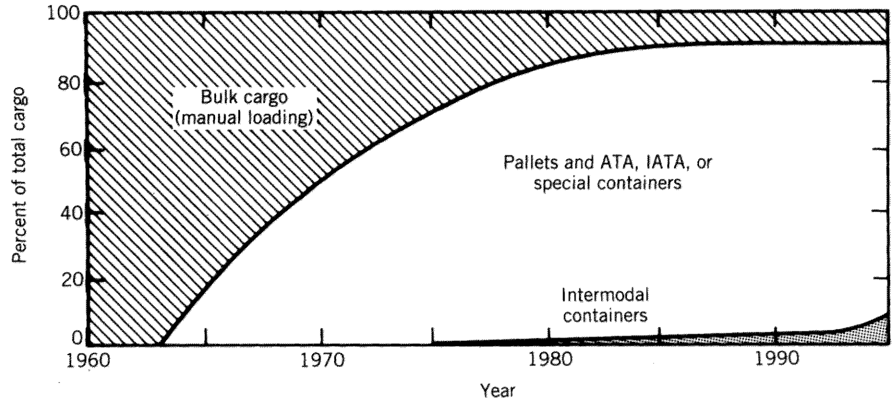


FIGURE 11.2 Air cargo unitization forecast. (*Source*: Reference 5, adapted from Aerospace Industries Association of America)

is still relatively insignificant. Its widespread introduction could generate further changes in cargo terminal handling procedures which would have to be accommodated in future designs. 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.

Automation and mechanization have been introduced successfully in the area of transfer vehicles (TV) and elevated transfer vehicles (ETV). These systems deal with the individual container as the unit to be moved and stored within the terminal. Modern ETV systems can produce very efficient utilization of terminal floor area by the use of multilever container storage and can also dramatically decrease expensive container damage that inevitably results from handling with mobile units such as forklift trucks. Figure 11.3 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 which 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 which must accommodate anticipated traffic flows. Unlike the passenger terminal, the air side and land side peaks of a freight terminal do not necessarily coincide. Air side peaks are closely related to the schedules of aircraft, particularly passenger aircraft which carry the majority of air freight. Land side 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 air side and land side peaking. Figures 11.4a, 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 com-

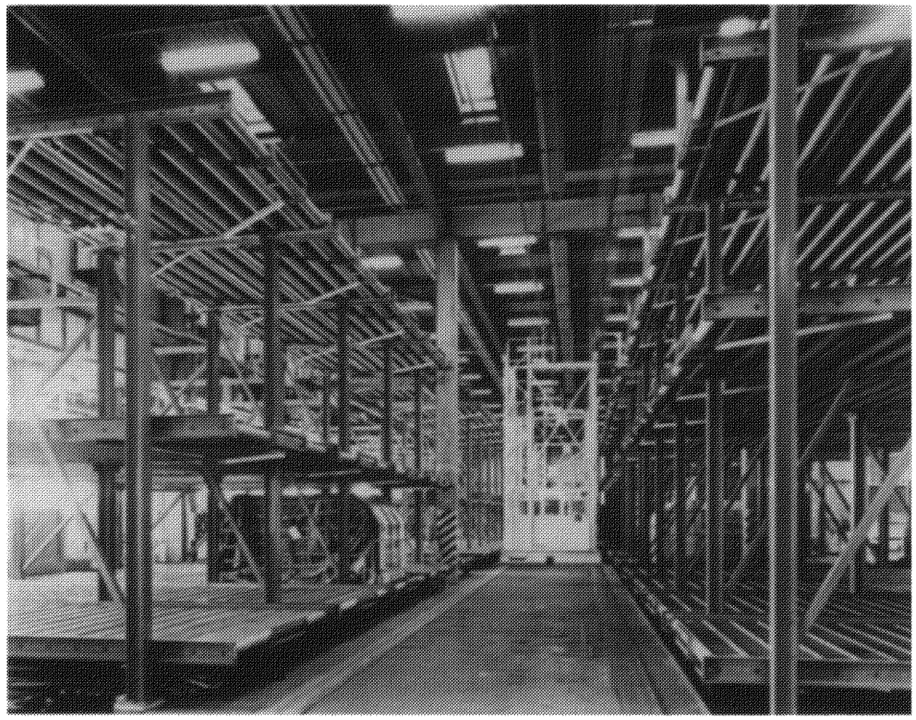


FIGURE 11.3 A modern ETV system. (Courtesy: British Airways)

modities 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, (land side reception, land side dispatch, air side outbound, air side 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 72 hours 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

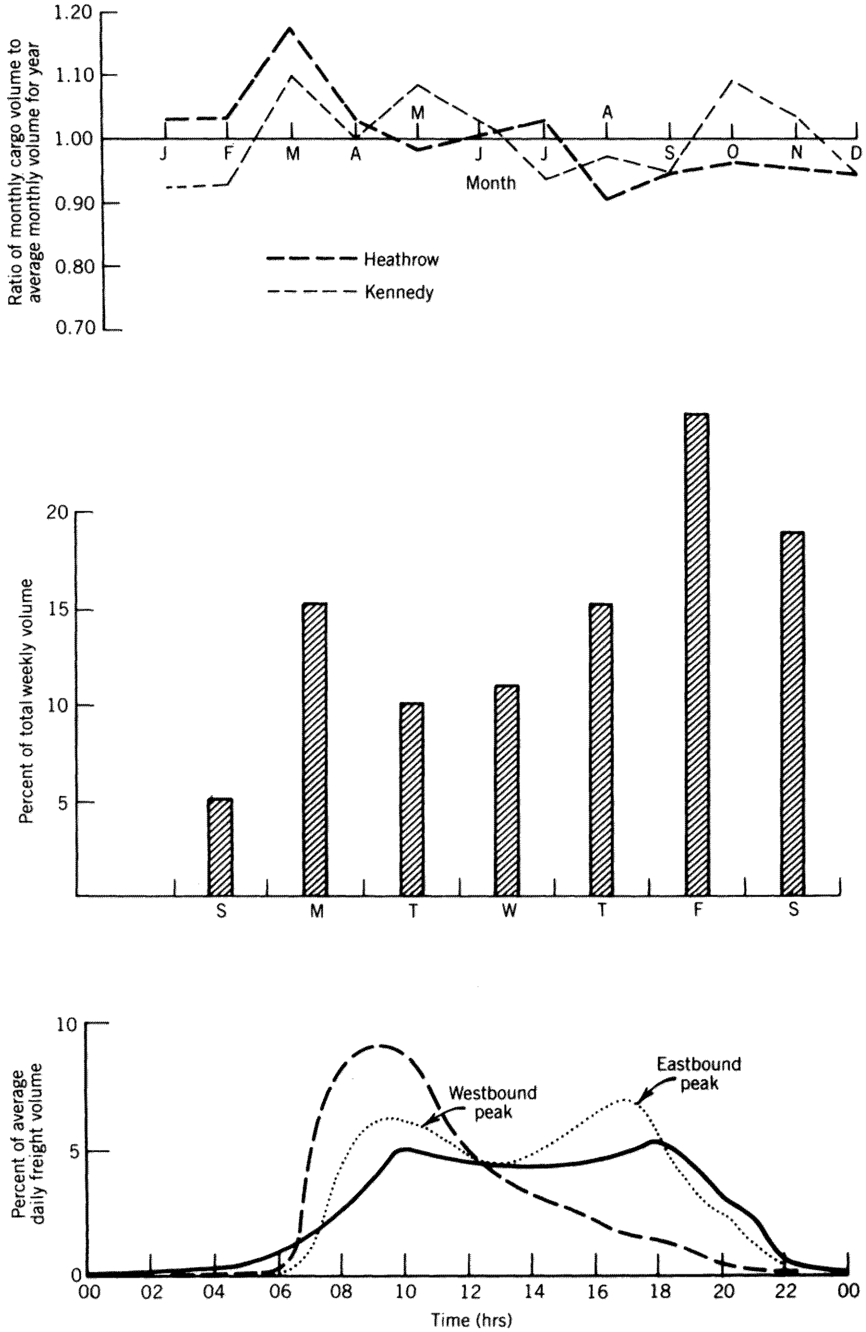


FIGURE 11.4 Peaking characteristics of air freight flows. (a) Annual peaking characteristics (*Source*: FAA and CAA). (b) Daily peaking characteristics. (c) Hourly peaking characteristics. (*Source* for (b) and (c): British Airways, London Heathrow) (*Note*: Solid line indicates land side freight received; dashed line, air side freight inbound; dotted line, air side freight outbound.)

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 adopted 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 is 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 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 terminal 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.

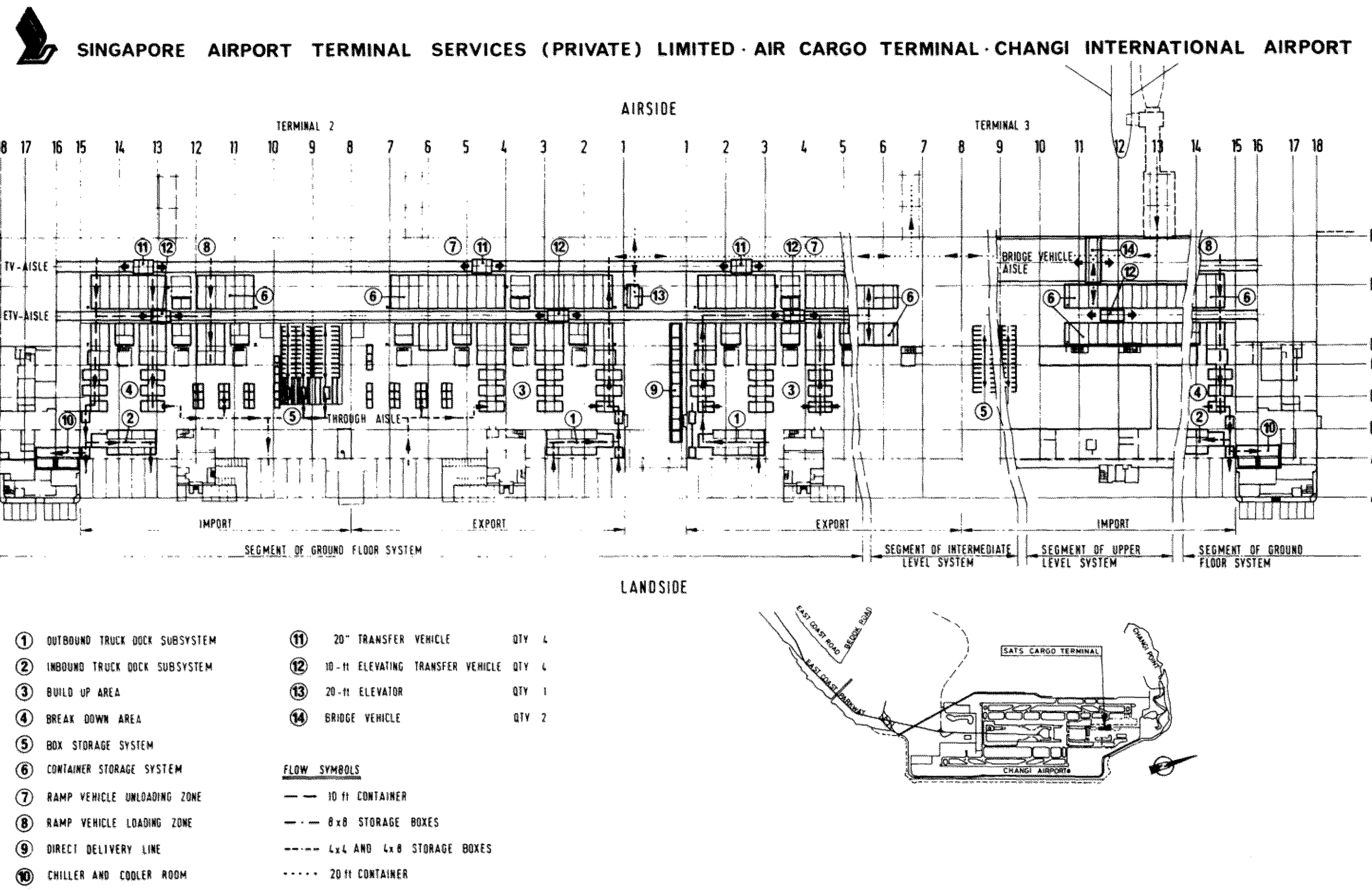


FIGURE 11.5(a) SATS air cargo terminal, Changi International Airport, Singapore. (*Source*: Mannesmann Demag)

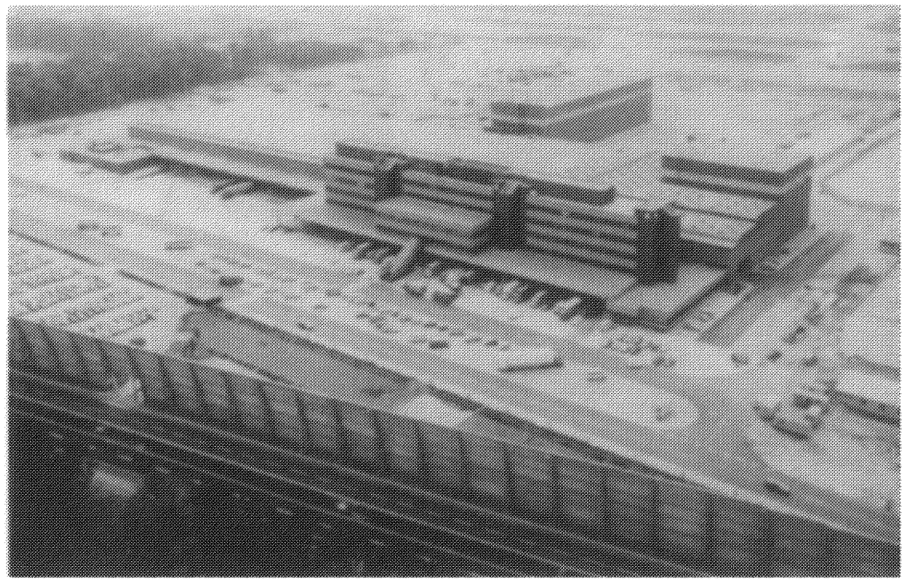


FIGURE 11.5(b) Lufthansa cargo center Frankfurt. (*Source*: Lufthansa German Airlines)

Figures 11.5a and b 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, automation of documentation through the application of electronic computer data processing (ECDP) has proved remarkably successful. 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. First introduced in London for Customs and Excise purposes, computerized documentation and expediting is now commonplace (2).

11.4 FLOW THROUGH THE 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

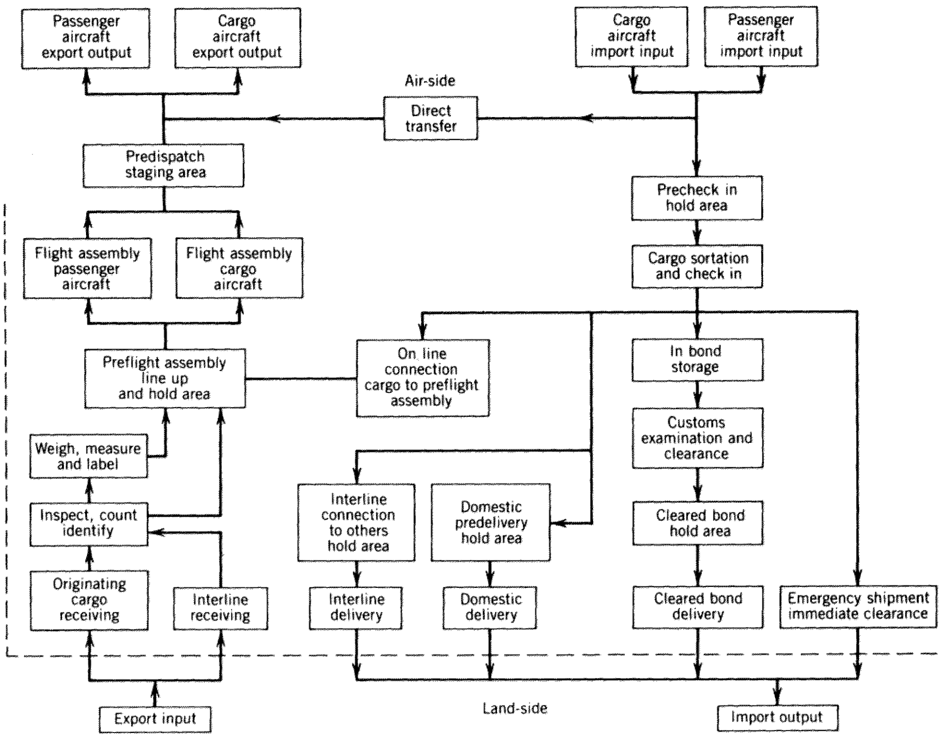


FIGURE 11.6 Flow through cargo terminal. (*Source*: Reference 3)

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. 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 the Frankfurt Lufthansa terminal, more than half of all incoming freight is transferred to outgoing flights; the terminal design reflects this specialized need.

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.

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 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 have dimensions of 60.4 × 61.5 in and 60.4 × 125 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 Figure 11.8). For narrow-bodied aircraft, standard pallet dimensions are 88 × 125 in for all-freight craft and 88 × 108 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 × 117.75 in in the upper hold. In the lower hold, 96 × 125 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

*International Standards Organization.

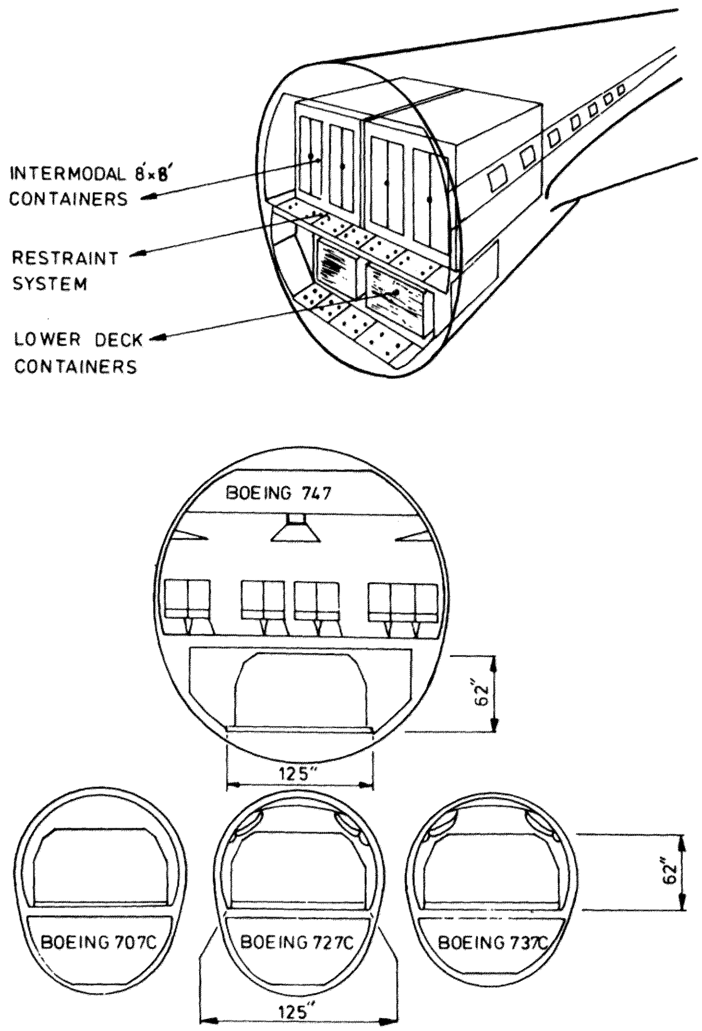


FIGURE 11.7 Container arrangements in wide- and narrow-bodied aircraft.

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.

IATA Unit Load Devices (ULDs)

The IATA system of classifying ULDs is shown in Figure 11.9. Each container type is identified by a multialphanumeric code, in which each alphanumeric identifies of particular category:

FIGURE 11.8 Palletized unit being transferred to an aircraft.

Alphanumeric 1:
- A. Certified container
- B. Noncertified container
- P. Aircraft pallet
- R. Thermal certified aircraft container
- U. Nonstructural igloo

Alphanumeric 2: Base dimensions
Alphanumeric 3: Contour and aircraft compatability

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. Narrow-bodied aircraft have only small holds for cargo and baggage, and they must be loaded with loose cargo. Small amounts of cargo are carried in this way, but the vast majority of freight is carried by all-freight aircraft or in the lower holds of the wide-bodied vehicles.

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 appears to have 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 707 (8074 ft^3). The rapid intro-

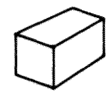
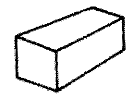
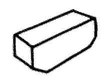
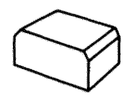
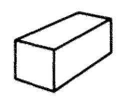
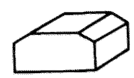
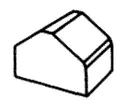
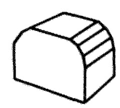
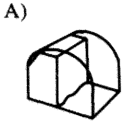
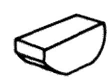
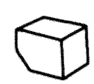
Type	Owner	Corresponding IATA container classification		Cubic capacity	External dimensions and cubic displ.	Weight: Minimum chargeable pounds	Weight: Maximum gross weight	Handling features for shippers
M-1	Airline provided (available at 747F cities)	Type 2		572 cu ft	L 125 W 96 H 96 cu displ 666 cu ft	4,400	15,000	Picked up or delivered on conventional truck trailer chassis
M-2	Airline provided (available at 747F cities)	Type 1		1077 cu ft	L 240 W 96 H 96 cu displ 1280 cu ft	12,363	25,000	Picked up or delivered on conventional truck trailer chassis
L-6	Airline provided			310 cu ft	L 160 W 60 4 H 64	2,800	7,000	Dolly transporters available
LD-7	Airline provided (available at 747DC-10 and L1011 cities)	Type 5		cu capacity 355 cu ft	L 125 W 88 H 63 cu displ 401 cu ft	2,800	10,400	Dolly transporters available
L-11 L-5	Airline provided (available at 747DC-10 and L1011 cities)	Type 6		cu capacity 265 cu ft	L 125 W 60 H 64 cu displ 277 cu ft	1,800	7,000	Dolly transporters available

FIGURE 11.9 Air freight unit load devices. (*Source*: IATA)

continued

Type	Owner	Corresponding IATA container classification		Cubic capacity	External dimensions and cubic displ.	Weight: Minimum chargeable pounds	Weight: Maximum gross weight	Handling features for shippers
L-10	Airline provided	Type 6		varies	L 125 W 60 4 H 63 cu displ 242 cu ft	1,694	6,500	Dolly transporters available
A-1	Airline provided (available at Freighter cities	CO1 CO2		cu capacity 393 cu ft	L 88″ W 125″ H 87″ cu displ 425 cu ft	3,000	13,300	Dolly transporters available Can be pallet & net
A-2 A-3	Airline provided (available at Freighter cities	CO1 CO2		cu capacity 440 cu ft	L 88″ W 125″ H 87″ cu displ 475 cu ft	3,200	12,500	Dolly transporters available Can be pallet & net
B	Shipper provided	CO3 CO4 CO5 CO6	(Insert for A) 	varies	L 84″ W 58″ H 76″-45″ cu displ 197 70 cu ft	1,800	5,000	Forkable
L-W	Airline provided			varies	L 98 W 42 2 H 41 6 cu displ 76 cu ft	500	1,200	Dolly transporters available
L-3	Airline provided (available at 747DC-10	Type 8		cu capacity 150 cu ft	L 79 0 L 62 0 W 60 0 H 64 0	1,100	3,500	Dolly transporters available

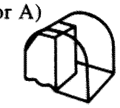
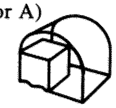
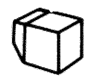
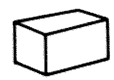
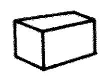
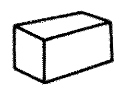
	and L1011 cities)				cu displ 166 0 cu ft			
B-2	Shipper provided	none	(Insert for A) 	varies	L 42″ W 58″ H 76″-45″ cu displ 98 85 cu ft	900	2,500	Forkable
D	Shipper provided	CO8, CO9, COJ	(Insert for A) 	varies	L 58″ W 42″ H 45″ cu displ 63 44 cu ft	500	2,000	Forkable
L-N	Shipper provided	CO7	(Insert for LD-3) 	varies	L 56 W 55 H 57 cu displ 101 6 cu ft	900	3,160	Forkable
E	Shipper provided	COS		varies	L 42 W 29 H 25 5 cu displ 17 97 cu ft	130	500	Side handles recommended
E-H	Shipper provided	COS(E)		cu displ. 9.03 cu ft	L 35 4″ W 21″ H 21″	100	250	Consult air carrier
Q	Shipper provided	none		varies	L 39 5 W 27 5 H 21 cu displ 120 cu ft	100	11,400	Side handles recommended

FIGURE 11.9 *Continued*

TABLE 11.1 Freight Capacities of a Typical Freight and Combination Aircraft

Aircraft Model	Maximum Freight Payload (lb)
B-707-320C	91,390
B-747-200F	254,640
B-757-200PF	50,000
B-747-200C	237,110
B-737-200QC	34,371
B-737-200C	34,996
B-727-100D	44,000
DC-8F	95,282
DC-8-63F	118,583
DC-100 (Series 30F)	155,700
MD-11F	122,700
MD-C-17	172,200
L-100-30	51,402
Merchantman 953-C	37,400
Hawker-Siddley Argosy	31,009
Caravelle 11R-SE210	20,000
Fokker F27-600	12,511
BAC-111-475	21,223
L-1011 Tristar	86,002

Source: *Janes All the World's Aircraft, 1989–90*. London: Jane's Information Group, 1989.

duction of wide-bodied aircraft over many long-distance routes, has made spare cargo capacity available. This space can 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.

All-freighter 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 well into the next century the vast majority of air freight will 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 number of freight and combination aircraft.

11.7 DOCUMENTATION AND CONTROL

Electronic data processing has become essential in the control of cargo flow through large terminals. Since cargo cannot move without documentation, the rapid movement of large volumes of cargo requires the rapid processing of

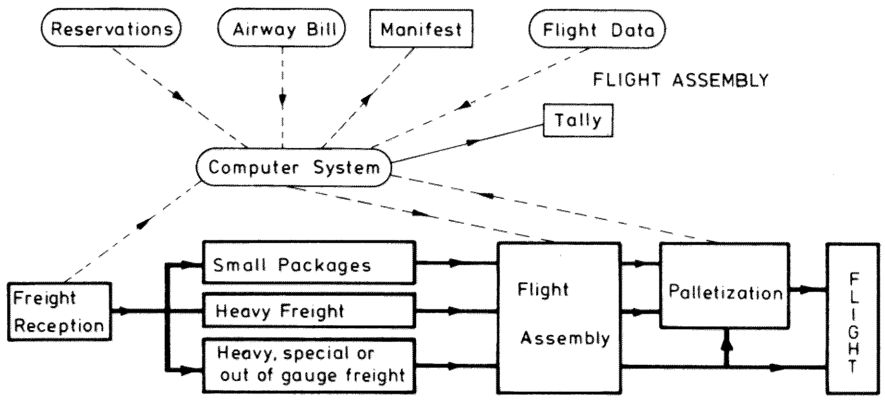


FIGURE 11.10 Idealized cargo data processing system for an export operation.

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.

Reservations of space are made by checking computer records of the current status of space available on individual flights. Then freight can be scheduled to arrive in time for the outgoing flight. At reception, the freight is weighed and checked, an airway bill is produced, then it is computerized from an on-line terminal, and an on-line manifest is printed out. In conjunction with flight data, the individual consignment information is aggregated into the flight tally for loading purposes.

The freight is sorted at reception into small, heavy, and special or out-of-gauge freight and is temporarily stored in the terminal stacks. Cargo is moved into the flight assembly area in accordance with the flight tally. Pallets and containers are packed or "stuffed" after passing through the live lanes in the flight assembly area, data on pallet contents are transmitted to the computer for information and location purposes during flight and on arrival. In this way, the locations of individual pieces are known, and stray consignments can be traced more easily than is possible with noncomputerized techniques.

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 must be capable of rapid unloading and loading times while achieving high payload densities. The type of equipment used depends on the exact nature of the cargo. Care must 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.

The palletized and igloo units comprise the most common cargo form. After the pallets have been assembled and rolled to the preflight holding area in the terminal, they must be transferred across the apron. This is frequently achieved by rolling the pallets onto 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.

Where containers are used, very similar loading strategies can be employed. A more sophisticated loading device is the mechanized nose dock system (Figure 11.11). The nose dock consists of two rows of container stacks with a transfer vehicle running between the two rows. Containers are moved on roller mats onto the transfer vehicle, which moves to the aircraft loading bridge. A second transfer is made across the powered roller floor loading bridge to the deck of the aircraft.

Loose cargo can be transferred across the apron by dollies and loaded either by cargo lift or small cargo conveyors, which handle light loads. Out-of-gauge and nonpalletized 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.

The choice of apron handling devices depends chiefly on the air vehicle to

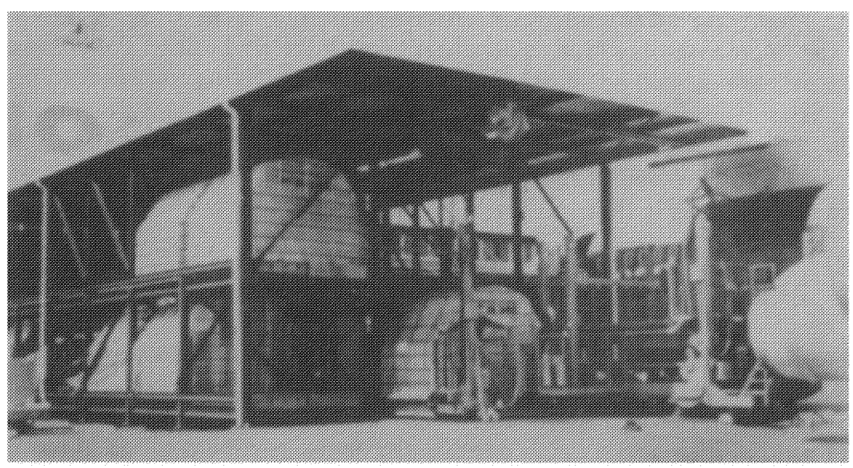


FIGURE 11.11 Nose dock system.

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 ft by 8 ft containers, in modular lengths up to 40 ft, and can be loaded by nose docks. 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, DC-10, MD-11, L1011, A300, A320, 757, 767, 707, 727, DC-9, DC-8, and so on.

3. Main Capacity Constrained Elements of Design

Overall area.
Build-up positions.
Pallet and container storage area.
Bins.
Air side and land side doors.

4. Cargo Handling Concept Choice

Low mechanization, high manpower.

Low manpower, mobile lifting, and loading equipment.

High mechanization with transfer vehicles (TVs) and elevating transfer vehicles (ETVs).

5. Site Selection Factors

Dimensions of terminal, apron, and land side access areas.

Layout of road access and degree of separation of commercial freight vehicles from passenger terminal traffic.

Proximity and ease of air side access to the passenger apron.

Layout and capacity of air side service roads.

Availability of utilities.

6. Architectural Decisions

Main floor level.

Land side and air side 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 build up/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 THE 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: 1½ 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/m²/yr)	13,500–22,500 (use 13500)	5,500
Land side truck loading and unloading doors: (Kg/door/hr)	2,500–4,500 (use 3,500)	1,800
Air side 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	Bypass	Processed
	(Kg × 1,000)	(Kg × 1,000)	(Kg × 1,000)
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
	(Kg × 1,000)	(Kg × 1,000)	(Kg × 1,000)
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*

$$\text{Pallets processed} = \frac{\text{peak hour flow (kg)}}{1{,}800\ \text{kg/pallet}} = \frac{16{,}200}{1{,}800}$$

$$= 9\ \text{pallets/peak hr, or 1 bypass door}$$

2. *Domestic and Export Nonbypass Facilities*

a. $$\text{Gross meter}^2\ \text{required} = \frac{\text{annual volume}}{13{,}500\ \text{kg/m}^2\text{/yr}} = \frac{37.2\ \text{mill. kg}}{13{,}500} = 2756\ \text{m}^2$$

b. $$\text{Land side truck doors} = \frac{\text{peak hr flow (kg)}}{3500\ \text{kg/door/hr}} = \frac{43{,}500\ \text{kg}}{3500}$$

$$= 12.4,\ \text{say 13 truck doors}$$

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. Air side doors:

$$\frac{\text{peak hr flow}}{\text{Pallet wt} \times \text{pallets/door/hr}} = \frac{43{,}500}{1800 \times 20} = 1.2\ \text{(not critical)}$$

3. *Import Facilities*

a. $$\text{Gross meter}^2\ \text{required} = \frac{\text{annual volume}}{5500} = \frac{16\ \text{mill. kg}}{5500} = 2910\ \text{m}^2$$

b. $$\text{Land side truck doors} = \frac{\text{peak hr flow (kg)}}{1800\ \text{kg/door/hr}} = \frac{24{,}000}{1800}$$

$$= 13.3,\ \text{say 14 truck doors}$$

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. Air side doors: not critical.

E. Summary Design Requirements

1. *Overall Requirements*

	Domestic/Export	Import	Total
a. Total area (m^2)	2756	2910	5666
b. Land side 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
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 ≏ 8% total

i. Customs clearance	450
j. ULD breakdown and build up	900
h. Maintenance	300 ≏ 5% total
i. Circulation and storage	3460
	5700

A typical layout of the above areas is shown in Figure 11.12.

F. Comparison with Industry-wide Standards

Frequently, even less rigorous methods of cargo terminal sizing are used, with the overall area being computed from annual tonnage throughout. Formerly, IATA recommended using 1.0ft^2 per ton per year for the outbound area and 1.1ft^2 per ton per year for the area calculations. General experience indicates now that those figures which approximate to 0.1m^2 per tonne per year may underestimate the space requirements.

This is especially true where there are high peak/annual volume ratios and where overall cargo dwell time in the terminal is high. In this case, space requirements are known to reach 0.3m^2/annual tonne. Recently reported throughputs at various terminals are shown in Table 11.2.

Using the flows in the above problem and 0.1m^2/outbound annual

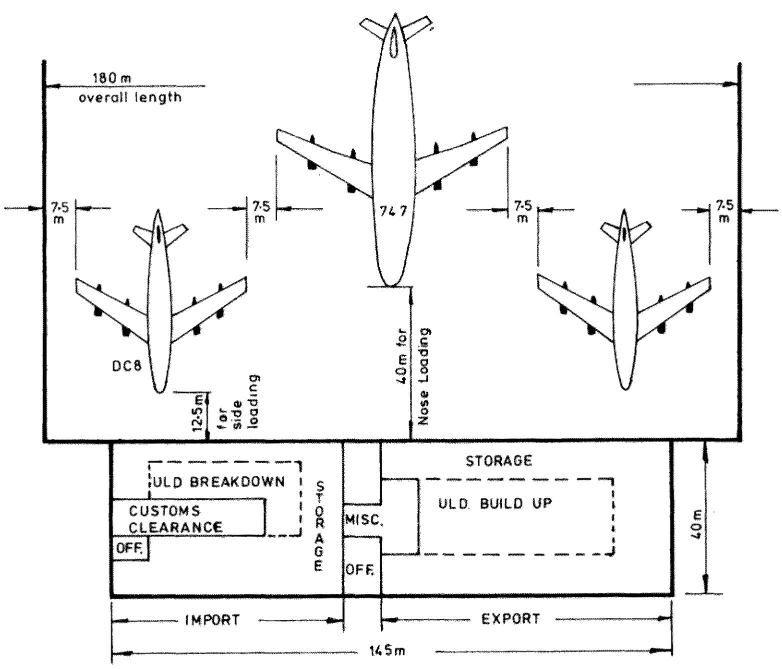


FIGURE 11.12 Example of a layout of a cargo apron and terminal.

TABLE 11.2 Typical Throughputs at Various Air Cargo Terminals (5)

	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

tonne and 0.11m^2/inbound annual tonne, the designer would arrive at the following overall areas:

Outbound: 26,000 tonnes = 28,636 tons	Requires 2600	
Inbound : 34,000 tonnes = 37,478 tons	Requires 3740	
Total area required:		6340m^2

11.11 DESIGN OF A HIGHLY MECHANIZED CARGO TERMINAL WITH CONTAINER STACKS AND ETV*

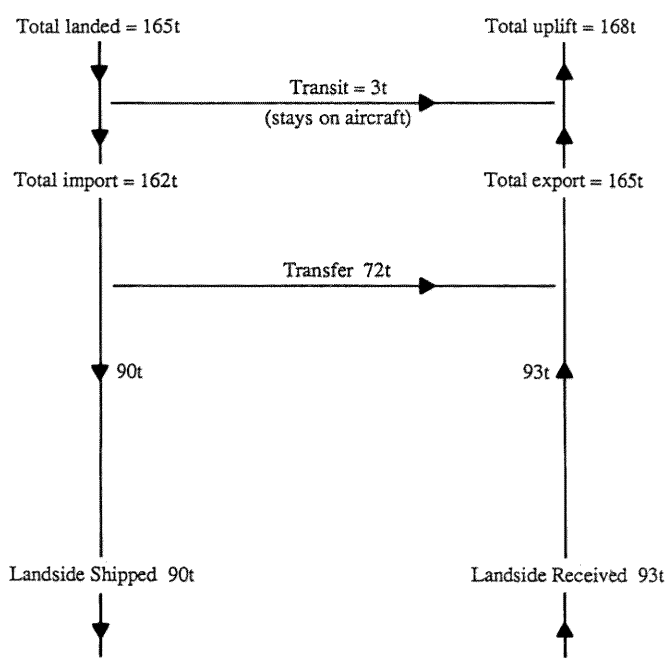
EXAMPLE 11.2

Assumptions and Data:

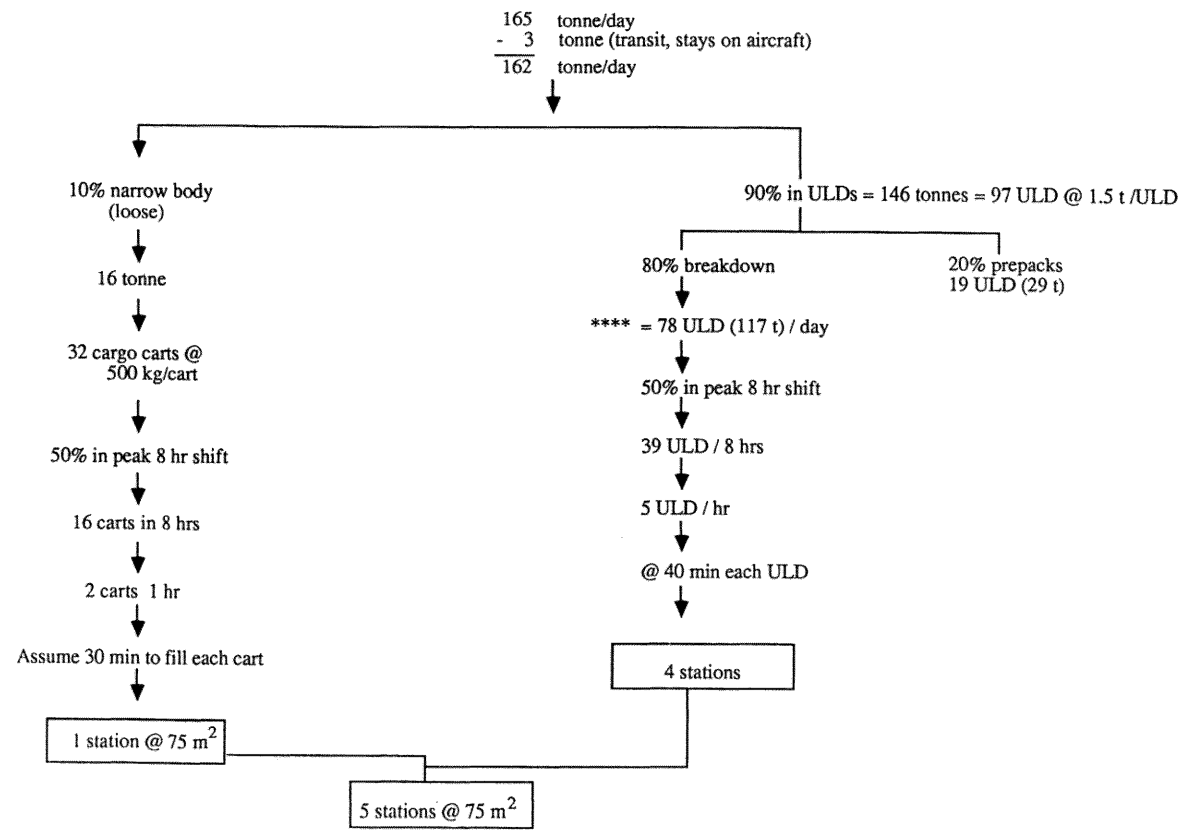
- Annual tonnage uplifted and landed.
- Peak day/annual tonnage ratio = 0.00333.
- % transit on peak day = 0.9%.
- % transfer on peak day = 21.62%.
- Build-up–breakdown areas: 75m^2 per station.
- Truck docks: 4m wide with 15m depth inside building and 4m width outside building on ramp.
- ULD dimensions: 2.5 × 3m; capacity 1.5 tonnes.
- Cargo carts for loose cargo, capacity = 500 kg. Each cart requires 30 mins to fill or unload.
- ULD breakdown 40 min, build-up 45 min.
- Inbound ULDs 20% prepacks.
- Outbound ULDs 20% prepacks.

*Example by kind permission of Hans Marx, Airport Consultant, Frankfurt.

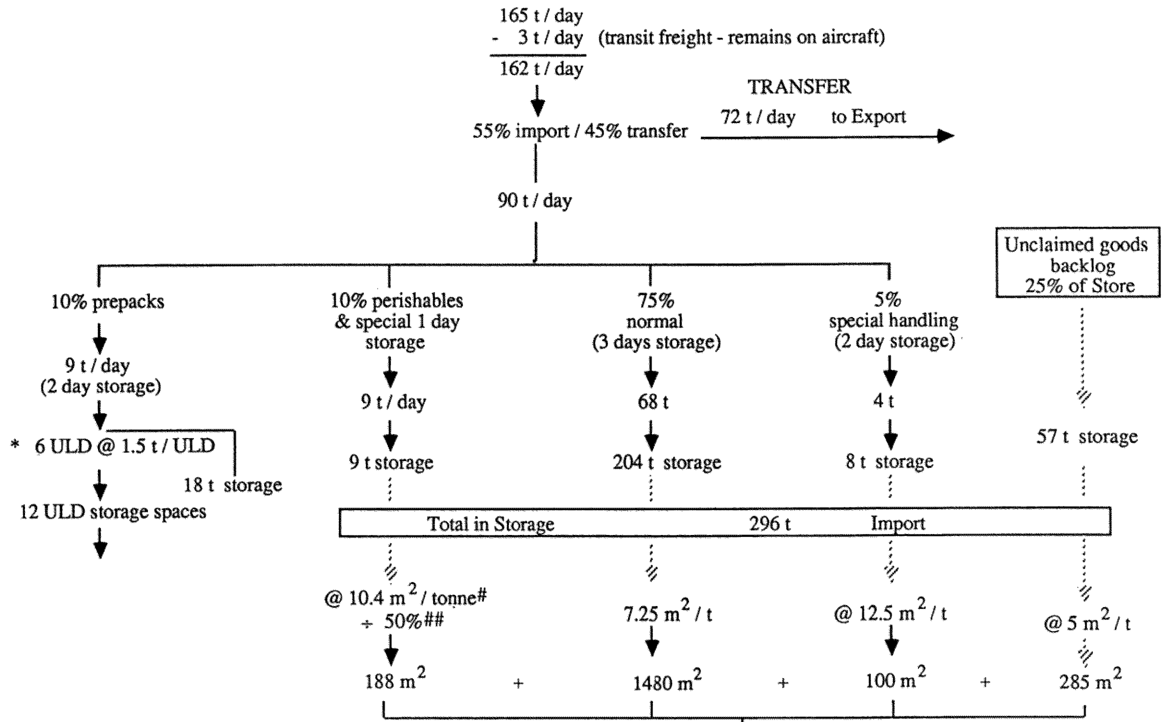
- Inbound storage times:
  prepacks, two days.
  perishables and special freight, one day.
  normal, three days.
  special handling, two days.
- Storage efficiency 90%.
- Storage areas:
  perishables and special freight 10.4m^2/tonne.
  normal 7.25m^2/tonne.
  special handling 12.5m^2/tonne.
  unclaimed goods 5m^2/tonne.
- Only 50% of special goods facilities (e.g., refrigerated, radioactive, etc.) are in use at one time.
- Export storage: 1 day at 12.5m^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 = 5.6m^2.
- Average delivery or pick up per truck land side = 1 tonne.
- Average land side dwell time per truck = 30 min.



INBOUND BREAKDOWN



IMPORT WAREHOUSE



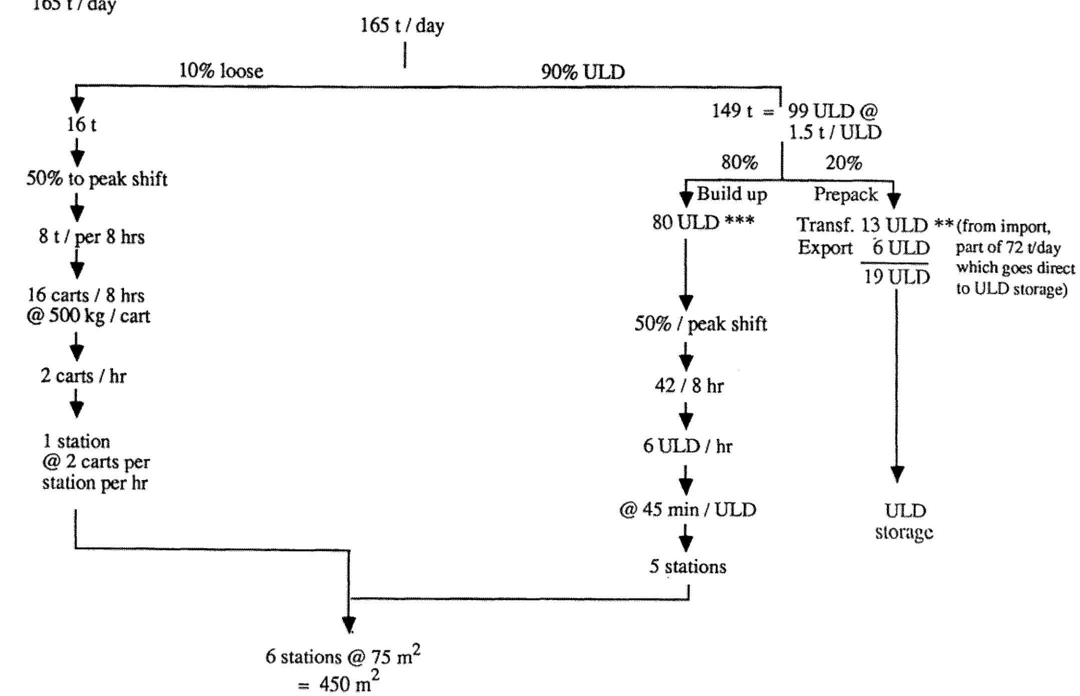
Total area 2053 m^2
Storage efficiency = 90%
Warehouse Storage approx. equal to 2300 m^2

\# *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

165 t
29 t prepacks → ULD storage → 19 ULD
136 t

↓

1 day storage - Floor Storage @ 12.5 m^2 / t

↓

1700 m^2

↓

Storage efficiency - 90%

↓

Warehouse 1900 m^2

ULD SYSTEM SIZING

Assume no physical separation of inbound or outbound

*	(see p.3)	6 = Import prepacks (2 day storage)	= 12
**	(see p.4)	13 = Transfer prepacks (1 day storage)	= 13
***	(see p.4)	80 x 50% of daily build up	= 40
****	(see p.2)	78 x 50% of daily inbound awaiting breakdown	= 39
		Total full ULD	104
		Empty containers / pallet stacks @ 50%	52
		Total storage spaces	156

@ 3 High System 5.6m^2 / ULD = 873.6 = (say) 900 m^2

LANDSIDE CAPACITY

Import

Daily flow	=	90 t
Hourly flow	=	15 t
@ 1 t / truck (including small goods)	=	15 trucks / hr
@ $\frac{1}{2}$ hr / truck	=	8 truck docks
Width = 8 x 4 m	=	32 m
Area = 32 m x 15 m approx.	=	500 m^2
Import inspection (+ 100%)	=	500 m^2
		1000 m^2

Export

Daily flow	=	93 t
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^2
Export				
Landside		500 m^2		
Storage		1900 m^2		
Build up		450 m^2		
		2850 m^2		2850 m^2
ULD System		1000 m^2		1000 m^2
SUB TOTAL				7525 m^2
Aisles, Equipment, Storage Repair, etc. (add 50%)		3763 m^2	approx.	4000 m^2
Airside Staging Area		2000 m^2		2000 m^2
Offices / Staff facilities		500 m^2		500 m^2
			approx.	14,000 m^2
Truck Ramp at 7 m				1500 m^2
				15,500 m^2

Overall check of requirements:

$$\frac{100{,}000 \text{ tonnes / yr}}{15{,}500 \text{ m}^2} = 6.45 \text{ t / m}^2 \text{ / yr} \quad \text{(cf. Table 11.2)}$$

11.12 MAIL AND EXPRESS PARCELS FACILITIES

One area of air freight which grew very rapidly during the 1980s was the transport of express or small parcel freight, usually guaranteed for overnight delivery domestically and everywhere on a rapid door-to-door basis. This freight is often processed through a centralized hub, for example, the Federal Express hubs at Memphis and Brussels, 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 air side and land side. There is little available literature on the design of such facilities. One approach, however, has tackled the estimation of express freight terminal capacity from the viewpoint of flow analysis, recommending a throughput figure of 18.5kg/m^2 or 3.8lb/ft^2 for design purposes (6). Because the annual growth rate of this market is expected to be so rapid until the year 2000 (13% in the United States, 18% in Europe, and 27% in Asia/Pacific) (7), it is essential that terminals be designed with maximum consideration for expansion and flexibility in adopting to changes in handling procedures.

11.13 CONCLUSION

The planning of 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 based on a 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 design 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).

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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 subsections, include the following:

1. Estimation of runoff.

Airport Engineering, Third Edition. Norman Ashford and Paul H. Wright

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, *Airport Drainage* (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.

Rainfall Intensity, Duration, and Frequency. Rainfall intensity is the

TABLE 12.1 Value of Factor C

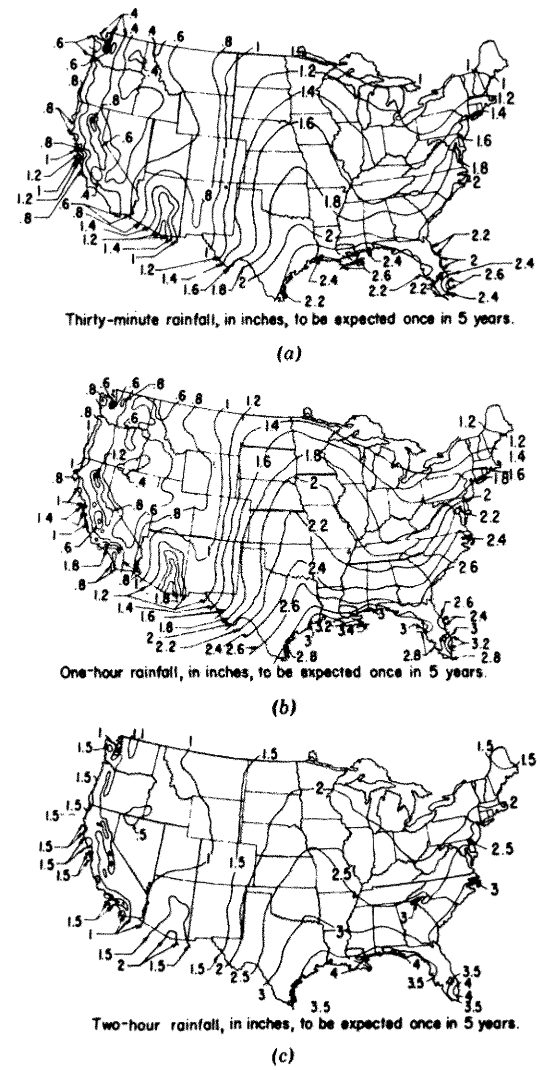
Type of Surface	Factor C
For all watertight roof surfaces	.75–.95
For asphalt runway pavements	.80–.95
For concrete runway pavements	.70–.90
For gravel or macadam pavements	.35–.70
For impervious soils (heavy)[a]	.40–.65
For impervious soils, with turf[a]	.30–.55
For slightly pervious soils[a]	.15–.40
For slightly pervious soils, with turf[a]	.10–.30
For moderately pervious soils[a]	.05–.20
For moderately pervious soils, with turf[a]	.00–.10

[a] For slopes from 1 to 2%.

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 fo 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 conterminous 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 5 years. By spotting the airport location on the charts like those of Figure 12.1, we can determine the amount of rainfall that can be expected once every 5 years for rainfalls lasting 30 min, 1 hr, and 2 hr. For example, Figure 12.1a indicates that a 30 min, 1.37 in. rainfall can be expected to occur in Chicago once every 5 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 in a 1-hour 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:



Thirty-minute rainfall, in inches, to be expected once in 5 years.

(a)

One-hour rainfall, in inches, to be expected once in 5 years.

(b)

Two-hour rainfall, in inches, to be expected once in 5 years.

(c)

FIGURE 12.1 Rainfall frequency maps. (*Source*: Reference 2)

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

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	$0.51 \text{ in.} \times \frac{60}{5}$	$= 6.12$
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.

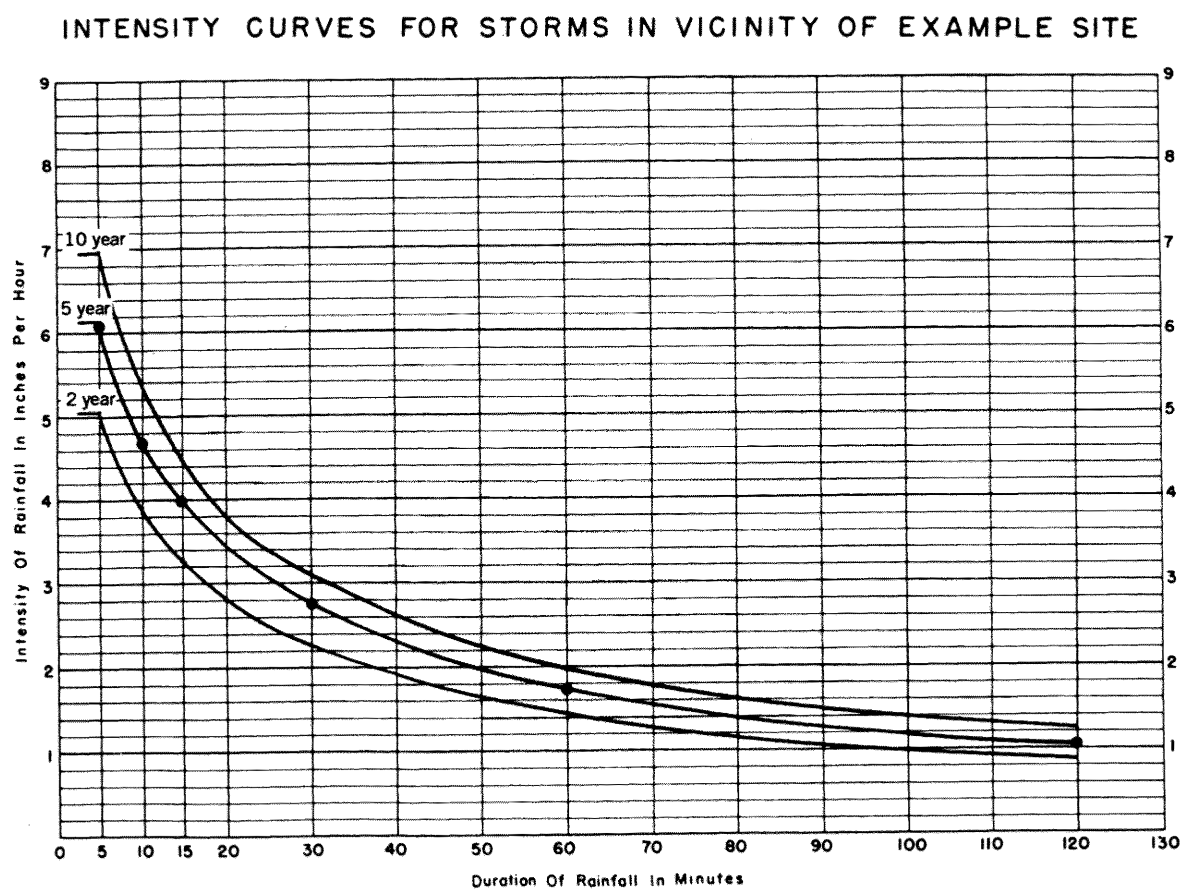


FIGURE 12.2 Intensity-duration curves for storms in vicinity of example site. (*Source*:, *Airport Drainage*, FAA Advisory Circular AC 150/5320-5A, 1965)

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):

$$T \approx \frac{1.8(1.1 - C)(D)^{1/2}}{(S)^{1/3}} \tag{12.1}$$

where

T = surface flow time (min)
C = the 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.

The 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.

$$Q = CIA \tag{12.2}$$

*In the United States, the Soil Conservation Service Method is growing in prominence. It can be used for larger drainage areas (3, 4).

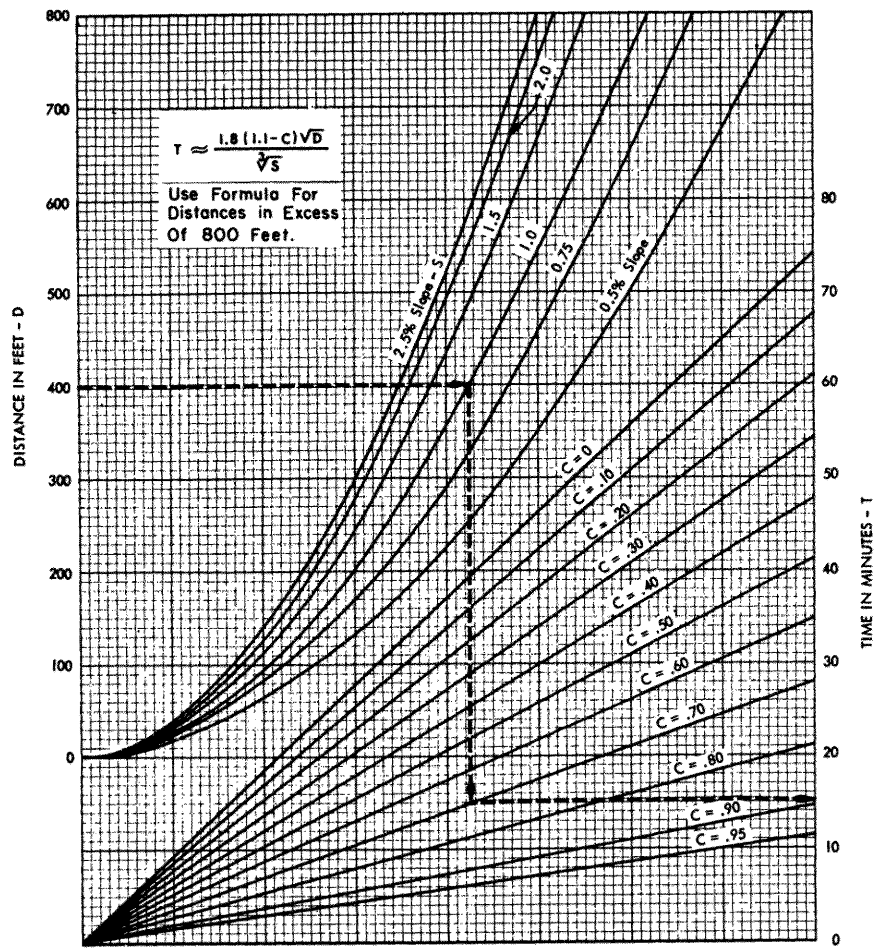


FIGURE 12.3 Surface flow time curves. (*Source*: Reference 1)

where

Q = runoff (cfs)
C = the runoff coefficient (typical values are given in Table 10.1)
I = intensity of rainfall (in/hr for the estimated time of concentration)
A = drainage area (acres); the area may be determined from field surveys, topographical maps, or aerial photographs

Example 12.1, which follows the subsection 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 the drainage system.
2. Design of underground pipe system.
3. Design of open channels.
4. Design of inlets, manholes, and other appurtenances.

Layout of the 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.

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 to 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.

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 to 500 ft on straight segments. A typical runway safety area and runway drainage plan appears in Figure 12.5.

Design of the Underground Pipe System. After 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.

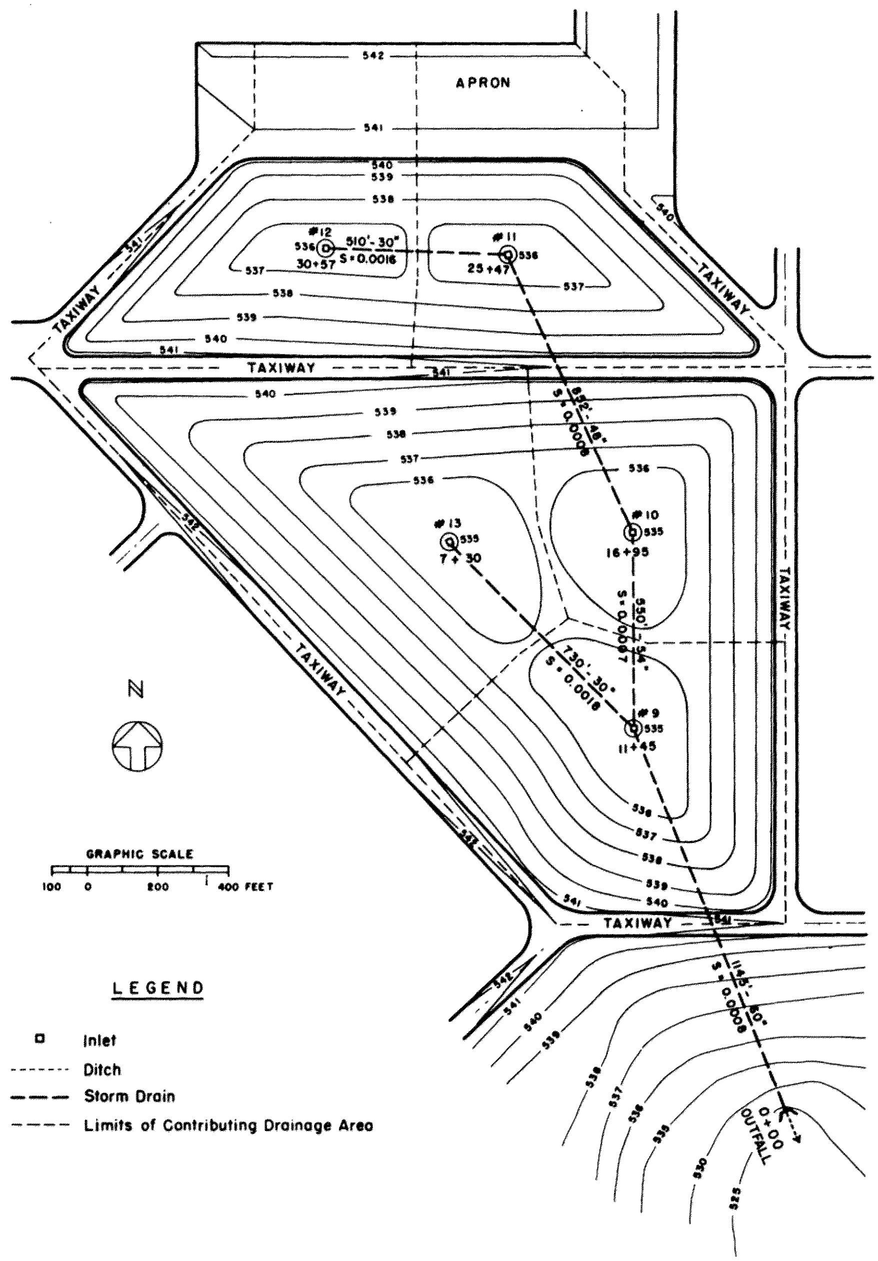


FIGURE 12.4 Portion of airport showing drainage design. (*Source*: Reference 1)

The Manning equation is the most popular formula for the 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:

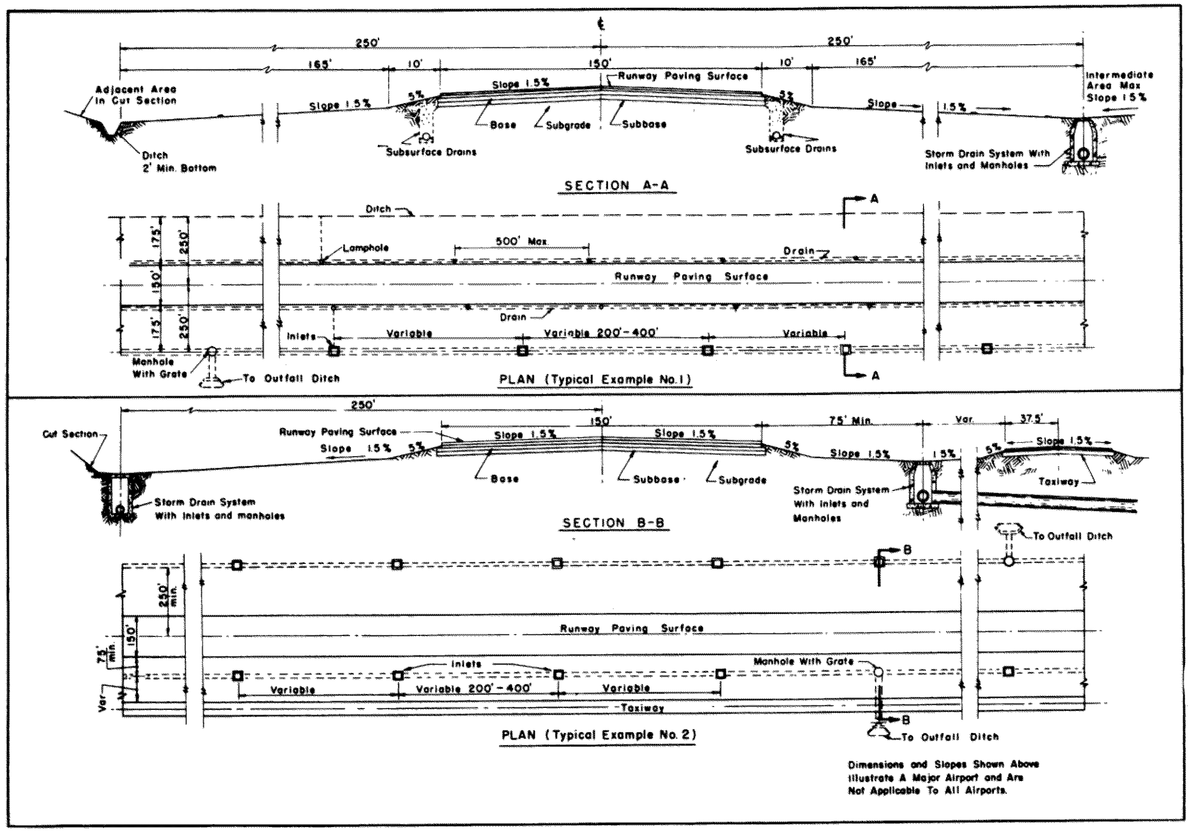


FIGURE 12.5 A typical runway safety area and runway drainage cross-section. (*Source*: Reference 1)

$$Q = \frac{1.486AR^{2/3}S^{1/2}}{n} \tag{12.3}$$

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 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

*This example constitutes a portion of an example published in Reference 1, to which the reader is referred for more detail.

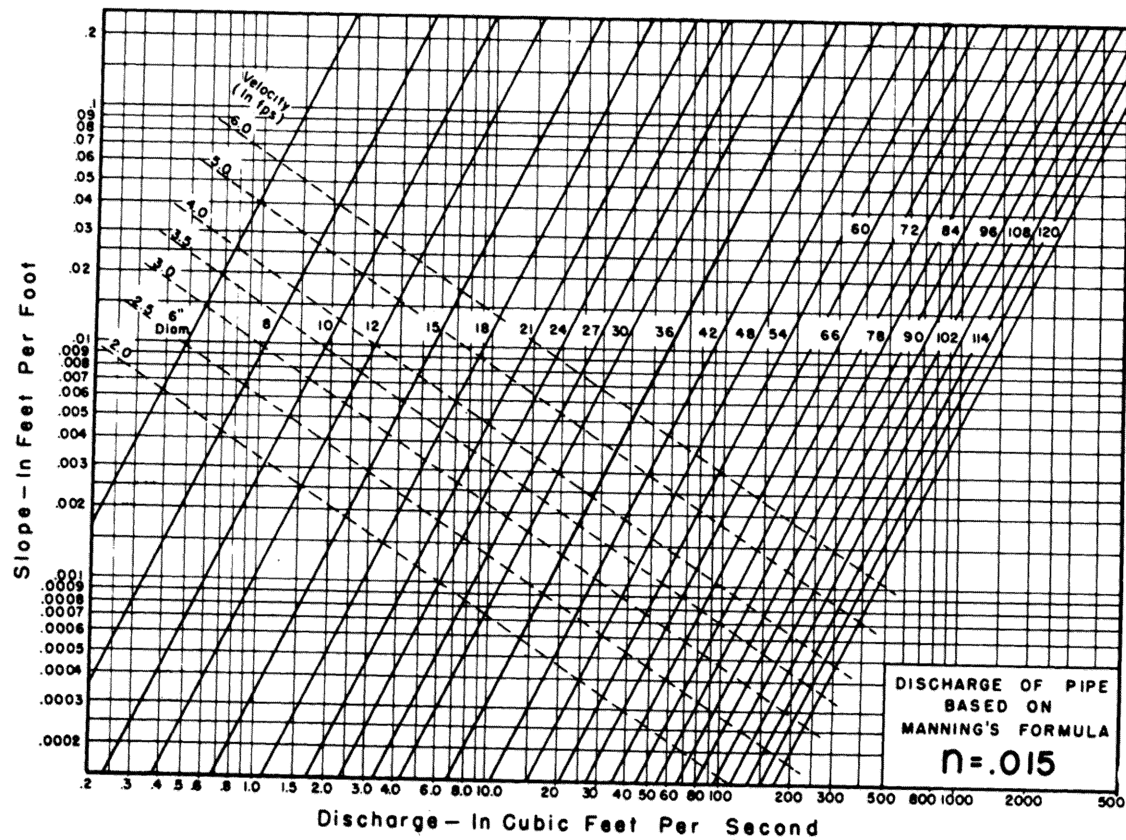


FIGURE 12.6 Design chart for uniform flow. (*Source*: Reference 1)

Use the 5-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 from Figure 10.3 = 4 min, and the surface flow time over turf,

$$T_t \approx \frac{1.8(1.1 - 0.3)(1140)^{1/2}}{(0.6)^{1/3}} = 58 \text{ min}$$

$$\text{total time of surface flow} = 62 \text{ min}$$

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

$$530.38 - (0.0018 \times 730) = 529.07 \text{ ft}$$

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 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 basis 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, t:

$$V_{\text{in}} = Qt = CIAt \tag{12.4}$$

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.

$$V_{\text{out}} = q_{\text{cap}}t \qquad \text{(12.5}$$

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, 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.

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

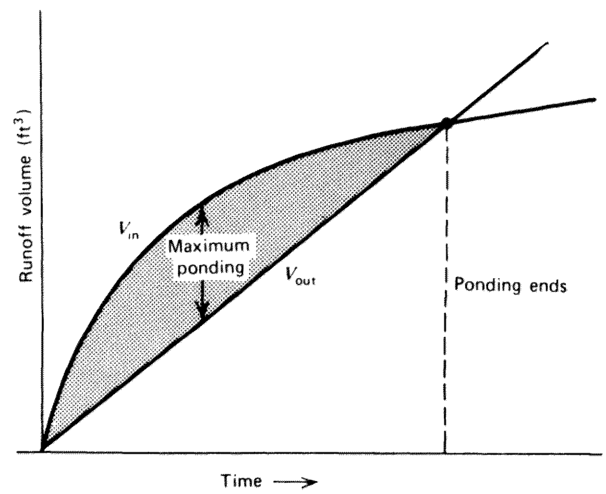


FIGURE 12.7 A cumulative runoff graph.

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+	.011–0.020
Asphalt	12–15+	.013–0.017
Rubble or riprap	20–25	.017–0.030
Earth		
Bare, sandy silt, weathered	2.0	.020
Silt clay or soft shale	3.5	.020
Clay	6.0	.020
Soft sandstone	8.0	.020
Clean gravelly soil	6.0	.025
Natural earth, with vegetation	6.0	.030–.150[a]
Turf		
Shallow flow	6.0	.06–.08
Depth of flow over 1 ft	6.0	.04–.06

Source: *Airport Drainage*, FAA, Advisory Circular AC 150/5320-5B, July 1970.

[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.

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.

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 office 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:

$$Q = CLH^{3/2} \tag{12.7}$$

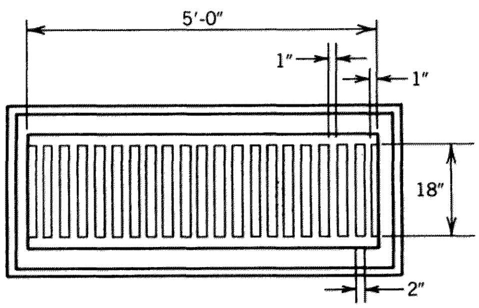
where

C = 3.0
L = gross perimeter of the 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 the use of safety factor of 1.25 for paved areas and 1.5 to 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, (b) with a head of 0.4 feet.



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 inc. 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 of $H = 0.4$ 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.

> 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 3½ ft and a height of 4 ft are usually considered sufficient, but they can be varied to suit particular situations (1).

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.

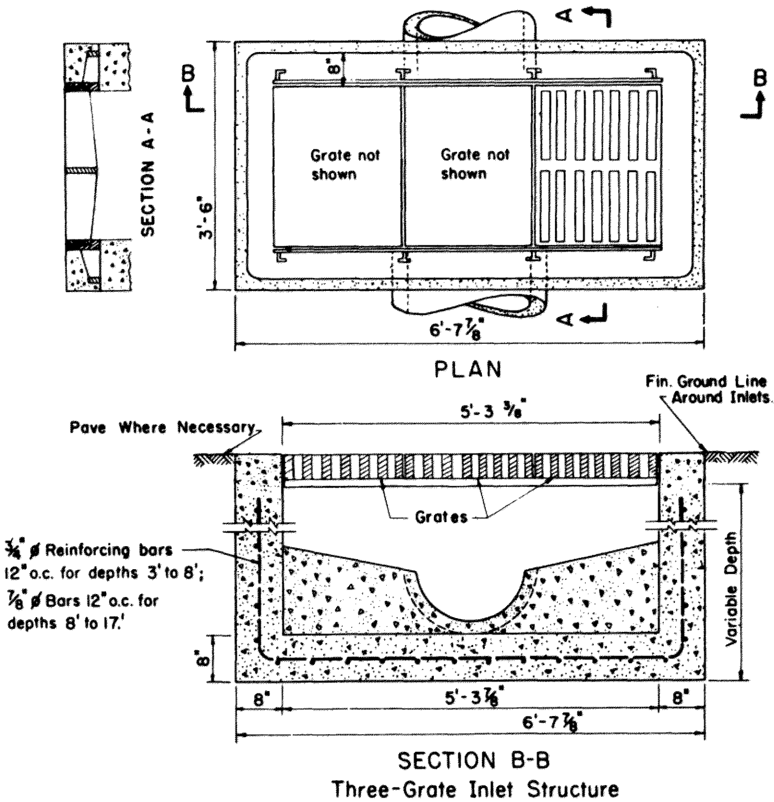


FIGURE 12.8 A typical three-grate inlet structure. (*Source*: Reference 1)

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 weakening of pavement foundation layers and to control or prevent damaging frost heave.*

Subsurface drainage has at least three functions: (1) to drain and upgrade wet soil masses, (2) to intercept and divert subsurface flows, and (3) 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 to 2.0 wide and backfilled with a

*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.

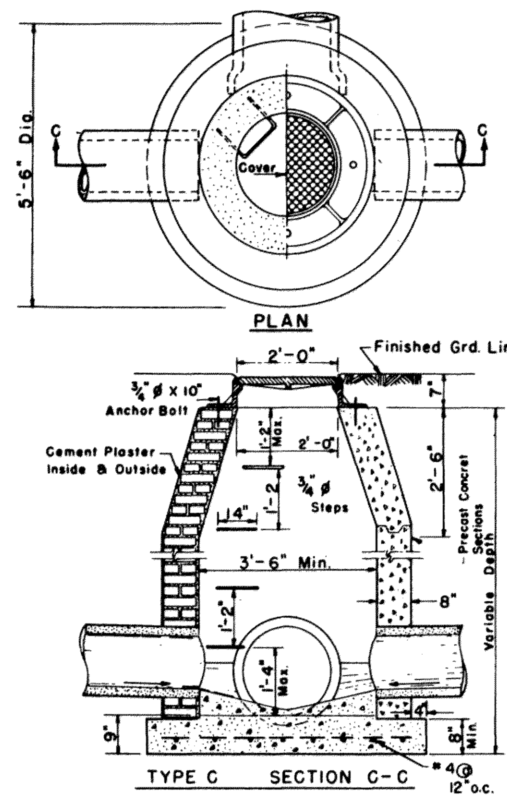


FIGURE 12.9 A suggested manhole design. (*Source*: Reference 1)

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.

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 to 0.50 in./acre in 24 hr be used. With appropriate unit conversion, this corresponds to a flow rate of 0.0105 to 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 backfill 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).

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 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. Since 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.

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, consisting of lower quality and less expensive material than that used in the base course, is sometimes employed. 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 slab of portland cement concrete 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 proposed for the structural design of airport pavements. Most are extensions of method 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 subsections that follow briefly describe some of the most popular design methods. First, we discuss some of the significant effects on pavement performance.

Factors That Influence 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.

TABLE 12.3 Variables That Influence Pavement Performance (9)

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 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 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) the 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 bleeding; (3) variables associated with the aircraft, such as jet blast, heat, and fuel spillage; and (4) the 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. Nevertheless, currently available design procedures, which contain empirical factors based on pavement performance, "will give generally good designs within the limits from which the methods were developed" (10). However, the reader is cautioned 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" (10).

12.6 FLEXIBLE PAVEMENT DESIGN METHODS (U.S. PRACTICE)

The California Bearing Ratio Method. The California bearing ratio (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. 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 CBR method is based on a relatively simple test of the shear strength of the supporting soil.

> 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 . . . (11).

The Departments of the Army and Air Force (11) 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 (12). 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:

$$t = \left[\frac{P}{8.1(\text{CBR})} - \frac{A}{\pi}\right]^{1/2} \tag{12.9}$$

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*):

$$t = f\left[\frac{ESWL}{8.1(\text{CBR})} - \frac{A}{\pi}\right]^{1/2} \tag{12.10}$$

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" (12)
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 12.10 for low-intensity traffic is adequate for all wheel-gear configurations. However, with an increase in coverages, the equation yields thickness 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:

$$t = \alpha_i\left[\frac{ESWL}{8.1(\text{CBR})} - \frac{A}{\pi}\right]^{1/2} \tag{12.11}$$

where

α_i = 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 12.4 lists representative load repetition factors.

Equation 12.9 is recommended for CBR values of 15 or less. For CBR values greater than 15, minimum pavement thickness based on durability may apply.

TABLE 12.4 Recommended Load Repetition Factors, α_i, for Use in Equation 12.9

	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: G. M. Hammitt II, 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.

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 12.9 for CBR, one may then develop a CBR versus design thickness curve for a particular aircraft.

A simple graphical procedure based on the California bearing ratio is recommended for the design of flexible pavements for military airfields. Fourteen CBR design curves, exemplified by Figure 12.10 have been published (11) for various classes of military usage and gear configurations (See Table 12.5).

The following procedure is recommended for use of the curves:

1. Determine design CBR of subgrade.

TABLE 12.5 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 shortfield pavement, Type A traffic areas and overruns

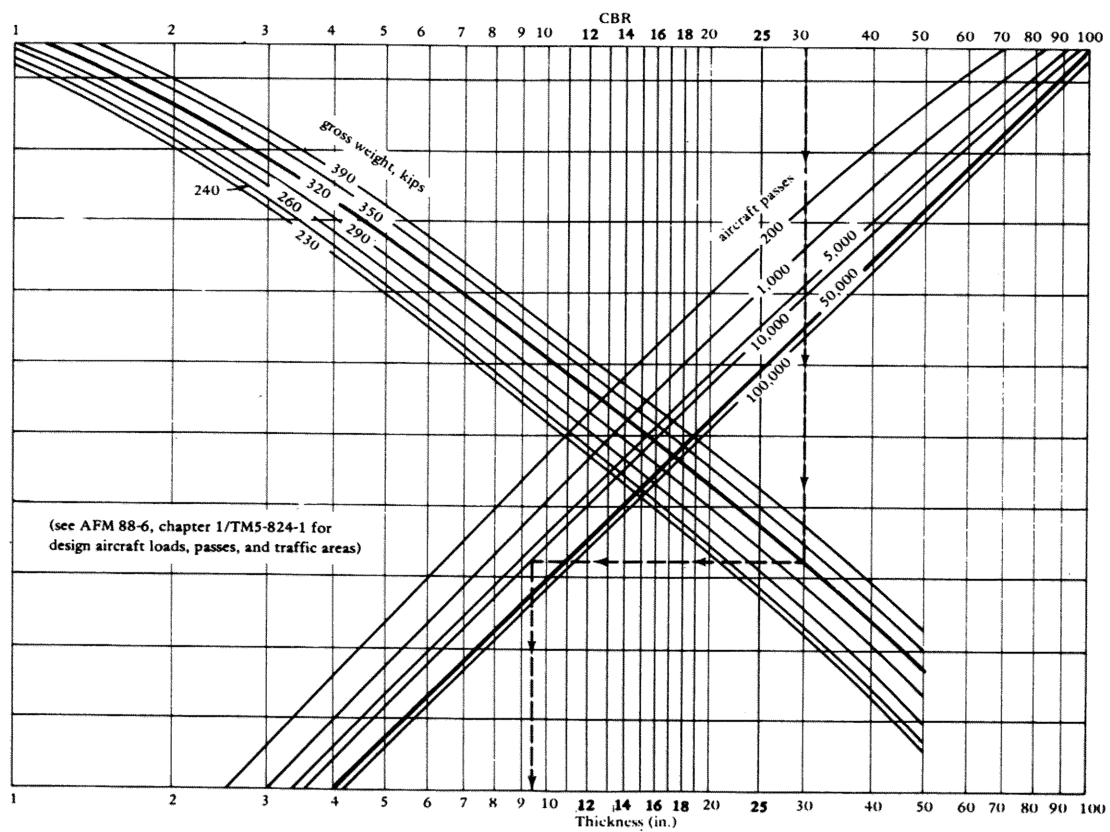


FIGURE 12.10 Example of California bearing ratio (CBR) design curve. (*Source:* Reference 13)

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 required total pavement thickness above subgrade.

The thickness of 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 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.

The FAA Method of Flexible Pavement Design. The FAA method (8) of flexible pavement design calls for accurate identification and evaluation of pavement foundation 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 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) recommends the use of the Unified Soil Classification System. 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. Specifically, the Unified Classification System 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.

Fifteen soil groups comprise the Unified Classification System. 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 12.6 Classification of Soils for Airport Pavement Applications

Major Divisions	Group Symbols	Field CBR	Subgrade Modulus, *k*
Coarse-grained			
Soils more than 50% retained on No. 200 sieve[a]			
Gravels 50% or more of coarse fraction retained on No. 4 sieve			
Clean gravels	GW	60–80	300 or more
	GP	35–60	300 or more
Gravels with fines	GM	40–80	300 or more
	GC	20–40	200–300
Sands less than 50% of coarse fraction retained on No. 4 sieve			
Clean sands	SW	20–40	200–300
	SP	15–25	200–300
Sands with fines	SM	20–40	200–300
	SC	10–20	200–300
Fine-grained			
Soils 50% or less retained on No. 200 sieve[a]			
Silts and Clays	ML	5–15	100–200
Liquid Limit	CL	5–15	100–200
50% or less	OL	4–8	100–200
Silts and Clays	MH	4–8	100–200
Liquid Limit	CH	3–5	50–100
Greater than 50%	OH	3–5	50–100
Highly organic soils	PT		

[a] Based on the material passing the 3-in (75-mm) sieve.

Source: *Airport Pavement Design and Evaluation*, FAA Advisory Circular AC 150/5320-C, including changes 1 and 2, September 14, 1988

Table 12.6 gives the criteria for classifying soils into the major divisions. Additional criteria for determining the specific soil class are given in Table 12.7. The coefficients of uniformity (C_u) and curvature (C_c) referred to in Table 12.7 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:

$$C_u = D_{60}/D_{10} \tag{12.12}$$

$$C_c = (D_{30})^2/(D_{10} \times D_{60}) \tag{12.13}$$

In these equations, the term D_{10} refers to the grain size (diameter) that corresponds to 10% on the grain size distribution curve. D_{30} and D_{60} have similar meanings.

TABLE 12.7 Soil Classification Based on Unified Soil Classification System

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests				Group Symbol (Soil Classification)	Group Name (Soil Classification)
Coarse-grained soils More than 50% retained on No. 200 sieve	Gravels More than 50% of coarse fraction retained on No. 4 sieve	Clean gravels Less than 5% fines[a]	$Cu \geq 4$ and $1 \leq Cc \leq 3$[c]	GW	Well-graded gravel
			$Cu < 4$ and/or $1 > Cc > 3$[c]	GP	Poorly graded gravel
		Gravels with fines more than 12% fines[a]	Fines classify as ML or MH	GM	Silty gravel
			Fines classify as CL or CH	GC	Clayey gravel
	Sands 50% or more of coarse fraction passes No. 4 sieve	Clean sands Less than 5% fines[b]	$Cu \geq 6$ and $1 \leq Cc \leq 3$[c]	SW	Well-graded sand
			$Cu < 6$ and/or $1 > Cc > 3$[c]	SP	Poorly graded sand
		Sands with fines More than 12% fines[b]	Fines classify as ML or MH	SM	Silty sand
			Fines classify as CL or CH	SC	Clayey sand
Fine-grained soils 50% or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	Inorganic	$PI > 7$ and plots on or above "A" line[d]	CL	Lean clay
			$PI < 4$ or plots below "A" line[d]	ML	Silt
		Organic	$\frac{\text{Liquid limit — oven dried}}{\text{Liquid limit — not dried}} < 0.75$	OL	Organic clay Organic silt
	Silts and Clays Liquid limit 50 or more	Inorganic	PI plots on or above "A" line[d]	CH	Fat clay
			PI plots below "A" line[d]	MH	Elastic silt
		Organic	$\frac{\text{Liquid limit — oven dried}}{\text{Liquid limit — not dried}} < 0.75$	OH	Organic clay Organic silt
Highly organic soils	Primarily organic matter, dark in color, and organic color			PT	Peat

[a] Gravels with 5 to 12% fines require dual symbols: GW-GM well-graded gravel with silt; GW-GC well-graded gravel with clay; GP-GM poorly graded gravel with silt; GP-GC poorly graded gravel with clay.

[b] Sands with 5 to 12% fines require dual symbols: SW-SM well graded sand with silt; SW-SC well-graded sand with clay; SP-SM poorly graded sand with silt; SP-SC poorly graded sand with clay.

[c] Refer to Equations 12.12 and 12.13.

[d] See Figure 12.11.

Source: Standard Test Method for Classification of Soils for Engineering, Designation D 2487-85, Philadelphia: American Society for Testing Materials, 1990.

Fine-grained soils are classified on the basis of liquid limit and plasticity index (see Figure 12.11).

A listing of the group symbols and an abbreviated description of each group reveals the general rationale for the Unified Classification System:

Gravels

GW—Well-graded gravels.
GP—Poorly graded gravels.
GM—Silty gravels.
GC—Clayey gravels.

Sands

SW—Well-graded sands.
SP—Poorly graded sands.
SM—Silty sands.
SC—Clayey sands.

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.

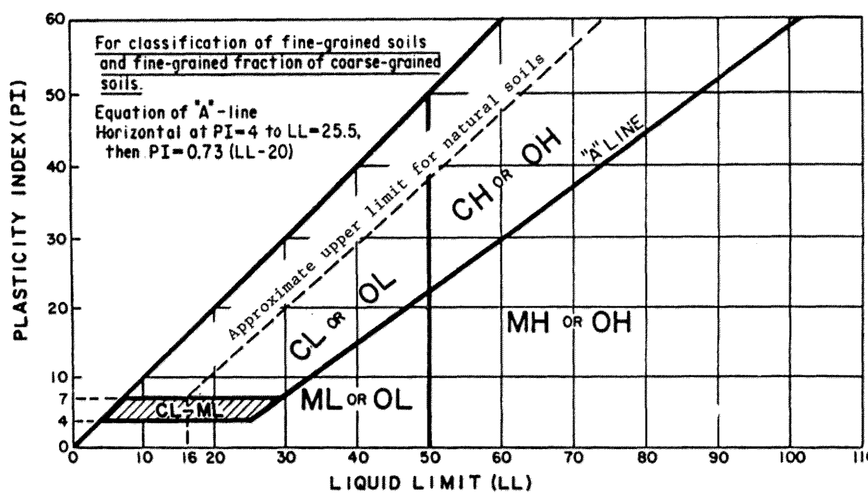


FIGURE 12.11 Graph for classification of fine-grained soils according to the Unified Soil Classification System. (*Source*: *Standard Test Method for Classification of Soils for Engineering*, ASTM, 1990)

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 Unified Classification System 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 CBR or plate-bearing tests. For flexible pavements, the FAA recommends the use of CBR tests. A comparison of CBR values and the various Unified Soil Classes is given in Table 12.6.

Load and Traffic Considerations. The FAA design method is based on total gross aircraft weight, which, for design purposes, is assumed to be the maximum takeoff weight. Since the maximum landing weight is usually only about 75% of the maximum takeoff weight, traffic is expressed in departures. Pavement design curves, exemplified by Figure 12.12, have been published in Reference 8 for single, dual, and dual-tandem landing gear configurations. Separate design curves have been provided for wide-bodied aircraft, such as the B-747, DC-10 and L-1011.

Usually it is necessary to account for the cumulative effect of wheel loads from several classes of aircraft. This is accomplished by expressing the traffic levels in terms of "equivalent annual departures by the design aircraft." The design aircraft is the aircraft type that produces the greatest pavement thickness. To select the design aircraft, it is necessary to determine the pavement thickness required for each aircraft type in the forecast by using the appropriate design curve with the forecast number of annual departures for that aircraft.

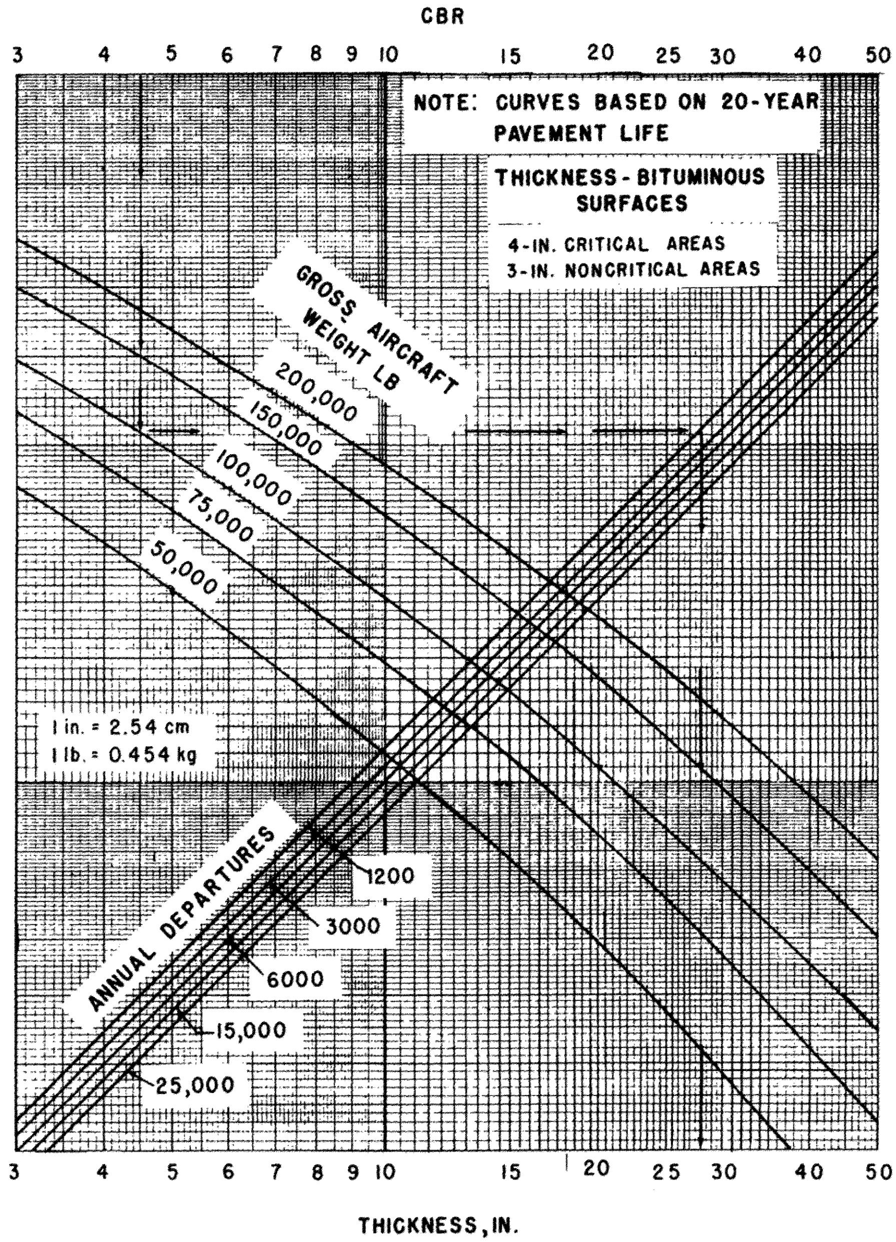


FIGURE 12.12 Flexible pavement design curves for critical areas, dual-wheel gear. (*Source*: Reference 8)

To account for the effects of all traffic in terms of the design aircraft, convert all aircraft to the same landing gear type as the design aircraft. This is done by multiplying the number of departures by a factor selected from Table 12.8.

TABLE 12.8 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: Airport Pavement Design and Evaluation, FAA Advisory Circular AC 150/5320-6C, including changes 1 and 2, September 14, 1988.

Then, to compute the equivalent design departures, the FAA (8) recommends the use of the following equation:

$$\log R_1 = \log R_2 \left(\frac{W_2}{W_1}\right)^{1/2} \qquad (12.14)$$

where R_1 and R_2 are repetitions of loadings or departures and W_1 and W_2 are corresponding wheel loads.

EXAMPLE 12.4 EQUIVALENT DESIGN DEPARTURES

An airport pavement is to be designed for the traffic mix tabulated below. Convert the traffic to equivalent DC-8-61 departures.

Aircraft (Wheel Configuration)	Departures, R	Load per Wheel, W
CV-880 (Dual-tandem)	3,100	21,800
DC-9-32 (Dual)	11,00	25,200
DC-8-61 (Dual-tandem)	3,000	39,400

For the CV-880 group,

$$\log R_1 = \log(1 \times 3{,}000) \left(\frac{21{,}800}{39{,}400}\right)^{1/2} = 2.5966$$

$$R_1 = 395$$

For the DC-9-32 group,

$$\log R_1 = \log(0.6 \times 11{,}000) \left(\frac{25{,}200}{39{,}400}\right)^{1/2} = 3.0547$$

$$R_1 = 1134$$

For the DC-8-61 group, $R_1 = 3000$, and

$$\text{total equivalent DC-8-61 departures} = 395 + 1134 + 3000 = 4529$$

The designer should recognize that different parts of a runway-taxiway system are subjected to varying demands because of differences in concentrations of traffic and aircraft speeds. Heaviest traffic concentrations tend to be near the runway ends and laterally near the runway and taxiway centerlines. The demands on pavements for aprons, taxiways, and runway ends tend to be greater because traffic moves at slower speeds in those areas.

The design 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 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).

Pavements for Lightweight 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. Bituminous pavements are generally used for pavements serving lightweight aircraft, and a high type bituminous surface course, such as bituminous concrete, is preferred. Figure 12.13 displays thickness design curves for pavements serving aircraft weighing less than 30,000 lb, based on the California bearing ratio. The thicknesses from the curves should not be reduced for "noncritical" areas of the runway-taxiway system.

The Asphalt Institute Method. The Asphalt Institute Method is based on the theory that the asphalt pavement structure is a multilayer elastic system. In this approach, characteristics of both the asphalt concrete and the subgrade are described by the classical terms "Poisson's ratio" and "modulus of elasticity" (14). Two critical load-induced elastic strains are separately examined in the design analysis: (1) the horizontal tensile strain, at the bottom of the asphalt concrete layer (surface course), and (2) the vertical compressive strain, at the top of the subgrade layer. Maximum allowable values for these two strains have been established, and thicknesses are determined to satisfy these values. The larger thickness is chosen as the design thickness. The design

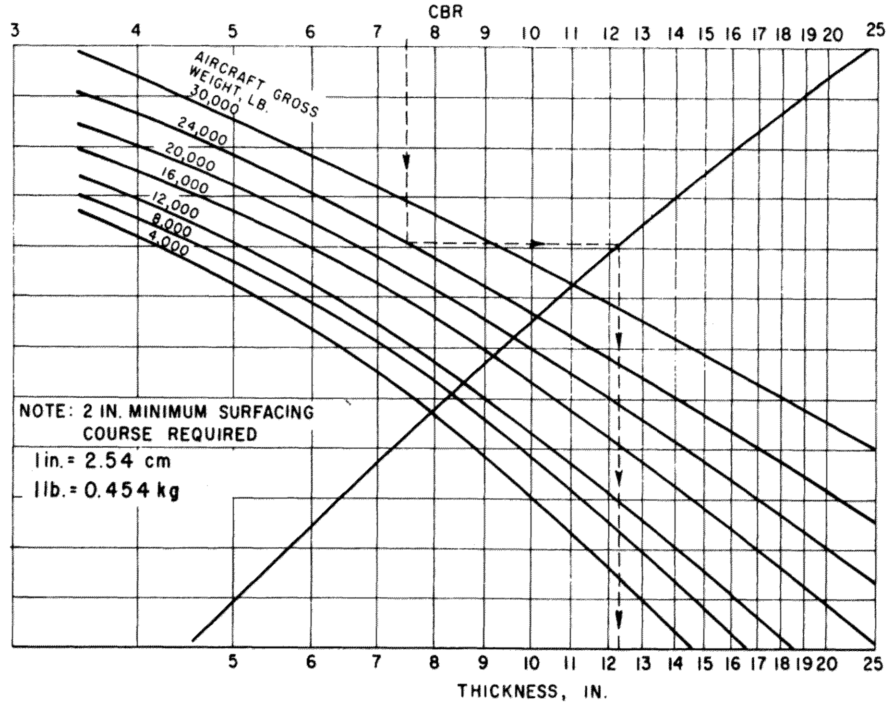


FIGURE 12.13 Design curves for flexible pavements—light aircraft. (*Source*: Reference 8)

method is available in the form of a computer program from the Asphalt Institute. Space limitations preclude the inclusion of an in-depth discussion of this subject. The reader is referred to the Asphalt Institute's Manual Series No. 11 (14) for a full description of the method.

12.7 RIGID PAVEMENT DESIGN METHODS (U.S. PRACTICE)

Ray, Cawley, and Packard (15) 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 (16), 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 (17). Using Westergaard's formulas, Pickett and Ray developed influence charts for analyzing pavement stresses and published them in transactions of ASCE in 1951 (18). 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 in 1967 (19).

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 designated as CAA) and the Portland Cement Association, published design procedures reflecting pavement condition surveys that were made to evaluate pavement performance with respect to the thickness design procedures employed. The Portland Cement Association conducted such a survey in the late 1940s in cooperation with the CAA. PCA performed additional surveys at civilian airports in 1962 and 1963 (2), 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. (15) compared four methods for designing and determining the thickness of rigid airport pavements. The methods employed the FAA, the Portland Cement Association, 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 that

> [D]ifferences 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 (15).

To avoid redundancy, the rigid pavement design methods of the Navy, the Portland Cement Association, and the Corps of Engineers are not described in this chapter. For detailed information, the reader should consult the respective references (10, 21, 22) at the end of this chapter. In the following description of the FAA design method, we have drawn freely on Reference 8.

The FAA Method of Rigid Pavement Design. The FAA has published design curves for rigid pavements similar to those for flexible pavements. Separate graphs, exemplified by Figure 12.14 are given in Reference 8 for single, dual, and dual-tandem landing gear assemblies. Design curves have also been prepared for the B-747, DC-10 and L-1011 aircraft. To use the design curves, information is required on the flexural strength of the concrete, the subgrade modulus, and the gross weight and annual departures of the design aircraft. One enters the design curves with the 90-day flexural strength of the concrete as determined by the American Society for Testing Materials test method T-78.

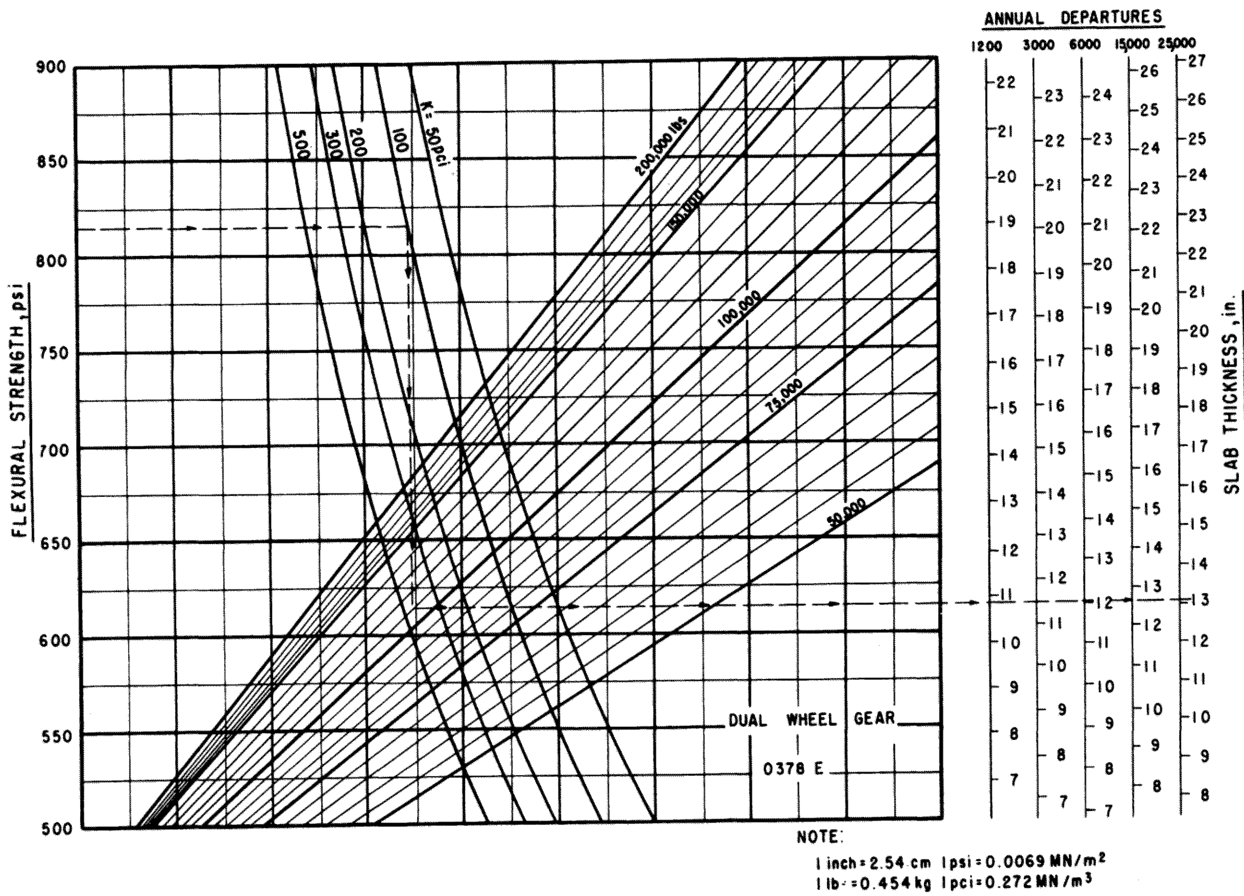


FIGURE 12.14 Rigid pavement design curves—dual-wheel gear. (*Source*: Reference 8)

The strength of the supporting subgrade or subbase is determined by 30 in. diameter plate-bearing tests conducted in accordance with test procedures specified by the American Association of State Highway and Transportation Officials procedure T-222. It is reported as a "k-value," which is referred to as the modulus of subgrade reaction. The k-value is measured in pounds per square inch of loaded area, divided by the deflection in inches of the subgrade under load. If the construction and evaluation of a test section is impractical, the approximate k-values shown in Table 12.6 may be used.

As was the case in flexible pavement design, the FAA design method is based on the total gross aircraft weight (i.e., the maximum takeoff weight). The equivalent design aircraft departures must be computed as described previously.

From the left ordinate of Figure 12.14, representing the flexural strenght of the concrete, a line is extended horizontally to its intersection with the foundation modulus line, vertically to the gross weight line, then horizontally to the right ordinate where the pavement thickness can be read from the appropriate annual departure line.

The thickness shown on the design graphs are for critical areas. For non-critical areas such as exit taxiways, a thickness of 0.9 times the critical thickness may be used.

Subbases are commonly placed under concrete slabs to provide drainage and a more stable and uniform foundation. The FAA requires that a minimum thickness of 4 in. of subbase be placed under all rigid pavements, except as noted in Table 12.9. If economical, subbase thickness in excess of 4 in. may be used to increase the modulus of subgrade reaction and reduce the required thickness of concrete. The cost of additional subbase thickness should be weighed against the savings of reducing the concrete thickness (8). The probable increase in the k-value due to the use of a subbase depends on the thickness and type of subbase material. Some guidance on the magnitude of this increase is given by Reference 8. The FAA recommends that stabilized subbases be placed under all new rigid pavements expected to accommodate aircraft weighing more than 100,000 lb gross weight.

TABLE 12.9 Conditions Where No Subbase Is Required

	Good Drainage		Poor Drainage	
Soil Classification	No Frost	Frost	No Frost	Frost
GW	X	X	X	X
GP	X	X	X	
GM	X			
GC	X			
SW	X			

Source: *Airport Pavement Design and Evaluation*, FAA Advisory Circular AC 150/5320-6C, December 7, 1978.

Reinforced Concrete Pavement. Reinforcing 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 slabs. The amount of steel in conventionally reinforced pavements depends on the joint spacing, slab thickness, and other factors; typically, 0.05 to 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 for 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 (22) requires reinforcement to control cracking (1) in odd-shaped slabs, (2) at mismatched joints in adjacent pavements, (3) in pavements incorporating heating pipes, (4) in pavements containing utility blockouts, such as storm drainage inlets, hydrant refueling outlets, and certain types of flush lighting fixtures, and (5) 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, 21, 22).

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. Various types of joints are shown in Figure 12.15, typical uses of these joints are described in Table 12.10.

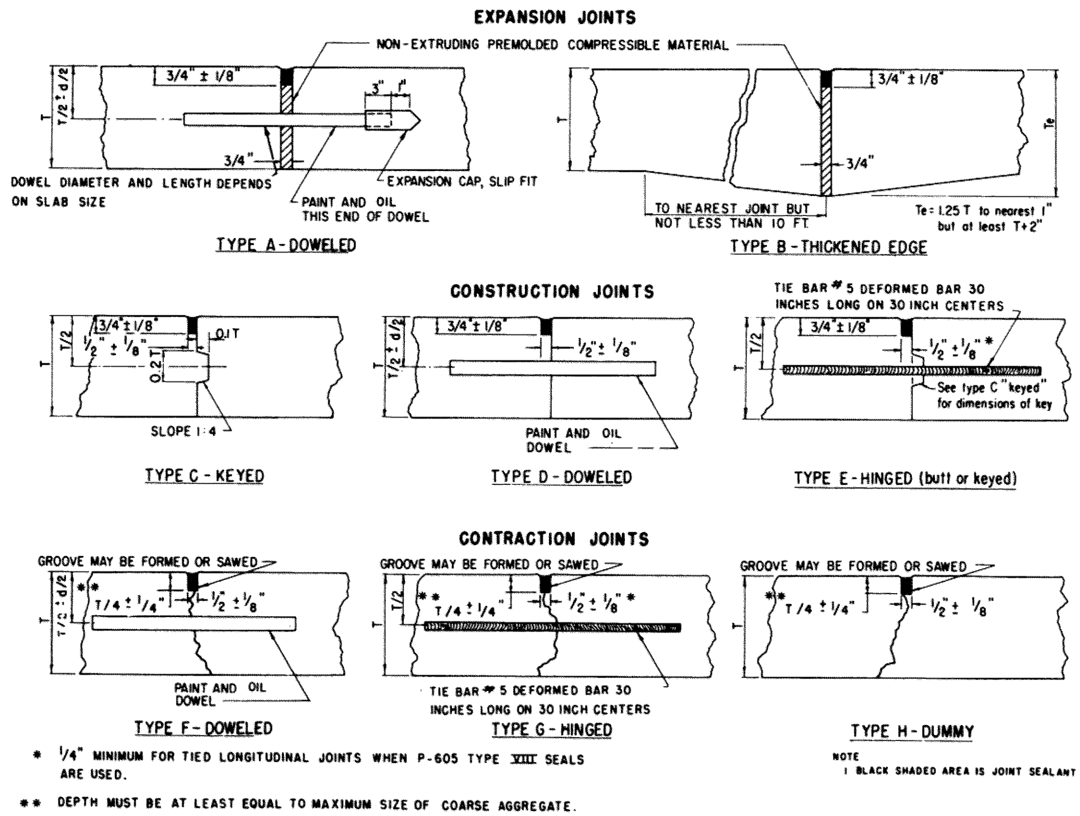


FIGURE 12.15 Details of joints in rigid pavement. (*Source*: Reference 8)

TABLE 12.10 Joint Types: Description and Use

Type	Description	Longitudinal	Transverse
A	Doweled expansion joint	—	Use near intersections to isolate them
B	Thickened edge expansion joint	Use at intersections where dowels are not suitable and where pavements abut structures	Provide thickened edge (or keyway) where pavement enlargements is likely
C or D	Keyed or doweled construction joint	Use for all construction joints except where type E is used; keyed joints are not recommended for slabs <9 in. thick	Use type D where paving operations are delayed or stopped
E	Hinged construction joint	Use for all contraction joints of the taxiway and for all other contraction joints placed 25 ft or less from the pavement edge, unless wide-body aircraft are expected	—
F	Doweled contraction joint	—	Use for contraction joints for a distance of at least three joints from a free edge, for the first two joints on each side of expansion joints, and for all contraction joints in reinforced pavements
G	Hinged contraction joint	Use for all contraction joints of the taxiway and for all other contraction joints placed 25 ft or less from the pavement edge, unless wide-body aircraft are expected	
H	Dummy contraction joint	Use for all other contraction joints in pavement	Use for all remaining contraction joints in nonreinforced pavements

Source: *Airport Pavement Design and Evaluation*, FAA Advisory Circular AC 150/5320-6C, including changes 1 and 2, September 14, 1988.

There are three functional classes of pavement joints: expansion, contraction, and construction joints.

1. *Expansion 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 that provide load transfer across the joint (Type A, Figure 12.15), and those that do not (Type B).
2. *Contraction joints* provide controlled cracking of the pavement that occurs because of contraction. The contraction may be caused by a decrease in moisture content, a drop in temperature, or by 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 F, G, and H in Figure 12.15.
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 Types C, D, and E in Figure 12.15 (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 12.11 summarizes the recommended spacing of joints for nonreinforced pavements. In conventionally reinforced pavements, the maximum allowable slab length is 75 ft (8). The Portland Cement Association recommends a maximum join spacing of 30 to 40 ft for pavements less than 12 in. thick and 50 ft for thicker pavements. With the exceptions noted earlier, continuously reinforced pavements are constructed without transverse joints.

TABLE 12.11 Recommended Maximum Joint Spacings for Nonreinforced Pavements

	Spacing (ft)	
Slab Thickness (in.)	Transverse	Longitudinal
Less than 9	15	12.5
9–12	20	20
Greater than 12	25	25

Source: *Airport Pavement Design and Evaluation*, FAA Advisory Circular AC 150/5320-6C, including changes 1 and 2, September 14, 1988.

12.8 AIRCRAFT AND PAVEMENT CLASSIFICATION NUMBERS

In 1981, the ICAO (23) 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 23 and 24.

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 California Bearing Ratio. (See Table 12.12)

Step 2. Using the reference thickness obtained in Step 1, obtain a derived single-wheel load for the selected subgrade category from Figure 12.16.

TABLE 12.12 Subgrade Categories for ACN-PCN Method

Subgrade Category	Modulus of Subgrade Reaction, psi/inch (Rigid Pavements)	California Bearing Ratio (Flexible Pavements)
High	550	15
Medium	300	10
Low	150	6
Ultra Low	75	3

Source: Aircraft Loading on Airport Pavements, ACN-PCN, Aerospace Industries Association of America, Inc., March, 1983.

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 12.16.

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 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 12.12)

Step 2. Using the reference thickness obtained in Step 1, obtain a derived single-wheel load for the selected subgrade category from Figure

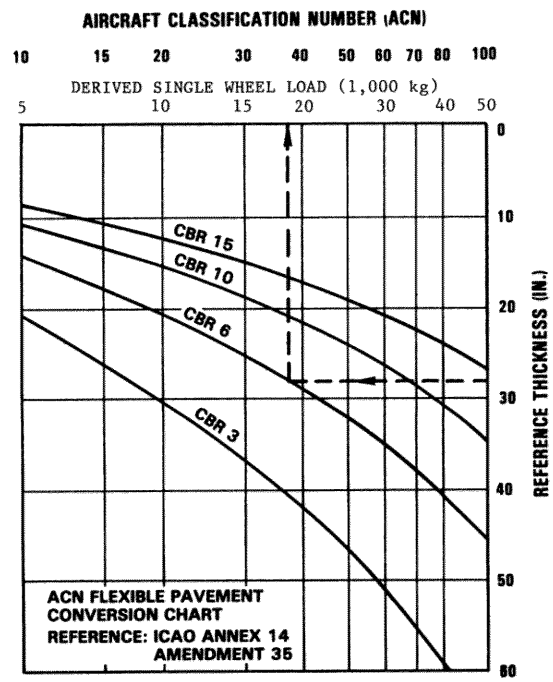


FIGURE 12.16 ACN flexible pavement conversion chart. (*Source*: Reference 24)

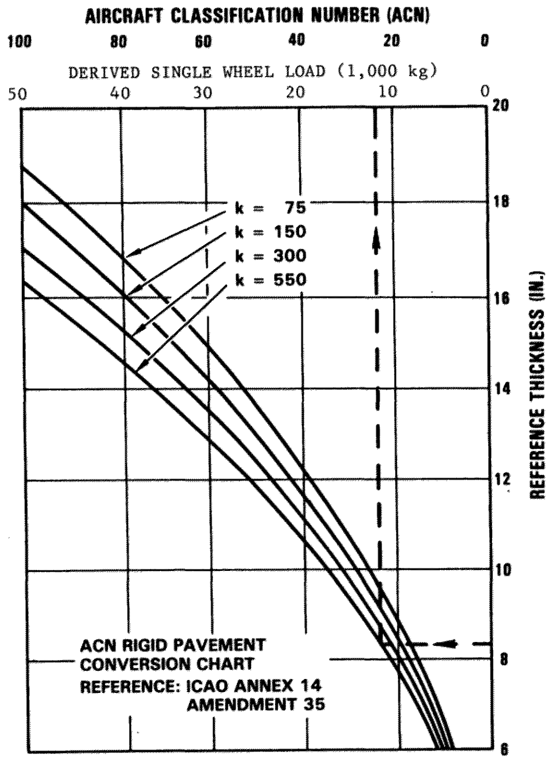


FIGURE 12.17 ACN rigid pavement conversion chart. (*Source*: Adapted from Reference 24)

12.17. 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 12.17.

Computer programs to determine ACN values have been developed by the U.S. Army Corps of Engineers Waterway Experiment Station and the Portland Cement Association for flexible and rigid pavements, respectively (23). For many aircraft currently in use, ACN values have been published by the ICAO (23), eliminating the need to use the programs or the graphical procedures.

Determination of Pavement Classification Numbers (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:

(1) make a technical evaluation, and (2) 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 (23) recommends that, in addition to a PCN, airport authorities publish the following information about each pavement:

1. Pavement type (rigid or flexible).
2. Subgrade strength category (high, medium, low, ultra low).
3. Maximum tire pressure allowable.
4. The evaluation method used to establish the PCN.

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13

AIRPORT ACCESS

13.1 THE 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. After the war, 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 brought about by the introduction of aircraft of an advanced technology. 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 resemblence 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 40 years. It is shown 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.

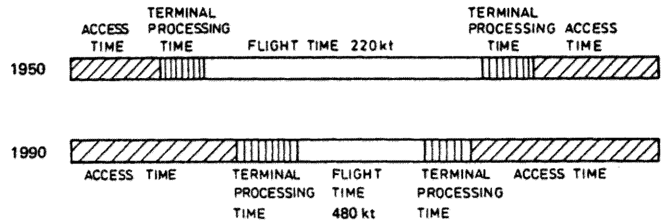

FIGURE 13.1 Comparison of short-haul city-center to city-center travel, 1950–1990.

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. The collection and processing, if necessary, of passengers in the central area of the city and other centers of high demand.
2. The 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.

TABLE 13.1 Proportion of Passengers, Workers, Visitors, and Senders/Greeters at Selected Airports[a]

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–Paya Labar	0.23	0.61	0.16	Negligible
Melbourne	0.46	0.32	0.14	0.08
U.S. Airports[b]	0.33–0.56	—	0.11–0.16	.31–.42 (includes senders and greeters)

[a] Derived from Institute of Air Transport Survey, July 1979.
[b] Reference (1).

By the late 1980s, many of the world's largest airports had large numbers of employees working within the airport complex: for example, London Heathrow, 48,000; Frankfurt, 41,000; Paris Charles de Gaulle, 29,000; Paris Orly, 27,000;

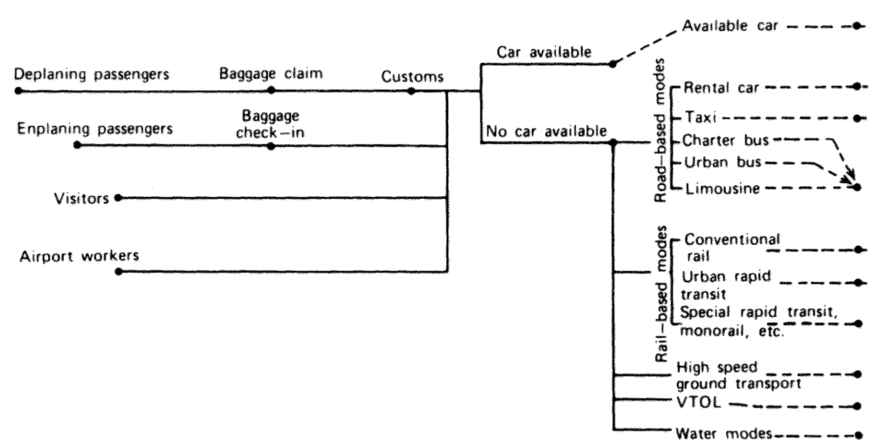

FIGURE 13.2 The access system.

Atlanta, 32,000; and Los Angeles, 35,000. These figures are equivalent to the entire population of a substantial town and generate the number of work trips equivalent to the central business district of a city of close to a half of a million persons. A study carried out by the Los Angeles International Airport showed that the airport generated over 120,000 daily vehicle trips in and out of the central terminal alone in the early 1980s. Clearly, the design of a movement system of this magnitude is a major consideration in the selection of a suitable airport site, and in the overall planning and design of any facility on the chosen location.

The 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,

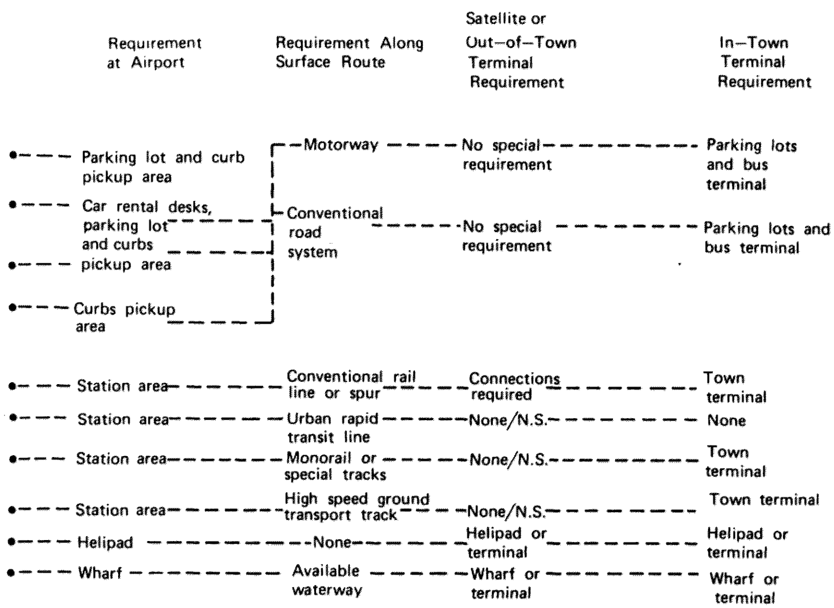

FIGURE 13.2 *Continued*

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 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 and Brussels) or urban rapid transit (e.g., Cleveland, Atlanta and London-Heathrow) 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.

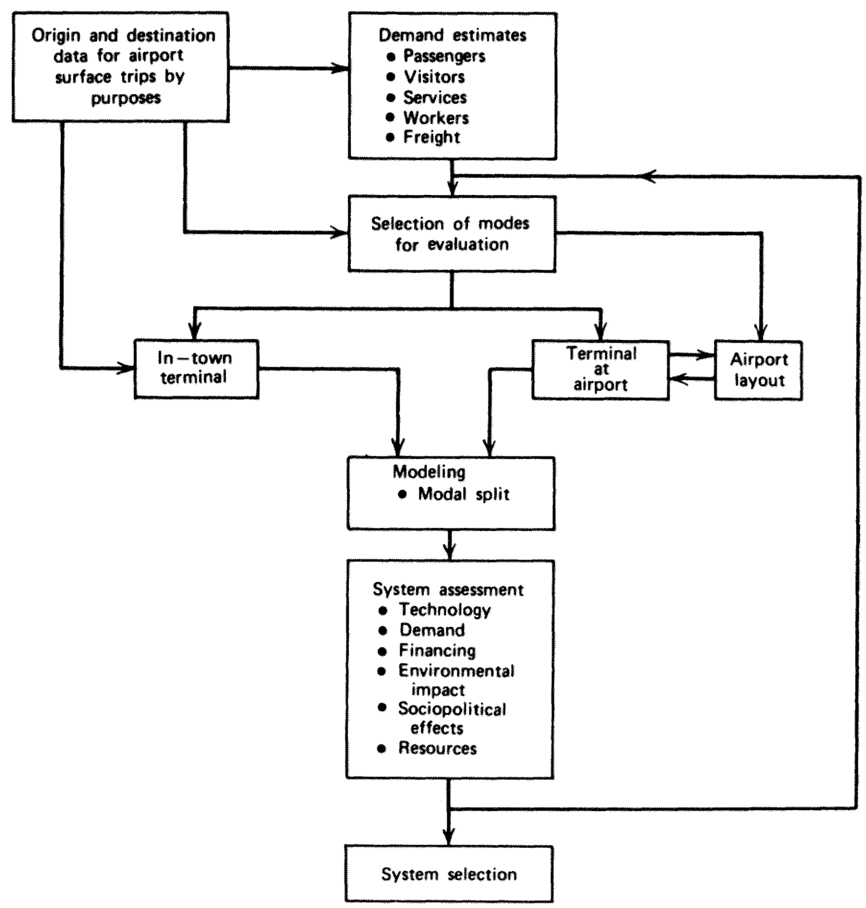

FIGURE 13.3 Access mode selection. (*Source*: Adapted from Reference 2)

13.2 DETERMINING THE MIX OF ACCESS MODES

Figure 13.3 presents a simplified conceptual model of the process by which the mix of access modes are selected. Demand estimates over time for passengers, employees, 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 terminal in New York, Les Invalides for Orly-Paris and Victoria Rail Terminal for London-Gatwick). 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 has been the difficulty of absorbing the additional number of airport access trips on the existing road network, which was considered 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 doubtless 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 airport and central city is not high (e.g., 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 land side 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. 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 anyway 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 pick-up and set-down areas. It is also necessary to provide bus parking areas where charter bus traffic is large, for example, Vienna.

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.

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 is 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 locations with nonstop service. However, having no segregated right-of-way, the mode is highly sensitive to surface congestion and tends to 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 concessionaire (Dorval Airport, Montreal) or by an airline (SAS at Arlanda Airport Stockholm).

Conventional Railway

A limited number of airports are served by conventional railway lines (e.g., Frankfurt, Brussels, Zurich, and London-Gatwick). As a rule, railway access links 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. Of great benefit, however, is the availability of service that does not entail additionally obtrusive transport 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. 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 proved 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, 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 area. Because the mode does not suffer from delays due to the surface road transport system, the air 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 consisted of short 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. 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, for example, Washington National airport.
2. The rail terminal, which is remote, is served by a shuttle bus, constituting a slow and inconvenient interchange, for example, New York (JFK Express), Paris (Orly-Rail), Boston, Paris Charles de Gaulle.
3. The interchange requires moving baggage up and down flights of stairs, which may present large perceived 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 60–80 mph. The attraction of specialized rail systems is

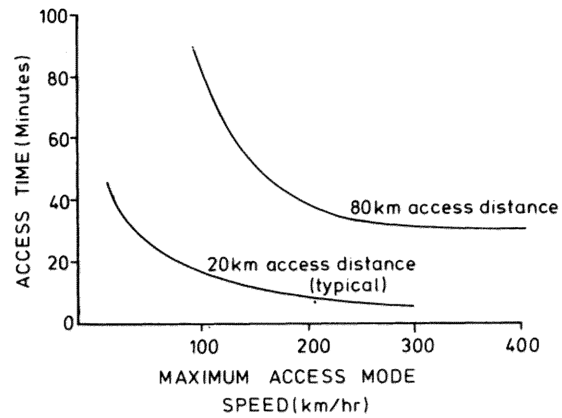

FIGURE 13.4 Comparative access times for different maximum access mode speeds. (*Source*: Reference 3)

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.

On careful examination, however, the disadvantages associated with high-speed dedicated systems become manifest. Such systems are likely to be very expensive, either overtly in the form of high fares, or covertly in the form of heavily subsidized total costs. Furthermore, systems as proposed or designed serve only the central city reasonably well; they therefore attract passenger traffic by other modes into the already congested city center. Transfer between other feeder and distribution systems at the central city terminal faces the baggage-impeded traveler with linkage problems with other modes.

Possibly the overriding difficulty associated with dedicated systems is the need for segregated rights-of-way through urban areas. This involves 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 a segregated right-of-way increases with the size of the urban area; concomitantly, the right-of-way costs more, either directly or in environmental terms.

It is frequently suggested that high-speed, dedicated rapid transit shuttles, operating between the airport and the central city, would solve the problem of airport access. Where such facilities have been provided, however, their performance often has been less than satisfactory (e.g., the monorail connecting central Tokyo with Haneda Airport). Moreover, the percentage of access trips made by way of these systems is only a small fraction of all access trips. Research has shown that even where special rail access facilities exist, in no case has more than 30% of access trips been carried, leaving 70% to be carried by road-based modes (1). Gatwick Airport (London) is 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 links around southern London improved, rail's modal share has dropped to less than 40%.

The feasibility of high-speed rail access has been studied in the United States and in Europe (3, 4). In the United States, the access situation was investigated at the 20 busiest airports. In the United Kingdom, the 13 major regional* airports were examined, excluding the five airports serving the London area where the economic and environmental problems associated with dedicated high-speed routes are so great that a solution of this type is ruled out almost automatically. Although the urban structure and the socioeconomic and demographic makeup of the two countries concerned were quite different, remarkable similarities were found in the conditions of airport access.

The attractiveness of the central business district (CBD) was found to be relatively low (less than 30% of passengers were destined or originated from the CBD). In general, however, the origins and destinations of access trips are found to be widely spread across the urban region, indicating that the special airport-CBD link can serve only a limited proportion of all trips. Where public transport was provided for airport access, 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.

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 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 will be severe. Cost estimates of providing rail service to Kennedy and Newark airports were in excess of $400 million for each scheme in 1973, even though existing tracks would have been used for a large part of the route in each case. In 1990 dollars, this would equate to more than $1.5 billion.

The level of social disruption that a ground-level dedicated-access rail system can cause can be inferred from an estimate that the special rail system to

*In Europe, regional airports are airports of lesser magnitude, serving noncapital or provincial cities. American usage of the word "regional" in the context of airports usually designates a remote airport serving two or more metropolitan areas.

connect the Maplin site for the Third London Airport in the early 1970s would have required the demolition of a number of dwellings equaling two-thirds of the annual number of houses built in the whole of the United Kingdom.

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. Each of these enterprises had an operational history that was less than satisfactoy, being plagued with accidents, financial troubles, and inadequate demand (5). More successful was the NASA-Houston link in Texas and the Heathrow-Gatwick link between the two main London airports. (The latter operation had to be abandoned due to environmental complaints concerning helicopter noise which were accepted by the British government.) Experience with helicopter airport access services indicate 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) or second a poor road and rail linkage, (such as existed between Heathrow and Gatwick airports at the time of the helicopter service).

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 competiton with road-based modes, and in a few cases, waterborne modes have a special scenic attraction for passengers as, for example, at Venice Airport and London City Airport, where the approach by water gives the visitor the traditional view of the cities rather than a more commonplace approach to the land side by car or bus. At neither of these airports were the initial promises of rapid access fulfilled. The mode proved to be inconvenient in its transfer at both ends and served only a few passengers. 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.

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 by public transport to generalized cost by automobile in the zone*
X_2 = percentage of zonal access origins and destinations made by non-residents 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

*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.

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:

$$P_k = \frac{e^{L_k(X_1 \ldots X_n)}}{\sum_{\text{all } j} e^{L_j(X_1 \ldots X_n)}} \tag{13.3}$$

where

P_k = percentage of trips by mode k
L_k = some generalized cost function in terms of variables, $X_i = X_1$ to 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:

$$L_k = 0.701 + 0.031\Delta C + 0.0216\Delta T \tag{13.4}$$

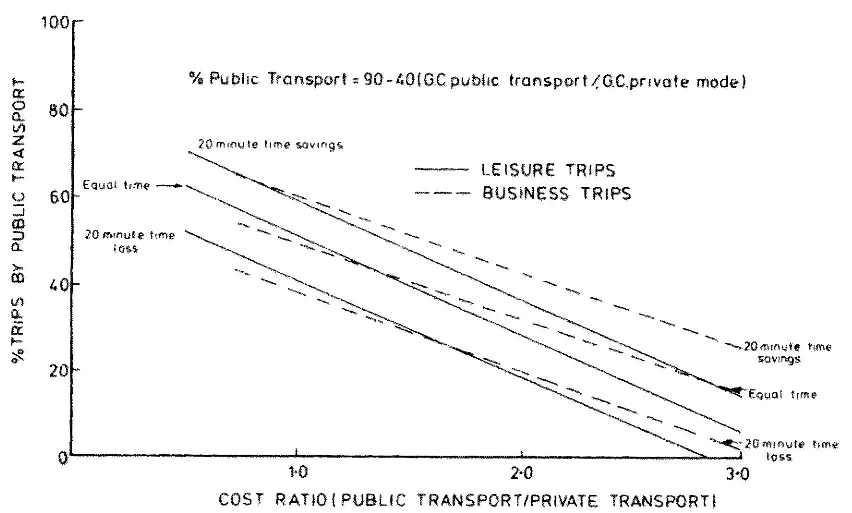

FIGURE 13.5 Modal split relationship for business and leisure trips: London Heathrow Airport. (*Source*: Reference 3)

where

ΔC = travel cost difference
ΔT = travel time difference

Figure 13.5 shows the general form of the linear modal choice model of equation 13.2 (3). 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.

13.5 PARKING SPACE AT AIRPORTS (7)

One of the greatest difficulties related to access is the determination of the location and number of parking spaces. 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 the airport population may be visitors and workers.

TABLE 13.2 Approximate Percentage of Total Passengers Transferring at 12 U.S. Airports (1991)

Airport	Transfer Passengers (%)
Atlanta	67
Dallas—Fort Worth	64
Chicago	48
Philadelphia	35
Denver	57
Kansas City	9
San Francisco	35
Miami	30
Minneapolis—St. Paul	49
Detroit	32
Boston	11
New York	33

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. Atlanta, for example, has a high number of annual enplanements, but Table 13.2 discloses that nearly three-quarters of

TABLE 13.3 Magnitude of Parking Provisions—Various Airports

Airport	Total Passengers (Millions)	Total Enplanements (Interlines Excluded)	Places per 1000 Total Passengers	Places per 1000 Annual Enplanements (Interlines Excluded)
Baltimore (BWI)	3.77	1.31	1.20	3.45
Boston (BOS)	15.20	6.35	0.60	1.45
Chicago (ORD)	47.84	11.98	0.36	1.42
Dallas–Fort Worth (DFW)	22.58	8.50	0.64	1.71
New York (JFK)	26.98	9.72	0.49	1.36
New York (LGA)	18.39	8.52	0.40	0.86
Los Angeles (LAX)	34.92	13.17	0.57	1.51
Miami (MIA)	19.63	5.25	0.28	1.06
New York (EWR)	9.30	4.30	1.24	2.68
Oakland (OAK)	2.68	1.32	1.33	2.69
San Francisco (SFO)	23.05	9.74	0.43	1.03
Washington D.C. (DCA)	14.28	5.37	0.30	0.81
Charles de Gaulle Paris (CDG)	9.99	—	0.53	
Dusseldorf (DUS)	6.85	3.24	1.21	2.56
Frankfurt (FRA)	16.64	4.72	0.50	1.78
London-Gatwick (LGW)	8.70	4.08	1.24	2.65
London (LHR)	27.98	11.68	0.36	0.86
Montreal (YUL) (Dorval)	6.15	—	0.59	—
Montreal (YMX) (Mirabel)	1.53	—	2.29	—
Orly–Paris (ORY)	14.78	5.96	0.53	1.32
Tokyo (HND) (Hameda)	20.54	—	0.11	—
Tokyo (NRT) (Narita)	7.26	—	0.45	—
Toronto (YYZ)	13.71	4.92	0.62	1.73
Vienna (VIE)	2.77	1.09	0.69	1.74
Zurich (ZRH)	7.51	2.54	1.11	3.27

Source: Reference: Institute of Air Transport Survey, July 1979.

the passengers are transfers from other flights, requiring no land side access. On the other hand, cities such as Kansas City and Boston behave much more as terminals. Enplanements alone, therefore, cannot be used as a guide to parking requirements. Table 13.3, giving the relationship between availability of parking space and air passenger activity for a number of U.S. and foreign airports, indicates that there is a large variation about any normative line that could be derived for the relationship. For planning purposes, the FAA recommends use of the graph shown in Figure 13.6, which shows a nonlinear relationship between originating passengers and public parking places, in both the long and short term (8). Whitlock and Cleary have produced design graphs that relate short-term parking requirements to peak hour originating passengers (see Figure 13.7). 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)
FAA (non-hub airports)(11)	1 space per 500–700 annual enplaned passengers

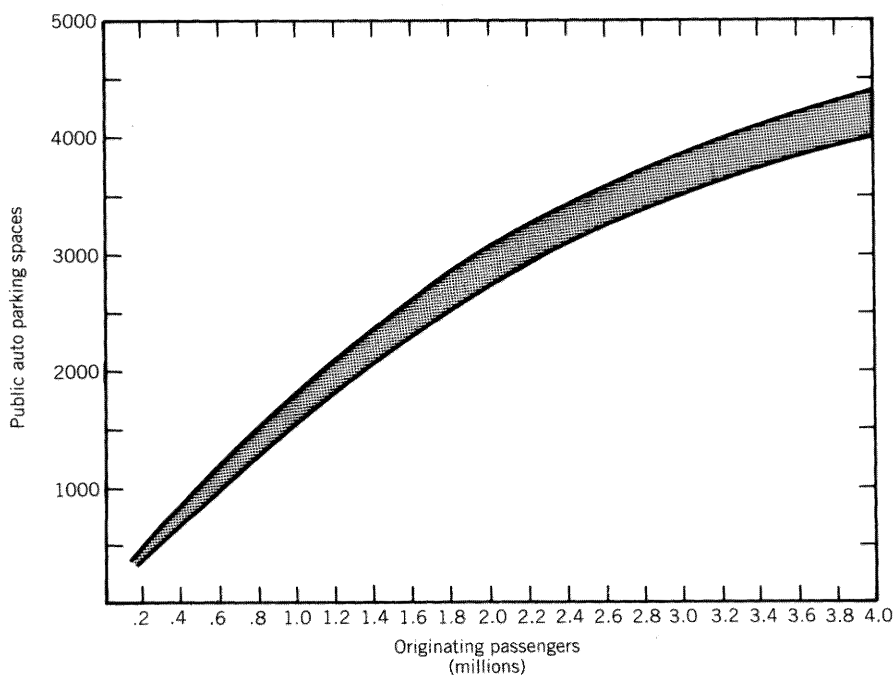

FIGURE 13.6 Relationship between annual originating passengers and public parking spaces (long- and short-term). (*Source*: Reference 8)

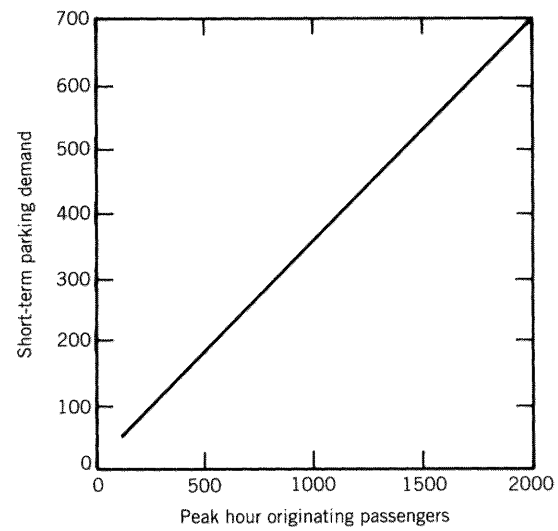

FIGURE 13.7 Relationship between peak hour originating passengers and short-term parking. (*Source*: Reference 14)

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 normally 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. To ensure the adequacy of parking provision, a special study of airport access traffic must 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.

13.6 CURBFRONT DESIGN

For space estimates in the master planning process, the length of drop-off/pick-up 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 13.4, 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

In theory, 1 lineal ft of curb space can provide 60 ft min of capacity in 1 hr. Cherwony and Zabawski 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 pick-up and drop-off, the total required would be less than 1583 lin 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 1 must be in general agreement with conditions found to operate at the airport under con-

TABLE 13.4 Curbfront Requirements at Fort Lauderdale–Hollywood Airport

Vehicle Type	Vehicle Length (ft)	Average dwell-time Enplaning (min:sec)	Average dwell-time Deplaning (min:sec)	Curbfront Required Enplaning (ft min)	Curbfront Required 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 7 and 9.

sideration, 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 7 and 15.

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 airport 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. Unfortunately, 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 13.5 may be used. To convert the vehicular volumes to passenger volumes, Table 13.6, 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 air side. However, access should not be subordinated to the needs of air

TABLE 13.5 Achievable Capacities of Airport Access Route Facilities

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 or2500 pass/hr/track

[a] Passenger car equivalents at levels of service 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.
Sources: References 7 and 16.

side and terminal layout; rather 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 by

TABLE 13.6 Typical Average Vehicle Occupancy Rates for Airport Ground Access

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.
Source: Reference 17.

the time that 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 land use so close to the terminal. Kennedy, O'Hare, and Newark airports are just three examples of terminal modifications which have in the long term had to take place within such areas which were 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 13.8a, Schiphol Airport Amsterdam, and Figure 13.8b, La Guardia, New York. Figure 13.8c shows 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 Toulouse airports have maximum opportunity for lateral expansion along the axis 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 Frankfurt (Figure 13.9a), the selection of the station site is fairly obvious, either under or immediately adjacent to the passenger terminal itself. Similarly, a centralized position was chosen for the rail station at the new Munich Airport (Figure

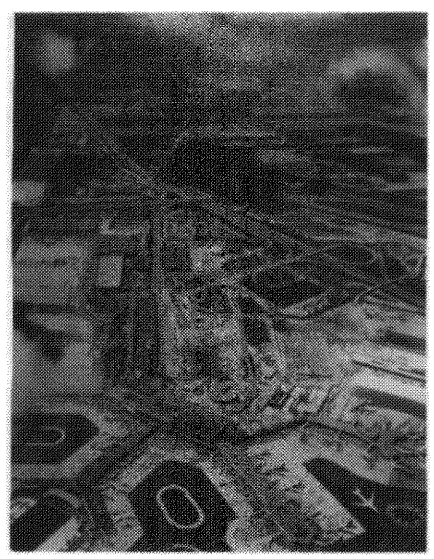

FIGURE 13.8(a) Land side access layout-Schiphol Amsterdam Airport. Copyright: Aerophoto-Schiphol B.V.

FIGURE 13.8(b) Land side access layout—LaGuardia Airport, New York). Courtesy: The Port Authority of New York and New Jersey.

13.9b). Here, however, the great length of the terminal will result in less than optimal walking distances for passengers. In a decentralized facility such as Charles de Gaulle, Paris (Figure 13.9c), the distances involved are so large that either there must be a rail station at each terminal or the station must be cen-

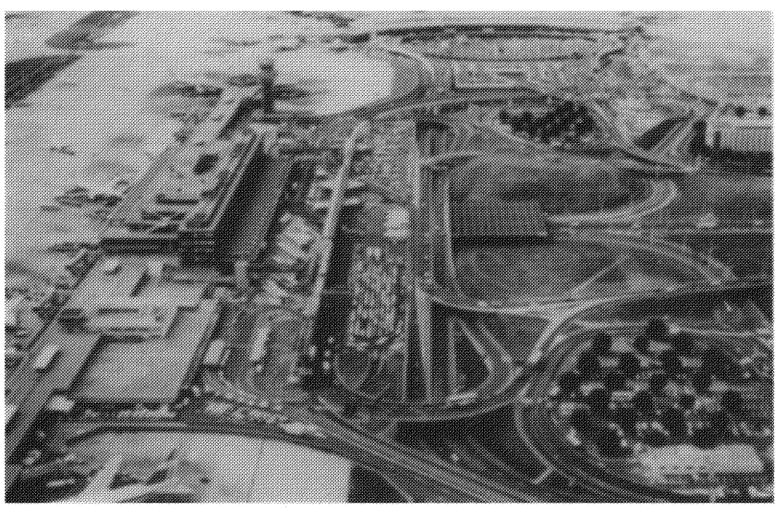

FIGURE 13.8(c) Land side access layout—Paris Orly Airport. Courtesy: Aeroports de Paris.

FIGURE 13.9(a) Land side access layout—Frankfurt Airport. (Copyright: Flughafen Frankfurt/Main AG. FAG-Foto: M. Skaryd.)

tralized and fed by some form of passenger shuttle. Neither solution is very satisfactory for the passengers. Multiple station stops at the airport slow the performance of the rail link with respect to connection times to the central city. Shuttles, especially bus operations, have not proved popular with the potential passenger clientelle.

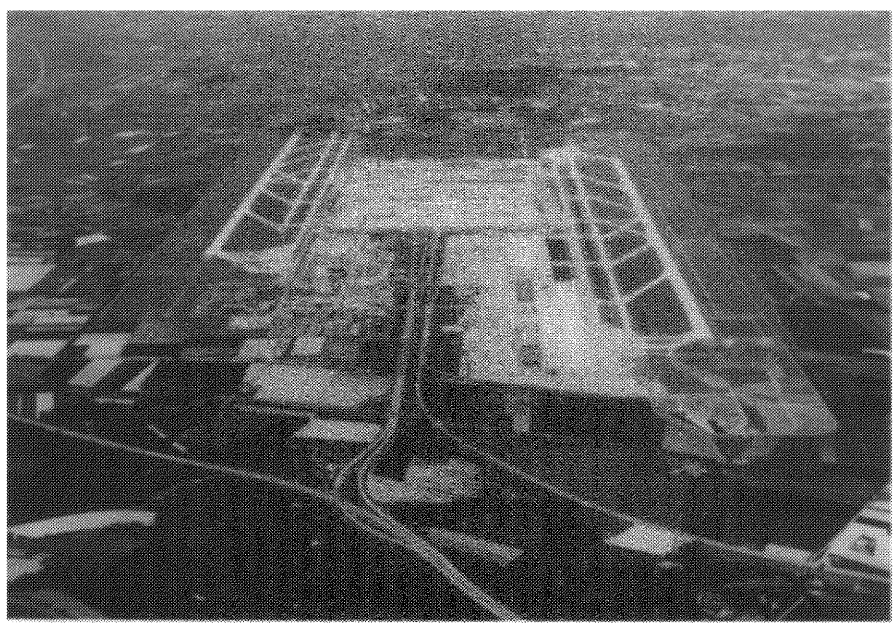

FIGURE 13.9(b) Land side access layout—Munich II Airport. Photo: Luftbildverlag Hans Bertram. Copyright: Flughafen Muenchen GmbH.

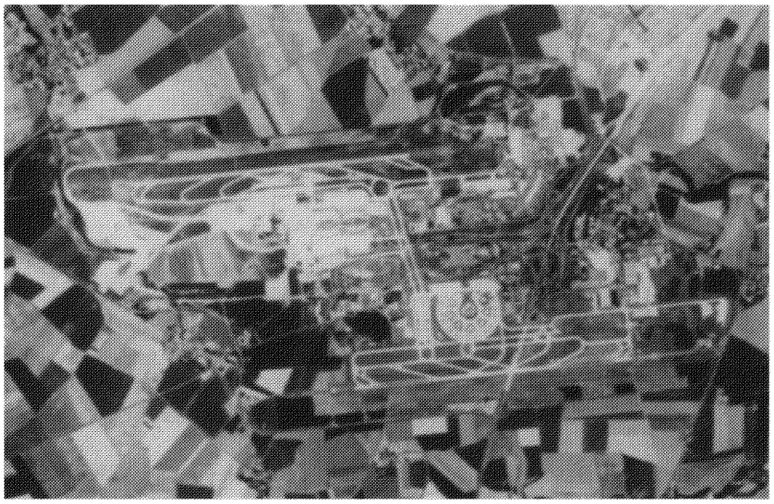

FIGURE 13.9(c) Land side access layout—Paris Charles de Gaulle Airport. Courtesy: Aeroports de Paris. Photo: G. Cadou.

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 sufficient to merit the construction of dedicated access modes. 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; to avoid an undue staff burden to the airlines, these would be operated by the airport authority or by bus concessions of ground transport to bus companies, 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 indicates 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 link, 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 where he or she can be served by public transport.

Finally, it must be acknowledged that access potentially constitutes the 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 (1). Therefore, care is essential in siting the airport, 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

REQUIREMENTS OF V/STOL SYSTEMS

14.1 INTRODUCTION

Air transport professionals have long recognized vertical takeoff and landing (VTOL) and short takeoff and landing (STOL) aircraft as important components of the air transportation system. This chapter describes existing and proposed V/STOL aircraft and considers some of the more important aspects of planning and design of VTOL and STOL airport facilities.

14.2 V/STOL AIRCRAFT CHARACTERISTICS AND TRENDS

V/STOL aircraft range from conventional helicopters which serve a variety of specialized functions but which are relatively insignificant as passenger common carriers to STOL aircraft that serve short- to medium-range routes and are barely indistinguishable from conventional aircraft.

Helicopters

Although Leonardo da Vinci produced a conceptual design for a helicopter as early 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, 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 lbs. The largest helicopters are capable of transporting 40 or more passengers, plus a crew of three, and have a maximum payload of over 40,000 lbs. (1). According to the FAA (2), 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 to 1500 ft, although many can fly at altitudes up to 10,000 ft above sea level. Helicopters are best suited for short-haul transportation,

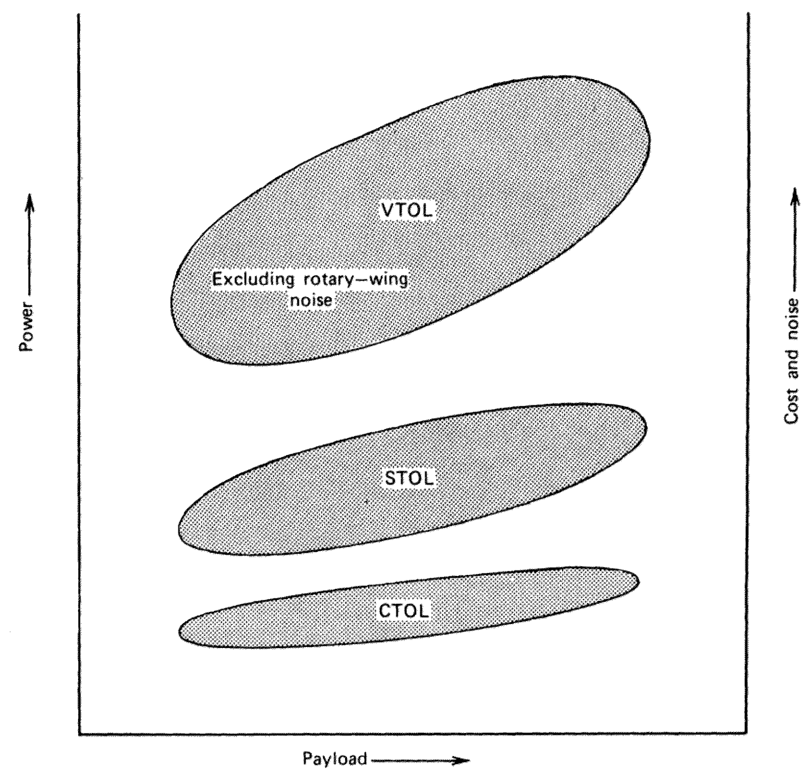


FIGURE 14.1 Basic technical and economic comparisons of various aircraft groups. *Source*: *A Brief Review of V/STOL Aircraft*, Douglas Aircraft Company, Report MDC-JO690/01.

TABLE 14.1 Dimensions of Typical Helicopters

	Manufacturer and Model		
Data Item	Bell Helicopter Company 206B	Sikorsky Aircraft Company S-76B	Boeing Vertol 234
Overall length (ft)	39.2	52.5	99.0
Overall height (ft)	11.6	14.5	18.7
Number of main rotor blades	2	4	3
Diameter of main rotor blades (ft)	33.3	44.0	60.0
Tail rotor diameter (ft)	5.4	8.0	60.0
Wheelbase (ft)	4.5	16.4	25.8
Tread (ft)	6.0	8.0	10.5
Number of crew	1	2	3
Number of passengers	1	12	44
Maximum takeoff weight (lbs)	3,200	11,400	48,500

Source: *Heliport Design*, FAA Advisory Circular AC 150/5390-2, January 4, 1988.

typically serving trips up to about 75 mi. However, certain large models, such as the Sikorsky S-65C, are capable of transporting full passenger loads up to 300 mi.

Table 14.1 gives dimensions of typical small, medium, and large helicopters; Figure 14.2 illustrates popular helicopter configurations.

Innovative VTOL Concepts

A number of innovative concepts have been considered for VTOL design to overcome the limitations of conventional helicopters: short range, low capacities and speeds, high noise levels and 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*. The 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 lift-off 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.

During the 1980s, research and development of VTOL aircraft systems progressed on a variety of fronts. Flight research and demonstration testing

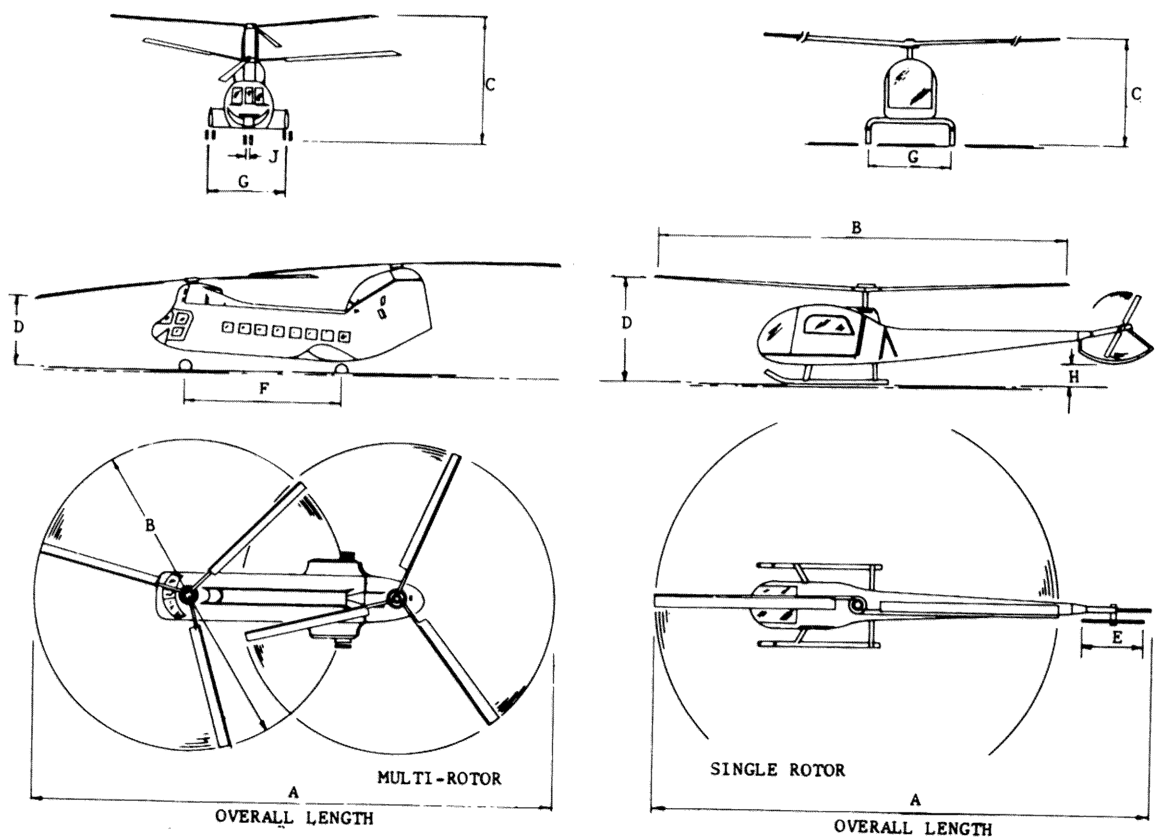


FIGURE 14.2 Typical helicopter configurations. (*Source*: Reference 2)

FIGURE 14.3 The XH-59 experimental helicopter. (Courtesy United Technologies Sikorsky Aircraft)

was being performed by Sikorsky Aircraft Division, United Technologies Corporation on the XH-59 helicopter. That experimental aircraft features two counterrotating rigid rotors mounted one above the other on a common shaft. This system permits the advancing side of both rotor discs to generate lift, offering high speeds without the need for a wing to off-load the rotor. With two outboard engines for auxiliary thrust, this helicopter, pictured in Figure 14.3, has been tested at speeds of 240 kt 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

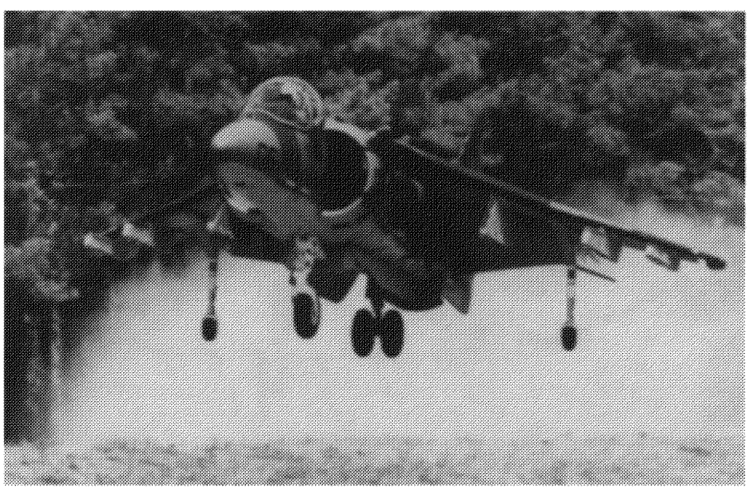


FIGURE 14.4 The Harrier vectored thrust aircraft. (Courtesy McDonnell-Douglas Corporation)

concept has been utilized successfully in the Harrier aircraft, which is manufactured by the McDonnell-Douglas Aircraft Company for the U.S. Marine Corps and the Royal Air Force. See Figure 14.4. The vectored thrust aircraft so far has been limited to military uses, and civilian applications are not expected in the foreseeable future.

Tiltrotor Aircraft

A promising tiltrotor research aircraft, the XV-15, has been developed by Bell Helicopter Division of Textron. The tiltrotor used large helicopter rotors for vertical lift in the helicopter mode and for forward thrust in the airplane mode.

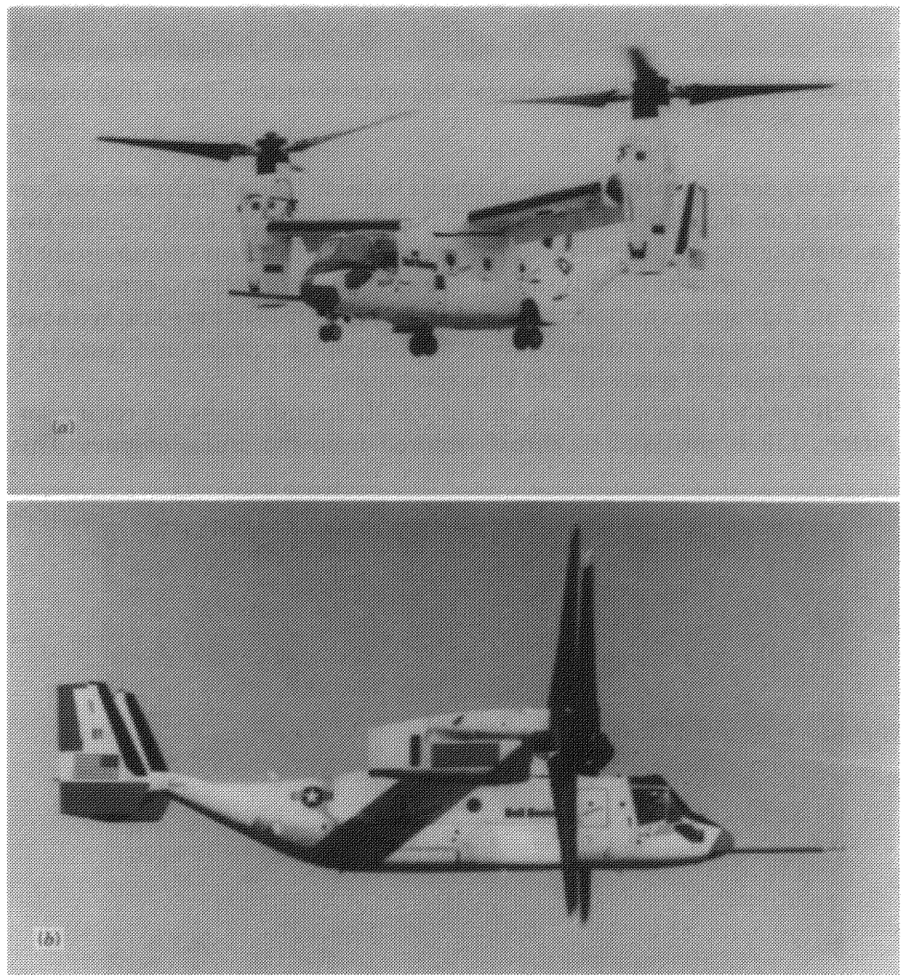


FIGURE 14.5 The V-22 Osprey tilt rotor aircraft. (a) Hover mode. (b) Cruise mode. (Courtesy Bell Helicopter Division of Textron, Inc.)

When the rotors are tilted forward, a wing provides the lift. The tiltrotor combines the hover efficiency and maneuverability of a helicopter with the cruise efficiency and speed of 301 kt in level flight. Figure 14.5 shows the tiltrotor aircraft in hover and cruise modes. A military version of the tiltrotor, known as the V-22 Osprey, was in full-scale development in the last 1980s.

A joint civil tiltrotor study was undertaken in 1983 under the sponsorship of the FAA, NASA, and the Department of Defense to document the potential of the commercial tiltrotor market (3). The study team, with representatives from Boeing Commercial Airplane Company, Bell-Textron, and Boeing Vertol, considered six configurations. See Figure 14.6 and Table 14.2.

One configuration developed by the study team, the CTR-800, is based on the XV-15 tiltrotor size. Two configurations, the CTR-22B and CTR-22C, are derivatives of the V-22 military tiltrotor. A third derivative of the military tiltrotor, the CTR-22D, was considered to evaluate a higher capacity and more

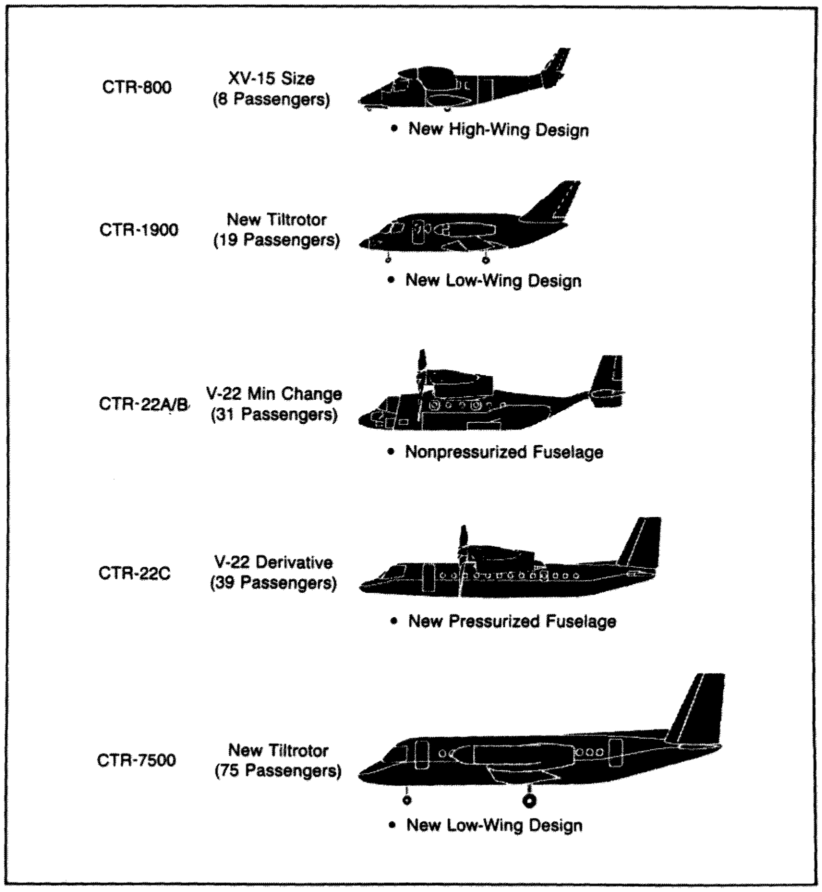


FIGURE 14.6 Five tiltrotor configurations that have been considered for civilian use. (*Source*: Reference 3)

TABLE 14.2 Six Tiltrotor Configurations That Have Been Considered For Civilian Use

	CTR-800	CTR-1900	CTR-22B	CTR-22C	CTR-22D	CTR-7500
No. passengers	8	19	31	39	52	75
Overall length (ft)[a]	41.5	46.6	57.3	68.6	71.7	83.7
Wing/rotor span (ft/ft)	32.2/26.0	37.0/28.0	45.8/38.0	45.8/38.0	48.0/38.0	63.0/46.0
TOGW (OEI hover) (lb)	15,750	22,800	45,120	46,230	49,260	79,820
Cruise speed (kt)	273	283	240	282	282	300
Range (nmi) (OEI hover)	600	637	600	600	280[b]	600
Engine	RTM 322 + 14%	Scaled RTM 322	T406	T406	Growth T406	Growth T406
Takeoff engine rating (HP)	2100	3440	6805	6805	7312	12,883
30 sec emergency rating (HP)	2625	4300	8506	8506	9140	16,100

[a] 1 ft = 0.3048 m.

[b] 600 nmi with 39 passengers.

Source: *Civil Tiltroter Missions and Applications: A Research Study*, Summary Final Report, NASA CR 177542, July 1987.

efficient fuselage. Two all-new tiltrotor designs, the CTR-1900 and the CTR-7500 were proposed for the civilian market.

The results of the tiltrotor study are quoted below with minor editorial changes:

> The civil tiltrotor is a unique vehicle with a large market potential. V-22 derivatives offer some market penetration, but new designs are required to meet full potential market. Pressurized verisions, in particular, show a high potential in several markets.
>
> The civil tiltrotor is superior to multiengine helicopters in most conditions, in performance as well as cost. Specific design studies for lower construction and operating costs are required to assure maximum viability in the civil marketplace.
>
> For the civil tiltrotor to achieve full potential benefits of congestion relief, a system infrastructure geared to its unique capabilities is needed.
>
> Six tiltrotor configurations were analyzed, including three V-22 derivatives. Several important conclusions were reached about the six configurations. The V-22 derivatives with new pressurized fuselages and modest engine growth can meet the 600 nmi design range and carry over 50 passengers. Additional capacity (still meeting the 600 nmi design range) is possible with all-new configurations.
>
> The civil tiltrotor can operate under current rules governing use of the airspace; however, changes that exploit the unique characteristics and capabilities of the tiltrotor will improve its competitiveness.
>
> The importance to the commercial market of one engine inoperative (OEI) hover takeoff capability cannot be overstated. However, if a very short runway (750 ft or shorter) is used,the OEI hover range can be more than doubled.

Tiltrotors could capture one-third to two-thirds of the high-density, short-haul air travel market; however, ticket price may be higher to include ground transportation and/or surcharge for time saved. The key to tiltrotor acceptance is the reduction of portal-to-portal trip time, minimizing the time and expense of the ground segments of the trip, and avoiding time-consuming airport/airway congestion. This requires the use of VTOL capability at one or both ends of the trip. Tiltrotor service will attract principally business travelers (3).

In addition, the study concluded that tiltrotor aircraft offered significant advantages in the corporate/executive market, for offshore drilling transportation, and for public service use. Opportunities also exist for cargo package express operations and for meeting transportation needs in low-density developing regions.

Certification of any of the civil tiltrotor aircraft is expected no earlier than the mid-1990s.

STOL Aircraft

Some STOL aircraft exist in concept only. Others have been extensively researched and flight tested. Some, by the early 1990s, had been placed in commercial service.

One approach to STOL service is to employ existing low-wing loading turbopropeller 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.

The de Havilland Aircraft Company has also manufactured a larger STOL aircraft, the DHC-7 or "Dash-7." This four-engine turboprop aircraft has a capacity of 50 passengers and a cruising speed of 266 mph. According to the manufacturer, very low noise levels are assured for the DHC-7 because of its large, slow turning propellers and moderate power requirements.

The de Havilland DHC-8, a wide-bodied, twin-engine turboprop aircraft with a capacity of 36 passengers and a cruising speed of 310 mph, was placed in service in 1984.

STOL aircraft make it possible to provide air service to remote mountainous areas that would be inaccessible by conventional aircraft. For example, in 1985, the Himalayan kingdom of Bhutan acquired two Dornier 228 STOL turbo-prop aircraft to provide regular air service between Calcutta, India and Paro, Bhutan. The 1350-m runway at Paro is at an elevation of 7300 ft above sea level and is surrounded by granite ridges and mountain folds which tower 10,000 ft above the site (4).

One of the shortcomings of existing STOL turboprop aircraft is a low ride quality, especially in gusty winds; this results from low wing loadings (~ 80 lb/ft^2). To improve ride quality, consideration has been given to the use of deflected slipstream turboprop aircraft, such as the McDonnell-Douglas 188 transport. "High-lift short-field capacity is attained on this aircraft from large, full-span, triple-slotted trailing edge flaps which are completely immersed in and turn the slipstream from the propellers in a downward direction" (5).

Physical characteristics of selected STOL aircraft are listed in Table 14.3.

Aircraft engineers have also studied the feasibility of developing a swept-wing fanjet STOL aircraft, to achieve higher cruising speed, larger capacity (typically 90 to 150 passengers), increased range, and a smoother ride. Such aircraft would attain higher wing loadings (and slower landing and takeoff speeds) by means of action of gas exhaust from the engines on a wing flap. Riebe explains:

> Basically, aircraft with powered-lift systems obtain short field length operation through low-speed flight resulting from generation of high lift on the wing through distribution of a sheet of high-momentum gas from the jet engines along the wing trailing edge and deflected downward by means of a trailing-edge flap. 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 (5).

TABLE 14.3 Physical Characteristics of Selected STOL Aircraft

Data Item	Aircraft Manufacturer and Model		
	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

Two basic variations of this concept have been proposed:

1. *Externally Blown Flap*. The engine exhaust gas is maintained outside the wing.
2. *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" (5).

Because aircraft noise is a primary factor in siting a STOL port, aircraft designers have attempted to develop quieter STOL aircraft. Notable progress in noise amelioration has been made by NASA and Boeing with the development of the Quiet Short-Haul Research Aircraft. Flight research and testing of that aircraft was being performed in the early 1980s.

14.3 PLANNING AND DESIGN OF HELIPORTS

A *heliport* is a prepared area that is used for landing and takeoff of helicopters. It may be either at ground level or elevated on a structure. A minimum facility heliport that does not have auxiliary facilities, such as 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, 2) into the following groups of usage and size:

Public-use.
Private-use.
Personal-use.
Federal.
Military.

The public 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, usage is restricted to the owner or to persons authorized by the owner. Special-use heliports that do not accommodate public transportation helicopters (e.g., police heliports) are classified as private-use heliports even though they are publicly owned. Personal-use heliports are owned by individuals, companies, or corporations and are used exclusively by the owner. 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 the 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 the 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.

Generally, community zoning regulations permit the use of heliports in industrial, commercial, manufacturing, agricultural, and unzoned areas (1). 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

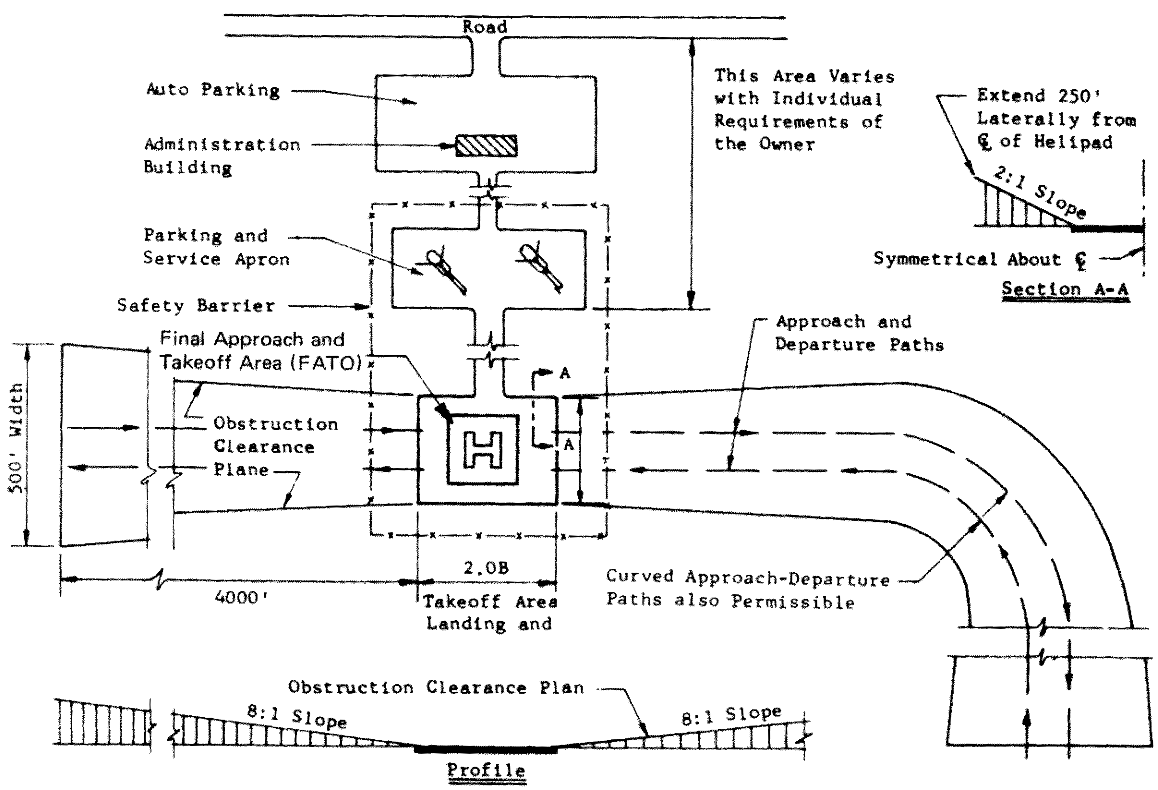
The size and shape of a heliport and the type of service facilities offered depend primarily on three factors:

1. The nature of the available site.
2. The size and performance characteristics of the helicopters to be served.
3. The number, size, and location of buildings and other objets in the vicinity of the heliport.

The principal operational components of a heliport are the final approach and takeoff area (FATO), the takeoff and landing area, and the obstruction clearance surface, as illustrated by Figure 14.7.

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" (1). The FATO may be a rectangle or a circle. Normally centered within the takeoff and landing area, its length and width or diameter should be at least equal to the rotor diameter of the design single-rotor helicopter. If the design helicopter has tandem rotors, the length and width or diameter should at least equal the overall length of the helicopter. The FATO may either be paved or stabilized soil. It must be capable of producing ground effect.

The takeoff and landing area is a cleared area containing the FATO. It may be located on the ground or a water surface, a roof of a building, or an elevated platform. The surface of the take off and landing area should be clear of objects, except for visual aids and other devices required for safe operations. The size of the takeoff and landing area is determined by the size of the design helicopter. Its length and width or diameter should be twice the rotor diameter of the design single-rotor helicopter. For heliports serving tandem-rotor heli-



NOTE: Dimension B Equals Overall Length of Helicopter

FIGURE 14.7 Principal components of a public-use heliport with visual approach procedures. (*Source*: Adapted from Reference 2) copters, the length and width or diameter of the takeoff and landing area should be at least one rotor diameter greater than the overall length of the design helicopter (1).

In certain circumstances, parking spaces for helicopters may be required at private-use heliports, and at least two spaces normally are needed at public-use heliports. A special study of helicopter traffic may be necessary to determine the number of parking spaces required. Helicopters may be parked on a paved or an unpaved apron, a *helipad* or *helideck*.* Parked helicopters should have a clearance of at least one-third the rotor diameter or 10 ft from a takeoff and landing area or fixed or moveable 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 public-use 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.

Table 14.4 summarizes design criteria for public-use heliports, including

*The term *helipad* refers simply to a surface used for parking helicopters; a *helideck* is an elevated surface used for that purpose.

TABLE 14.4 FAA Recommended Design Criteria for Public-Use Heliports

Design Feature	Dimension
Takeoff and landing area—length, width, diameter	2.0 × rotor diameter of design helicopter or length of design tandem helicopter + 1.0 rotor diameter
Final approach and takeoff area—length, width, diameter	Rotor diameter of design helicopter or length of design tandem helicopter
Clearance between takeoff and landing area and buildings, fences, and other objects	⅓ rotor diameter of ⩾ 10 ft.
Taxiway width	2.0 × rotor diameter of largest helicopter to hover taxi; 1.5 × rotor diameter of largest helicopter to ground taxi + 14 ft
Helipad length, width, diameter	Larger of 1.5 × design helicopter's undercarriage length or width
Helideck length, width, diameter	Rotor diameter of design helicopter or length of design tandem helicopter
Pavement grades	0.5% to 5.0%; max. 2.0% in fueling areas
Other grades, turf stabilized	Variable 1% to 5%

Source: *Heliport Design*, FAA Advisory Circular AC 150/5390-2, January 4, 1988.

taxiway widths, slopes and clearances to buildings and obstacles, as recommended by the FAA. Reference 1 gives guidance on the planning and design of private-use heliports.

These criteria do not apply to offshore helicopter facilities. Recommendations for the design of such facilities are given in Reference 6.

Approach-Departure Paths

The VFR obstruction clearance plane for heliports is part of Figure 14.7. The imaginary approach-departure surfaces shown make it possible to identify objects that may constitute a hazard to helicopter operations. The surfaces shown are applicable to heliports serving helicopters using VFR nonprecision approach procedures. Reference 1 specifies the approach-departure surfaces for heliports with precision instrument procedures.

Note that curved approach-departure paths are permitted. The FAA recommends that the curved path begin at least 300 ft from the landing and takeoff areas. The radius of curvature for the paths will depend on the operating characteristics of the helicopters but will generally range from approximately 700 to about 1500 ft.

It is suggested that at least two approach-departure paths be provided, separated by arcs of 90 to 180. In configuring the routes, the heliport planner should take into account prevailing winds, noise-sensitive areas, visual aids, and hazards to air navigation.

Marking of Heliports

Several marking configurations have been used to identify heliport facilities. The preferred marking of the takeoff and landing area, illustrated in Figure 14.8, consists of a letter "H", at least 10 ft in height, 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 below and to the right of the heliport symbol. The number shows the maximum allowable weight in thousands of pounds.

Standard heliport markings are white, but when placed on a light-colored surface, they should be outlined in black to make them more conspicuous.

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 an 8 ft wind cone be located in a prominent but unobstructive place adjacent to the landing area. The color of the wind cone should contrast with its background, and it should be lighted if night operations are expected.

Taxiway centerline markings and apron parking positions markings may also be necessary at busy heliports. These markings are typically yellow.

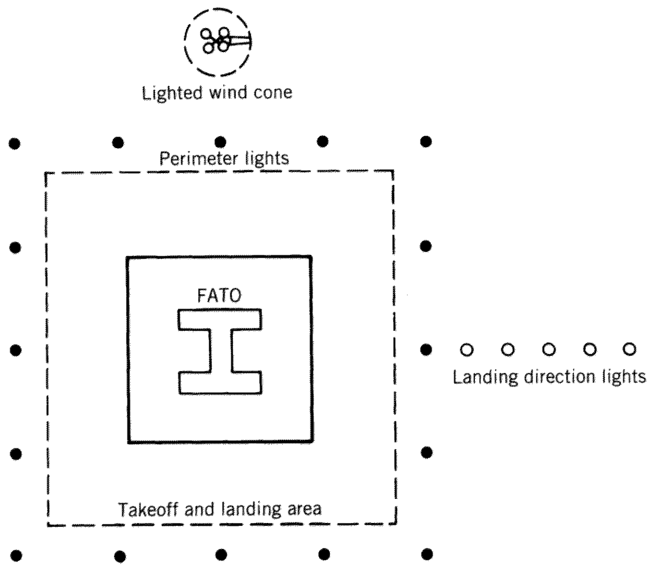


FIGURE 14.8 Recommended heliport marking and lighting. (*Source*: Adapted from Reference 1)

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 indentification 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 to 53 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 obstuction 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 *Obstruction Marking and Lighting* (7). 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 7.

As Figure 14.8 illustrates, the FAA specifies that five or more yellow lights be equally spaced along the boundary of the FATO or the takeoff and landing area. 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 communicate to the pilot the desired direction for landing and takeoffs.

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. Taxiway 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.

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. Helidecks, which are supported by columns or pedestals and framing that transmit the loads to existing building columns.

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 long should be installed around a helideck. 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 a helideck 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 design 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 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 surface may be suitable for helicopters with gross weights up to 10,000 lb.

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 be 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 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 ares 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.

14.4 PLANNING AND DESIGN OF VERTIPORTS

By the early 1990s, knowledgeable professionals in industry and government anticipated the development and certification of civil tiltrotor aircraft to provide rapid, reliable, and convenient interurban air transport service. Based on this expectation, the FAA has developed guidelines for the planning and design of facilities for tiltrotor aircraft (8). In this section, we present a summary of tentative standards and recommendations for the design of such facilities.

Facilities providing full support for the takeoff and landing of tiltrotor aircraft are known as vertiports. Such facilities would normally be capable of accommodating the operation of helicopters as well. Limited service vertiports intended to be used soley for tiltrotor aircraft and rotorcraft engaged in picking up passengers or cargo are known as vertistops.

Vertiports and vertistops may be developed as public-use or private-use facilities. They may be ground level or elevated.

A variety of sites may have potential for development as vertiports, including rooftops of buildings, land along waterfronts, space over expressways, and unused land at existing airports. Vertiports may be developed on as little as 25 acres in suburban areas and 5 acres in urban areas (3). Because tiltrotor aircraft tend to be less noisy than helicopters or turboprop aircraft, the development of vertiports near close-in and convenient population centers may be possible.

The chosen site for a vertiport should, of course, provide suitable airspace, be accessible and convenient to users, and take advantage of prevailing winds. Other factors that should be considered in selecting a site for a vertiport include the costs of acquiring and developing the site and the social and environmental impacts.

Layout and Design of Vertiports

The principle operational components of a vertipoint are the final approach and takeoff area (FATO), the touchdown lift-off surface (TLOF), and the obstruction clearance surfaces. The FATO is a defined area over which the final phase of the approach maneuver to a hover or a landing is completed and from which the takeoff maneuver begins (8). The FATO may have any shape, but it must be large enough to circumscribe a square with 250 ft sides. See Figure 14.9a. The FATO length should be increased by 100 ft per 1000 ft of elevation. When site conditions permit, the FATO may be wider and elongated, as shown in Figure 14.9b.

The TLOF is a hard or paved surface capable of supporting the heaviest air-

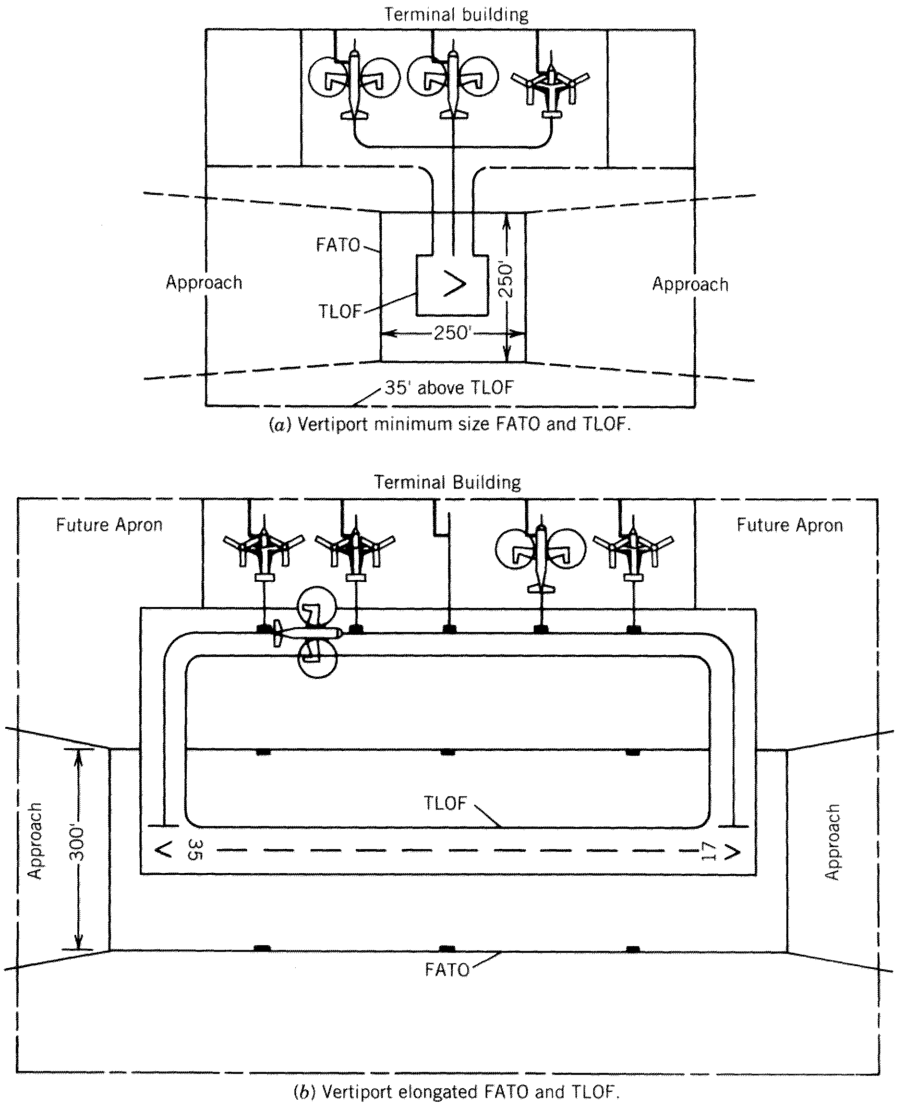


FIGURE 14.9 FATO and TLOF relationships (a) vertiport with minimum size FATO and TLOF; (b) vertiport with elongated FATO and TLOF. (*Source*: Reference 8)

craft that is expected to use the facility. It is normally centered within the FATO with at least 75 ft clearance between its edges and those of the FATO, as Figure 14.9 illustrates. For IFR operations, the primary axis of the TLOF should be centered on the final approach course.

The FAA recommends that the longitudinal and transverse gradients of a TLOF not exceed 1%. A rapid runoff shoulder with slopes of up to 5% should be used to facilitate drainage. Heavily used vertiports should have paved shoulders, at least 25 ft in width, to minimize the effects of exhaust heat and prop-rotor downwash.

The recommended obstruction clearance surfaces consist of (1) the primary surface, (2) the approach-departure surface, and (3) the transitional surfaces. These surfaces are similar in concept to those for a conventional airport, and they are defined in Section 7.18. Figure 14.10 illustrates recommended obstruction clearance surfaces for vertiports operating under visual conditions. The 1200 ft portion of a visual approach and departure surface abutting the primary surface must be straight. Beyond that point, visual approach and departure surfaces may be curved.

The imaginary approach surfaces for vertiports operating under instrument conditions are more complex and demanding than those under visual conditions. Recommended dimensions of such surfaces are given in Reference 8.

Taxiway and Hover Taxi Routes. Tiltrotor aircraft may either ground taxi or hover taxi between the TLOF and an apron or ramp. For ground taxiing, the FAA recommends a 75 ft wide paved taxiway to assure that the exhaust of the tiltrotor's engines is directed onto a heat and blast resistant surface. A 25-ft minimum clearance from the tips of the rotors to a fixed or moveable object is recommended. This clearance should be at least one-half the rotor-tip to rotor-tip span. See Figure 14.11.

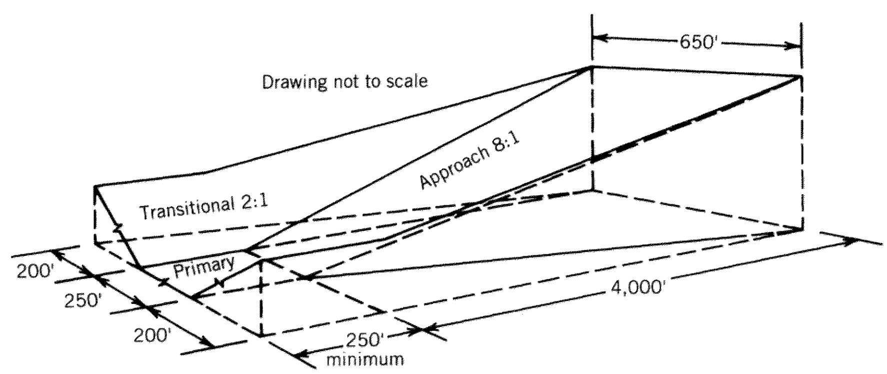


FIGURE 14.10 Obstruction clearance surfaces for vertiports under visual conditions. (*Source*: Reference 8)

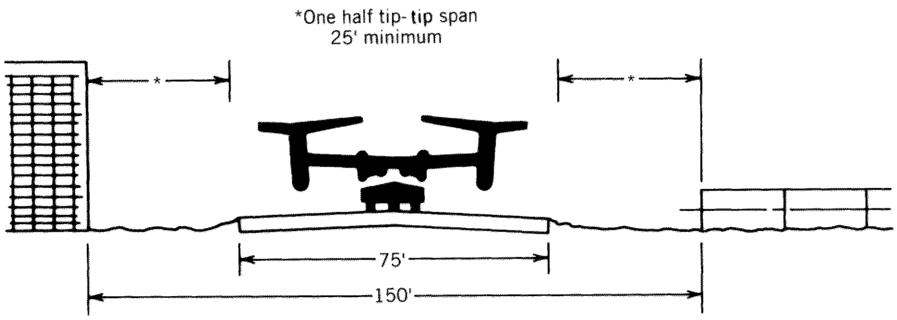


FIGURE 14.11 Vertiport taxiway. (*Source*: Reference 8)

A 250 ft wide taxi route safety area is recommended when tiltrotor aircraft or rotorcraft are to hover taxi between the TLOF and the apron or ramp.

Taxiway longitudinal and transverse gradients generally should not exceed 2% but can be as much as 3% in the unpaved portions of the taxiway safety area and in the nonload-bearing portions of the taxiway.

Aprons. Sufficient apron space should be provided to accommodate the maximum number of aircraft expected to use the facility at one time. The FAA recommends that, if the aircraft ground taxi, a clearance of 25 ft be provided between the rotor tips of adjacent aircraft and between the rotor tips and a fixed or moveable object. If the aircraft hover taxi, a clearance of 75 ft is recommended (8). Figure 14.12 shows a recommended layout of a vertiport apron or ramp.

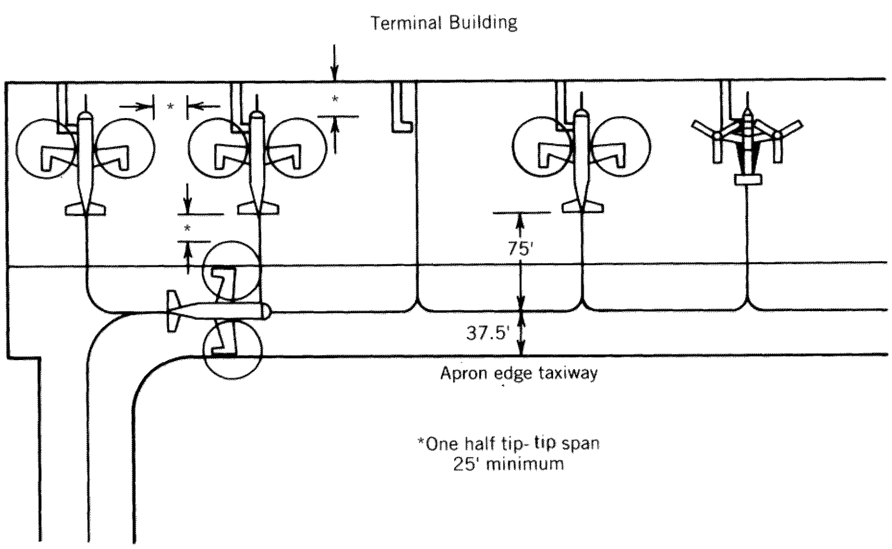


FIGURE 14.12 Vertiport apron or ramp. (*Source*: Reference 8)

Aprons should be sloped to assure good drainage, but apron slopes should not exceed 1%.

Marking of Vertiports

Numerals, letters, painted lines, and markers are used to identify vertiport and vertistop surfaces. Figures 14.13 and 14.14 illustrate vertiport markings proposed by the FAA (8).

The recommended identification for a public-use vertiport is a 50 ft high letter "V" painted in the center of a square TLOF and oriented to be read from the primary direction of approach. In addition, a number based on the nearest 10° of magnetic heading of the approach may be used to identify the ends of an elongated TLOF.

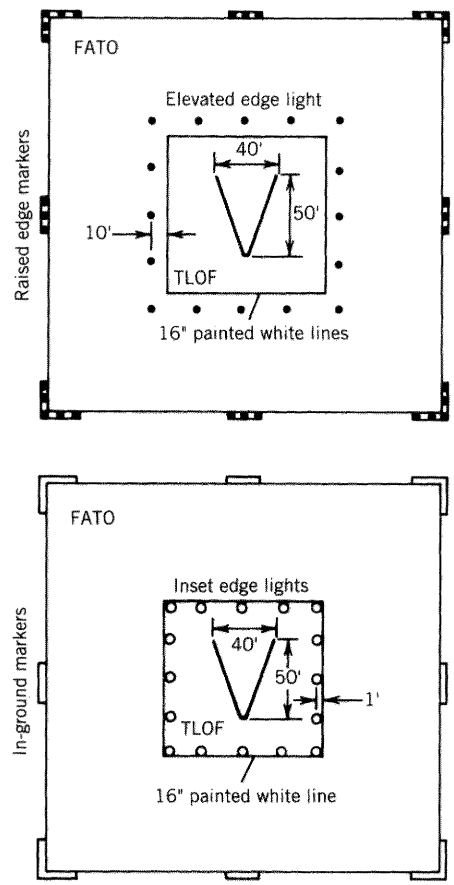


FIGURE 14.13 Typical vertistop marking and lighting. (*Source*: Adapted from Reference 8)

The edges of the TLOF should be marked by a 16 in wide painted white line located not more than 1 ft in from the edge of the TLOF. The centerline of an elongated TLOF should be marked with a 16-in wide dashed stripe with 50-ft long segments separated by 25-ft spaces.

The limits of a paved FATO should be defined with 16-in wide painted lines. The boundary of unpaved FATOS may be defined by in-ground or raised markers, not more than 6 in in height, spaced at intervals of approximately 125 ft along the FATO edges.

Taxiway centerlines should be marked with yellow 6-in wide lines, and taxi-

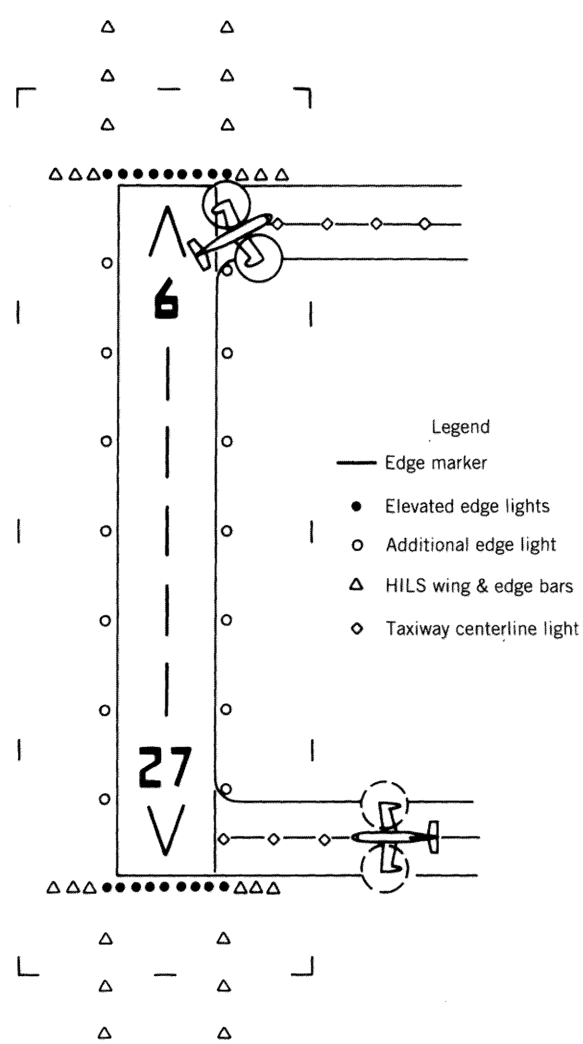


FIGURE 14.14 Typical marking and lighting of a vertiport with elongated TLOF. (*Source*: Reference 8)

way edges should be marked with double yellow 6-in wide lines spaced 6 in apart. Any portion of a taxiway pavement that is not full strength should be marked with yellow 3-ft wide bars perpendicular to the taxiway centerline at intervals of not more than 30 ft (8).

The FAA recommends that 3-ft high cylindrical raised markers be used to define the outer edges of the hover taxi route safety area. Such markers should be retroreflective and provide maximum color contrast with the natural background.

Aprons and ramps at vertiports should be marked with yellow 6-in wide lines to guide aircraft into lettered or numbered parking positions.

Lighting of Vertiports

Standard aviation lighting fixtures should be used to light vertiports. Recommended lighting systems include the following (8):

1. Shielded floodlights to illuminate passenger boarding positions on the apron.
2. An odd number of blue lights to define the limits of a ground level FATO.
3. An odd number of red double lens obstruction lights to define the edges of a building supporting an elevated vertistop or vertiport. A minimum spacing of 50 ft is recommended.
4. At least three amber lights located at least 10 ft beyond the pavement edge to define a TLOF. These lights should be flush-mounted if the surface is paved and otherwise no higher than 8 in above the ground.
5. Blue omnidirectional lights, not more than 8 in high and mounted 10 ft beyond the edge of the full-strength pavement to define the taxiway edges. Alternatively, inset, bidirectional green lights may be used to mark the centerlines of taxiways.
6. Blue omnidirectional lights, spaced not more than 50 ft apart to mark the edges of hover taxiways.
7. An identification beacon flashing white-green-yellow pulses of light to identify the presence of a lighted vertiport.

In addition, the FAA has designed enhanced lighting systems, including high-intensity lights (HILS) which extend to the TLOF edge lights and an approach lighting system (HALS) to aid pilots making precision instrument approaches. These are further described in Reference 8.

Some of the recommended lighting systems are sketched in Figures 14.13 and 14.14.

Pavement Design for Vertiports

Standard pavement design procedures (9) generally apply to the design of vertiport pavements. Such pavements must be capable of supporting the heaviest aircraft expected to use the facility. The design should allow for dynamic loads assumed to be 150% of the critical aircraft's static load. It may further be assumed 75% of the dynamic load is distributed through the aircraft's main landing gear. The loads imposed by service vehicles should also be considered in the pavement design, especially in the design of elevated facilities.

In the design of vertiport pavements, measures should also be taken to prevent or minimize dust and debris being blown about by rotor downwash and the erosion of pavements due to a tiltrotor's exhaust heat and velocity.

14.5 PLANNING AND DESIGN OF STOL FACILITIES

One approach to relieve congestion at conventional airports is to provide STOL facilities to accommodate short-haul demand. Such facilities may be added 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 STOL ports. Because of the limited interest in the development of STOL ports, 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 STOL port location. Some of the factors of special concern include the following:

1. *Air Safety Factors.* The air traffic generated by STOL port must be separated from other air traffic in the area, both existing and proposed. VFR and IFR traffic procedures must be reviewed, and an airspace utilization study by the FAA is required. Each potential site must be evaluated to determine whether man-made or natural obstructions would be present that would adversely affect air safety.
2. *Land and Land Use Factors.* Clearly, a major consideration in the location of a STOL port is the availability and cost of land. Although much less is required for a STOL port than for a conventional airport (16 to 50 acres vs. 5,000 to 10,000 acres), the desirability of choosing a site in close proximity to the users may make it difficult to identify suitable locations.
3. *Atmospheric Factors.* Atmospheric or climatological conditions that influence the selection of a STOL port site include direction and magnitude of winds (especially turbulence and crosswinds), temperatures, precipitation, and visibility.
4. *Engineering Factors.* The relevant engineering factors relate to the costs of construction and include such considerations as the ruggedness of the terrain (amount of earthwork), the quality of the foundation soil, the availability of construction materials, and problems of surface drainage.

*A notable exception is the London City Airport, a privately owned STOL port located between the Royal Albert Dock and the King George Dock, approximately 6 mi from the financial center of London (10).

5. *Social and Environmental Factors.* Perhaps the most important consideration is the compatibility of the STOL port with the users of neighboring property, especially with respect to noise.

It is important that the evaluation of STOL port sites be closely coordinated with the FAA, state, and local governments, and members of the aviation community. In view of the desirability of location STOL ports near centers of population, the need for participation of citizens groups in the planning process described earlier has special significance.

The general principles of airport layout and design given in Chapter 8 are applicable to STOL port design. However, there are major differences in scale between conventional airports and STOL ports.

A runway length of 1500 to 2000 ft will generally be sufficient for STOL operations from a paved surface at sea level and temperatures up to 90°F. The minimum runway length for a given STOL port depends on the FAA's airworthiness standards, the performance characteristics of the aircraft, and its design mission. Runway lengths for STOL aircraft may be determined from performance curves similar to those in Figures 8.1 and 8.2, taking into consideration the STOL port elevation and temperature, and the aircraft weight.

Both STOL and R/STOL* aircraft have a direct operating cost (DOC) penalty that is a function of the available field length. The shorter the allowable landing and takeoff distance, the higher the DOC penalty. These higher operating costs are, of course, offset by reductions due to lack of congestion and real estate and airport development costs.

STOL port planners may refer to the standards of the FAA (11) and ICAO (12) for guidance relative to separations and runway and taxiway dimensions. The planners should work closely with the FAA or other traffic control authority on matters relating to visual aids and obstructions to air navigation.

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*Reduced/short takeoff and landing.

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15

ENVIRONMENTAL IMPACT OF AIRPORTS

15.1 INTRODUCTION

In the early years of aviation, there was little concern about harmful environmental effects that attended the construction of airports and other public facilities. The principal thrust of government aviation actions was to foster the development of the aircraft industry. Complaints regarding environmental issues were rare and were viewed by government officials as irritants that threatened to impede the progress of air commerce.

A dramatic turnabout in public and offical concern about the environmental impact of airports developed in the late 1960s. The increased emphasis on the environmental effects of airports was partly a result of heightened public awareness of environmental problems in general. Perhaps more important, it was attributable to the alarming worsening of airport environmental problems that accompanied the sharp increases in aviation activity and the introduction of large jet aircraft.

This chapter calls attention to important federal environmental laws and describes how this legislation has changed the airport planning process. It covers briefly the most important areas of environmental concern and indicates how these effects may be evaluated and ameliorated. Some of the fundamental material in this chapter has been abstracted from a report (1) prepared for the U.S. Department of Transportation by CLM/Systems, Inc., to which the reader is referred for a more comprehensive treatment of the subject.

15.2 ENVIRONMENTAL LEGISLATION

Several important laws require airport sponsors and planning agencies to give appropriate consideration to environmental amenities and values when planning for airports. The most significant provisions relating to environmental

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planning are contained in the Department of Transportation Act, the National Environmental Policy Act of 1969, the Airport and Airway Development Act of 1970, the Uniform Relocation and Real Property Acquistion Policies Act of 1970, and the Clean Air Act and its amendments.

The Department of Transportation act, passed October 16, 1966, declared it a matter of national policy to make special efforts to preserve the natural beauty of the countryside. Section 4(f) of that act stated that the Secretary of Transportation may not approve any program or project that requires any land from a public park, recreation area, widlife and waterfowl refuge, or historic site unless there is no feasible and prudent alternative to the use of such land. Furthermore, transportation programs that require land from such areas must employ all possible measures to minimize environmental harm.

The National Environmental Policy Act of 1969 declared another national policy, namely, that the federal government would use all practicable means and measures "to create and maintain conditions under which man and nature can exist in productive harmony." It established a three-member Council on Environmental Quality in the Executive Office of the President to develop guidelines for agencies affected by the law. Section 102 of the act, quoted in part below, established the requirement for environmental impact statements.

> *Section 102.* The Congress authorizes and directs that, to the fullest extent possible: (1) the policies, regulations, and public laws of the United States shall be interpreted and administered in accordance with the policies set forth in this Act, and (2) all agencies of the Federal Government shall
>
> **1.** *(a)* Utilize a systematic, interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts in planning and in decision making which may have an impact on man's environment.
>
> **2.** *(b)* Identify and develop methods and procedures, in consultation with the Council on Environmental Quality established by title II of this Act, which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in decision making along with economic and technical considerations.
>
> **3.** *(c)* Include in every recommendation or report on proposals for legislation and other major federal actions significantly affecting the quality of the human environment, a detailed statement by the responible official on:
>
> (a) The environmental impact of the proposed action.
>
> (b) Any adverse environmental effects which cannot be avoided should the proposal be implemented.
>
> (c) Alternatives to the proposed action.
>
> (d) The relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity.
>
> (e) Any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented.

The Airport and Airway Department Act of 1970 authorized the Secretary of Transportation to make grants for airport development and to set conditions for the approval of federally sponsored airport projects. Several of these conditions related specifically to the environmental effects of airport development. The act required that appropriate consideration be given to the economic, social, and environmental effects of the location of an airport on nearby communities, and that the proposed development be consistent with the community's planning goals and objectives. It required that citizens of neighboring communities be afforded the opportunity for public hearings. The law directed the Secretary of Transportation to consult with the Secretaries of the Interior and Health and Human Services in the evaluation of possible adverse environmental effects of airport projects. It further required compliance with appropriate air and water quality standards. Under the law, no federally assisted development projects that would have adverse environmental effects may be authorized unless the Secretary of Transportation certifies that no feasible and prudent alternative exists and that all possible steps have been taken to minimize the adverse effects predicted.

The Uniform Relocation Assistance and Real Property Acquisition Policies Act of 1970 provides for equitable and uniform treatment of persons displaced from their homes, businesses, or farms by federally assisted programs. If land is acquired for federally assisted airport development, the airport sponsor must reimburse persons displaced from their homes, businesses, or farms for the costs of moving and for expenses in searching for replacement property. Persons displaced from their homes may be paid an additional amount up to $15,000 for the purchase of comparable housing. Tenants may receive up to $4,000 for rental payments or for a down payment on a house. Under the law, replacement housing may be constructed by a public agency if suitable housing is not available to those displaced by the development program. The act calls on public agencies receiving federal assistance to provide advisory services to assist displaced persons in relocating to new houses, businesses, and farms.

The Clean Air Act, as amended in 1977, provided for the establishment of ambient air quality standards and required that the governors of the various states submit implementation plans designed to meet those standards. The law provides for sanctions against those states that fail to make reasonable efforts toward compliance with the air quality standards. In such standards, the law states that the Secretary of Transportation shall not approve any projects or award any grants under Title 23, United States Code, other than for safety, mass transit, or transportation improvement projects related to air quality improvement or maintenance.

Thus, federal laws and directives have brought about fundamental changes in the airport planning process. Environmental factors must now be considered with the same degree of thoroughness as safety, efficiency, and construction costs. Whenever possible, airport planning should be accomplished by a multidisciplinary team of engineers, architects, economists, planners, and environmental specialists. A wide range of alternatives should be developed and compared, including the "do not build" option. Airport planners must seek out and consider the views of government agencies, members of the aviation community, and the public at large. Every effort must be made to minimize the hardships to persons displaced from homes, businesses, and farms by airport development, and payments for moving expenses and replacement housing are mandated.

> A new dimension has been added to the airport planner's job. Airport development that focuses only on the requirements of the user without emphasis on the protection, and even enhancement, of the environment, will no longer be tolerated. This added dimension should not be viewed as a deterrent to technical progress, but as an opportunity to develop new and innovative ideas that enhance technical progress by linking it to the preservation of natural aesthetic land functions (2).

15.3 ENVIRONMENTAL IMPACT STATEMENTS

As a means of implementing the various environmental laws, directives (3, 4) issued by the Department of Transportation provide guidance for the preparation of environmental impact statements. Applicants for federal aid must submit a proposed draft environmental impact statement for all airport developments that would significantly affect the quality of the environment.

Where doubt exists about the need to prepare an environmental impact statement, a document called an "environmental assessment" is prepared concisely describing the environmental impacts of the proposed work and its alternatives. This assessment serves as a basis for deciding the nature of further environmental analysis and documentation. If it is determined that a proposed project would not have a significant effect on the environment, a statement to that effect is prepared. This document, which is called a finding of no significant impact (FONSI), must be made available to the public on request but normally does not have to be coordinated outside the originating office.

Certain actions are so patently innocuous that they are categorically excluded from the requirement of an environmental assessment or an environmental impact statement. Such actions include administrative procurements, personnel actions, and project amendments that do not significantly alter the environmental impact of the action.

In the early stages of an environmental analysis, local agencies and other affected groups and persons should be invited to participate in a process known as "scoping." In this process, the significant issues to be analyzed in depth are identified, and those that are insignificant are eliminated from further study. The process also provides an opportunity for assigning the preparation of the environmental impact statement among the lead and cooperating agencies, and for the scheduling of these assignments.

In the development of airport master plans and other complex proposals, the Department of Transportation encourages the preparation of tiered environmental impact statements. The first tier of such statements focuses on broad issues such as airport location, area wide air quality, and land use implications of the development. The second tier is site specific and describes detailed project impacts and measures to mitigate harmful impacts.

The elements of a comprehensive environmental impact statement have been well defined by federal laws and directives. These elements are briefly described in the following subsections.

Description and Purpose of the Project

The statement should contain a quantitative description of the proposed development, including the amount of land to be acquired and cleared and the extent of construction. The purpose of the project should be set forth, showing anticipated aviation and community needs, based on aviation demand and population forecasts. If the work is to be completed in stages, the proposed scheduling of various phases of the development should be indicated. The location of nearby communities and airports should be identified, as well as public parks, historic areas, and wildlife sanctuaries. Such areas of environmental interest should be shown on a map in relation to the proposed airport development. The relationship of the development to short- and long-range land use plans for surrounding areas should be indicated.

Probable Impact of the Development on the Environment

The environmental impact statement should include a discussion of the likely temporary and permanent impacts on the biosphere. Temporary impacts consist primarily of those related to the construction process, such as siltation and erosion, flooding, and air pollution that results from clearing and burning operations.

The environmental impact statement should document the probable permanent impact on the human environment, including social as well as environmental concerns. Any potential division or disruption of communities should be described, and the locations of neighboring churches, schools, hospitals, and other places of public assembly should be graphically portrayed. Changes in ground traffic and flight patterns should be described, and the effects of such changes on ambient noise levels should be included as an attachment to the environmental impact statement.

The statement should describe the probable permanent impact of the development on fish and wildlife sanctuaries, scenic and recreation areas, and historical or archaeological sites. The potential for the alteration or destruction of wildlife breeding, nesting, or feeding grounds, and possible effects of water pollution on marine life should be described. Locations of open spaces, parks, golf courses, and other public and private recreational areas should be indicated.

Probable Adverse Environmental Effects That Cannot Be Avoided

Except for relatively minor improvements, airport development projects normally produce unavoidable adverse environmental effects. For example, acquisition of additional airport land may cause persons to be displaced and business and farming activities to be relocated. Increased air traffic causes more air pollution and increases in ambient noise levels. Improvements to lighting systems resulting in more nighttime operations may cause greater annoyance to nearby residents.

The environmental impact statement should recognize unavoidable adverse environmental effects and, to the extent possible, describe them in quantitative terms. The statement should provide the numbers of houses, businesses, and farms affected by the development and the type, suitability, and location of relocation housing. It should identify any community interests that conflict with the proposed development and indicate why these interests have not been satisfied. Adverse noise impacts should be described by means of noise contours, showing the levels of noise exposure, the land use activities affected, and the extent of such effects.

Alternatives to the Proposed Action

The environmental impact statement should identify and describe alternative actions that have been investigated to meet community interest and to lessen the adverse effect on the natural environment and recreational lands and historic sites. Four different groups of alternatives may be considered (1):

1. Basic alternatives.
2. Site location alternatives.
3. Developmental alternatives.
4. Nonphysical alternatives.

Examples of these classes of alternatives appear in Table 15.1 Reasons for rejecting the various alternative actions should be stated, and the estimated cost of each alternative should be given. If no feasible and prudent alternative to the proposed course of action exists, the steps that have been taken to minimize adverse environmental effects must be described.

Relationship Between Local Short-Term Uses of the Environment and Maintenance and Enhancement of Long-Term Productivity

The environmental impact statement should compare the short-term environmental problems with the long-term environmental benefits that are claimed for the airport development. The short-term problems are generally those associated with the construction process. A variety of long-term benefits may

TABLE 15.1 Examples of Alternative Environmental Actions

1. Basic Alternatives
Should the airport be built?
Should part of transport service be provided by another mode?

2. Site Location Alternatives
Where should new airport be located?

3. Developmental Alternatives
Which runway alignment should be chosen?
Should existing runway be extended rather than building a new one?
What is the best runway configuration?

4. Nonphysical Alternatives
Should flight schedules be rearranged so that there are fewer night operations?
Should landing fees be raised to discourage aviation traffic?

be identified, including those related to increased safety and efficiency of aircraft operations, economic advantages associated with increased air commerce, and environmental gains. Table 15.2 gives examples of short-term problems and long-term benefits that might be included in an environmental impact statement.

Irreversible or Irretrievable Commitments of Resources

The environmental impact statement should list any irreversible or irretrievable commitments of resources that would be made if the airport project were undertaken. Examples of such commitments are as follows:

1. Destruction of wildlife habitats.

TABLE 15.2 Examples of Short-Term Problems and Long-Term Benefits Due to Airport Development

1. Removal of trees in runway approaches.	1. Turfing and landscaping.
2. Erosion and siltation during construction.	2. Recharging groundwater supplies.
3. Dust, mud, and related annoyances.	3. Supplying need for air transport.
4. Ground traffic congestion due to detours, road closures.	4. Inducement of economic development.
5. Construction-related noise problems.	5. Increase of safety and efficiency of airport.
	6. Diminution of noise by shifting aircraft flight patterns to less densely populated areas.

2. Creation of groundwater or other hydrologic imbalances.
3. Removal of areas of scenic beauty (e.g., streams, primeval forestland).
4. Use of construction materials for the airport project.
5. Loss of natural resources (e.g., minerals, special crops), which will become inaccessible because of the airport development.

15.4 PUBLIC HEARINGS

FAA directives (3, 4) require that airport sponsors afford the opportunity for public hearings on the environmental effects of certain airport development projects. Specifically, citizens must be given such opportunity in the case of federally assisted projects that involve the locatiton of an airport, the location of a runway, or a major runway extension. A public hearing may also be required if it is requested by another agency with jurisdiction over the proposed action if the project is expected to cause substantial controversy. The opportunity for a public hearing is normally given before the submission of the sponsor's environmental assessment.

The requirement for a public hearing may be satisfied by publishing a notice of opportunity in a newspaper of general circulation and by holding a hearing if one is requested. The sponsor must certify that an opportunity for a public hearing was given and must document the various steps taken in the hearing process. If a hearing is held, the sponsor must include a summary of the issues raised and the sponsor's reaction and conclusions on those issues.

15.5 STATE AND LOCAL REVIEW PROCESS

During past years, a major stumbling block to the orderly development of airports in urban areas was the multiplicity of political jurisdictions affected. Often a dozen or more local governments with conflicting goals and little direction became involved in the planning of a single airport. The need for coordination was obvious.

Planners of federally assisted airport projects are now encouraged to coordinate the airport planning activity through a "single point of contact." Regulations of the Office of Management and Budget allow each state to adopt its own process for review of proposed airport actions and to delegate the review to local officials. The objective is to assure that proposed federally assisted airport programs and projects are reviewed and evaluated in advance in terms of their potential impact on and conflict with statewide, areawide, and local comprehensive planning (4).

Sponsors should notify the single point of contact as soon as project planning has developed in sufficient detail to describe the nature and scope of the proposed development. The point of contact is asked to inform state and local agencies known to be interested in the proposed project. The comments and recommendations made by these agencies become part of the environmental assessment and must be addressed in the FAA's environmental documentation (4).

During past years, a major stumbling block to the orderly development of airports in urban areas was the multiplicity of political jurisdictions affected. Often a dozen or more local governments with conflicting goals and little direction became involved in the planning of a single airport. The need for coordination was obvious.

Many and varied agencies and organizations normally participate in the planning of an airport. With specific reference to environmental matters, airport planners should receive imput from the following government agencies, where applicable:

1. Federal Aviation Administration.
2. State aeronautics commission.
3. City planning commissions.
4. State Department of Transportation or Highway Department.
5. Rapid transit authority.
6. Air and water pollution district.
7. Local environmental agencies.

In addition, the planners should consult with members of the aviation community and the public at large. In the former category, air carriers, pilots associations, flying clubs, and travel industry groups are particularly noteworthy. Input from the general public may be received from civic organizations and environmental groups, and from individual participants in public hearings.

15.6 AIRPORT NOISE

One common environmental impact of airport development is also probably the most troublesome to control: airport noise. We will examine the nature and scope of the noise problem, describe some of the noise measurement and rating techniques, and discuss some remedial programs to reduce noise levels and lessen its harmful effects.

Before 1960, there was little concern about aircraft noise. Earlier airport engineering textbooks and design manuals mentioned airport noise only peripherally, if at all. Solutions to aircraft noise problems were limited almost exclusively to preventing encroachment of urban development in the vicinity of airports.

Since the introduction of commercial jet aircraft in 1959, there have been dramatic changes in the nature and magnitude of the airport noise problem. The sharpening focus on airport noise as a serious environmental problem has resulted from a combination of factors, including the following:

1. Increases in air traffic, especially flights utilizing larger and more powerful jet aircraft.
2. Increased urbanization of airport neighborhoods.
3. Increased public awareness of environmental problems generally and airport noise problems particularly.

The seriousness of the noise problem was manifested in 1969 by the promulgation in Federal Aviation Regulations, Part 36, of FAA noise standards for the certification of turbojet aircraft of new design. The regulations were amended in 1973, extending the same standards to all new aircraft of older design. In late 1976, the FAA announced that older, noisier, four-engine jet airplanes must be modified to meet the Part 36 noise levels or be retired from service within eight years (5). The aircraft noise problem is, of course, worldwide in scope, and ICAO similarly has adopted noise certification standards for jet aircraft (6).

The Environmental Protection Agency (EPA) estimated that the total area in the United States subjected to excessive aircraft noise (as evidenced by numerous complaints) grew about sevenfold between 1960 and 1970. By 1976, it was estimated that aircraft noise was a significant annoyance for 6 to 7 million Americans (5).

Noise detracts from the amenities of a pleasant living environment and may cause land values to decrease. It can be a source of great annoyance, interrupting sleep, interfering with conversation, and depriving people from full enjoyment of many recreational activities. Many experts now recognize noise as a serious threat to public health. People repeatedly exposed to high noise levels may exhibit increased irritability, severe nervous tension, loss of ability to concentrate, and impaired aptitude to perform even simple tasks (7).

Noise Measurement Techniques

Noise is defined as excessive or unwanted sound. It is unwanted because it annoys people, interferes with conversation, disturbs sleep, and, in the extreme, is a danger to public health. Sound, whether noisy or noiseless, is produced by vibrations in a medium (e.g., air, water, steel). When an object vibrates, it produces rapid small-scale variations in the normal atmospheric pressure. This disturbance is propagated from the source in a repetitive spherical pattern at a speed (in air) of approximately 1100 ft/sec (340 m/sec). It may be reflected, partially absorbed, or attenuated before reaching an eardrum to produce a sensation of sound.

Noise is characterized by its sound level, its frequency spectrum, and its variation over time. "Sound level" refers to a physical measure that corresponds to the hearer's subjective conception of loudness. It is a function of the magnitude of the pressure fluctuations about the ambient barometric air pressure. One can speak of the strength of these fluctuations in terms of several variables, the most common being *sound intensity* and *sound pressure*.

Sound intensity (also called "sound power density") is the average rate of sound energy transmitted through a unit area perpendicular to the direction of sound propagation, typically measured in picowatts* per square meter (pW/m^2). The human ear can detect sound intensities as weak as 1 picowatt and can tolerate intensities as high as 10^{13} pW. Because of the difficulties of dealing with such a large range of numbers, a logarithmic measure called the decibel (dB) is used to describe sound level. The sound intensity, expressed in decibels, is

$$\text{sound intensity} = 10 \log_{10} \left(\frac{I}{I_0} \right) \tag{15.1}$$

where

I = sound intensity (pW/m^2)
I_0 = 1 pW/m^2, a standard reference intensity representing approximately the weakest audible sound

Since no instrument is available for directly measuring the power level of a source, sound pressure, which is usually proportional to the square root of sound power, is used as a measure of the magnitude of a sound disturbance (8). The sound pressure, in decibles, is

$$\begin{aligned} \text{sound pressure} &= 10 \log_{10} \left(\frac{P}{P_0} \right)^2 \qquad (15.2) \\ &= 20 \log_{10} \left(\frac{P}{P_0} \right) \end{aligned}$$

where

P = the root mean square sound pressure, typically expressed in newtons per square meter (N/m^2)
P_0 = 20 $\mu N/m^2$ or 0.0002 $dyne/cm^2$, a standard reference pressure corresponding to the weakest audible sound

Sound level is measured by a sound level meter, which consists essentially of a microphone that converts the pattern of sound pressure fluctuations into a similar pattern of elctrical voltage, one or more amplifiers, and a voltage meter, which is normally calibrated to read in decibels. For practical purposes, the decibel scale ranges from zero, the threshold of hearing, to about 140 dB, the onset of pain. For every increase of about 10 dB, there is a doubling of the sound's apparent loudness.

The apparent loudness of a sound also depends on the *frequency* of the

*1 picowatt = 10^{-12} watt.

sound. Frequency is the rate of occurrence of the sound pressure fluctuations, commonly expressed in cycles per second or hertz (Hz). The frequency determines the pitch of the sound; the higher the frequency, the higher the pitch. The lowest note on a piano has a frequency of about 27 Hz, and the highest note has a frequency of 4186 Hz. The normal human ear can hear sounds with frequencies from about 20 to 20,000 Hz, but it is more sensitive to sounds in the middle- to high-frequency range. Since most people consider high-frequency noises more annoying than low-frequency noises at the same sound level, a frequency analysis may be required to properly evaluate noise sources. Schultz explains:

> Most noises are made up of a mixture of components having different frequencies: the sound of a diesel tractor/trailer at high speed on the freeway combines the high-pitched singing of the tires and the low-pitched roar of the engine and exhaust, both of which the ear readily distinguishes. A landing jet aircraft has a clearly distinguishable whine from the compressor, mixed with the "random" noise of the engine exhaust (sounds like a big waterfall). A flute, on the other hand, if played softly, makes an almost pure tone containing only a single prominent frequency. Depending on how the components of a noise are distributed in frequency, our ears make a subjective judgment of "quality." Consequently, it is important to have an objective measure of the frequency distribution (7).

A frequency analysis is performed by means of a sound meter that can be tuned to different parts of the frequency range. The meter eliminates or "filters out" all of the sound components except those in a relatively narrow band of frequencies. Thus, it is possible to measure selectively the sound level for different bands and to describe the frequency distribution of noise as a set of partial sound levels in contiguous frequency bands covering the entire audible range. These measurements can be displayed on a graph, such as Figure 15.1, showing an octave-band (or third-octave band) analysis of the noise (7).

> [The terms octave and third-octave] describe the bandwidth of the filter according to the ratio of the upper and lower frequencies that bound the band: in an octave band, the upper bounding frequency is always exactly double the lower bounding frequency; in a ⅓-octave band, the upper frequency is always 1.26 ($= \sqrt[3]{2}$) times the lower frequency. Each octave band is made up of (or contains) three equal, contiguous ⅓-octave bands (7).

The annoyance a person experiences because of noise depends to a considerable extent on its variation over time. The temporal effect is manifest in the duration of a single noise event, as well as its frequency and time of occurrence. Clearly, the longer a noise lasts, the greater the interruption of human activity and the more pronounced the annoyance. Laboratory tests have indicated that, for durations ranging from a few seconds to 60 sec, a noise decreases in acceptability roughly at a rate of 3 dB per doubling of duration (9). Thus, two sounds of equal frequency distribution will be judged equally

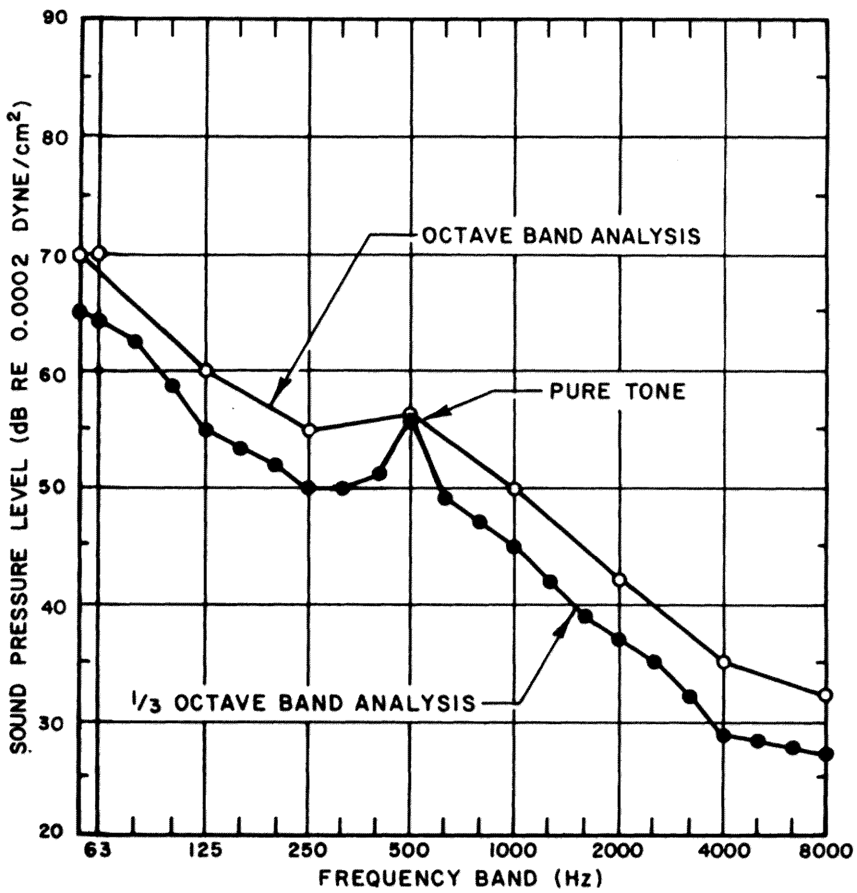


FIGURE 15.1 Typical points on the A-level and EPNL noise scales. (Courtesy U.S. Department of Transportation)

acceptable if one has an amplitude of 3 dB less than the other and a duration of twice the other.

The number of aircraft operations per day and their time of occurrence can strongly influence the degree of annoyance experienced by those residing near airports. In research performed in the vicinity of Heathrow Airport, a comparison was made of Londoners' noise exposure and the results of social surveys taken around the airport. The study identified the number of aircraft exposures as one of the most important factors influencing the degree of public annoyance by aircraft noise. It was found that the number of events alone had a higher contribution to the total variance in response than did the noise level itself (9). This suggests that the very existence of a noise event may be more significant than the magnitude of the event.

For obvious reasons, aircraft noise is more annoying during evening and nighttime hours than during the day. Nighttime aircraft operations cause more interference with social conversation, detract more from recreational activities, and are more likely to interrupt sleep than operations during daylight hours.

Noise Rating Techniques

A great many scales have been used to express noise levels. Although there is no generally accepted noise scale, only a few of the available scales have gained wide acceptance. Several of the more commonly employed noise scales are described below. One of the simplest and most straightforward noise measurement techniques consists of measuring the *overall sound pressure level*, which is related to total sound energy over the audible frequency range. However, the unweighted overall sound pressure level is not strongly correlated with a hearer's subjective response to the noise. As indicated earlier, the human ear tends to be more sensitive to sounds with relatively high frequencies.

The *A-weighted sound level* was devised to more closely represent a person's subjective response to sounds. In the A-weighted filter network, the lower frequencies are deemphasized in a manner similar to human hearing. Like the overall sound level, the A-weighted sound level is measured in decibels [dB (A)]. The A-weighted scale is a widely accepted measure of surface transportation noises but is less commonly used to measure aircraft noise.

In 1959, K. D. Kryter developed a scale called the *perceived noise level* (PNL) that correlates with the annoying properties of jet aircraft noise. It is measured in decibels and is evaluated in units of PNdB. The PNdB level is measured for a single event, such as an aircraft flyover. Its evaluation requires the instantaneous measurement of sound pressure levels in the various octave (or ⅓ octave) bands for each half-second increment of time during the noise event. It is based on a series of calculations that weight the octave (or ⅓ octave) band levels of the noise according to the degree of annoyance it causes.

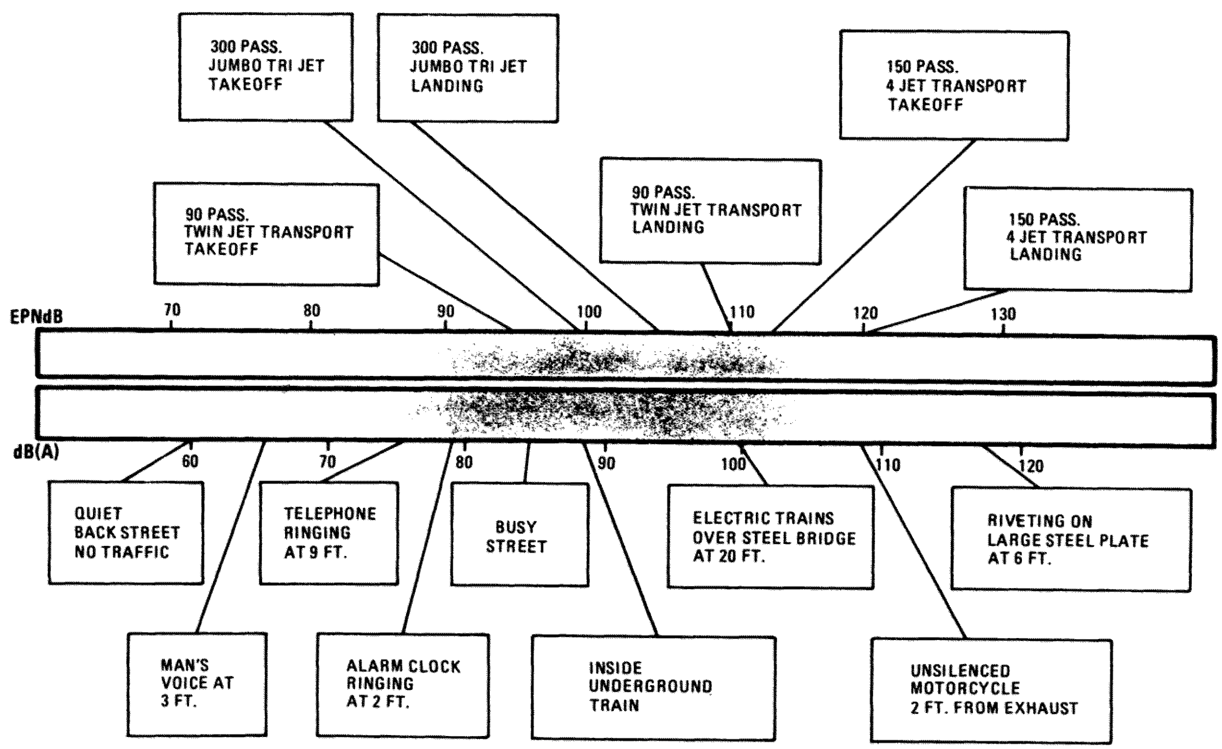
A modification to the perceived noise level acounts for the duration of the event and the subjective response to pure tones in the noise spectrum. Termed the *effective perceived noise level* (EPNL) and measured in EPNdB, it has been adopted by the FAA and the ICAO as the standard measurement for aircraft noise. Typical points on the A-level and EPNdB scales appear in Figure 15.2. Note that

$$\text{EPNdB} \approx \text{dB(A)} + 12 \tag{15.3}$$

The procedures for calculating perceived noise levels are complex. For planning purposes, the ICAO (6) recommends that the approximate methods described below be used to determine EPNL values.

To determine the EPNL, a series of instantaneous sound pressure levels is measured in each of the octave bands for each half-second increment of time during the aircraft flyover. Figure 15.2 plots a typical instantaneous measure-

TYPICAL NOISE LEVELS



Note:

Approximate relation between EPNdB scale and dB(A) scale is shown in this comparison of various noise sources.

FIGURE 15.2 Typical instantaneous measurement of noise spectrum. (*Source*: Reference 7) ment for the various octave bands. The following steps are taken to compute the EPNL for a noise event.

Step 1. Let SPL(i, k) indicate the sound pressure level for the ith frequency band measured at time increment k. Convert each SPL (i, k) in the spectrum to perceived noisiness $n(i, k)$ in noys,* by usiing Table 15.3.

Step 2. Compute the total perceived noisiness $N(k)$ for time increment k by combining the perceived noisiness values $n(i, k)$ by means of the following formula:

$$N(k) = 0.7n(k) + 0.3 \sum_{i=1}^{8} n(i, k), \qquad \text{noys} \tag{15.4}$$

where

$$n(k) = \text{the largest of the } n(i, k) \text{ values}$$

Step 3. Convert the total perceived noisiness $N(k)$ into the perceived noise level PNL(k) by employing the following formula:

$$\text{PNL}(k) = 40.0 + 33.3 \log N(k), \qquad \text{PNdB} \tag{15.5}$$

Step 4. In case of landing turbofan aircraft operations, correct the PNL(k) value obtained in step 3 for subjective response to the presence of pure tones by adding 2 PNdB. No correction of PNL values is required for other aircraft operations.

Step 5. Following steps 1 to 4, determine the tone-corrected PNLs, designated PNLT, for each of the k half-second increments of time during the noise event. Figure 15.3 shows a typical pattern for a 20 sec aircraft flyover.

Step 6. Compute a duration correction factor, D, by the formula

$$D = 10 \log \frac{[t(2) - t(1)]}{20} \tag{15.6}$$

where $t(2) - t(1)$ is the approximate time interval during which a recording of PNLT is within 10 dB of its maximum value.

*The noy is a subjective unit of noisiness. A sound of 2 noy is twice as noisy as a sound of 1 noy; a sound of 3 noy is 3 times as noisy, and so on.

TABLE 15.3 Noys as a Function of Sound Pressure Level

Sound Pressure Level (dB)	⅓ Octave Band Center Frequencies (Hz)							
	63	125	250	500	1000	2000	4000	8000
50	—	—	1.56	2.00	2.00	3.46	4.26	3.02
55	—	1.38	2.25	2.83	2.83	4.89	6.01	4.26
60	1.00	2.08	3.26	4.00	4.00	6.90	8.49	6.01
65	1.60	3.12	4.71	5.66	5.66	9.74	12.0	8.49
70	2.55	4.69	6.81	8.00	8.00	13.8	16.9	12.0
75	4.06	7.05	9.85	11.3	11.3	19.4	23.9	16.9
80	6.48	10.6	13.9	16.0	16.0	27.4	33.7	23.9
85	10.3	14.9	19.7	22.6	22.6	38.7	47.6	33.7
90	14.9	21.1	27.9	32.0	32.0	54.7	67.2	47.6
95	21.1	29.9	39.4	45.3	45.3	77.2	94.9	67.2
100	29.9	42.2	55.7	64.0	64.0	109.	134.	94.9
105	42.2	59.7	78.8	90.5	90.5	154.	189.	134.
110	59.7	84.4	111.	128.	128.	217.	267.	189.
115	84.4	119.	158.	181.	181.	307.	377.	267.
120	119.	169.	223.	256.	256.	433.	533.	377.
125	169.	239.	315.	362.	362.	611.	752.	533.
130	239.	338.	446.	512.	512.	863.	1062.	752.
135	338.	478.	630.	724.	724.	1219.	1499.	1062.

Source: *Environmental Protection, Annex 16 to the Convention on International Civil Aviation, Vol. I, Aircraft Noise*, 1st ed., International Civil Aviation Organization, Montreal, 1981.

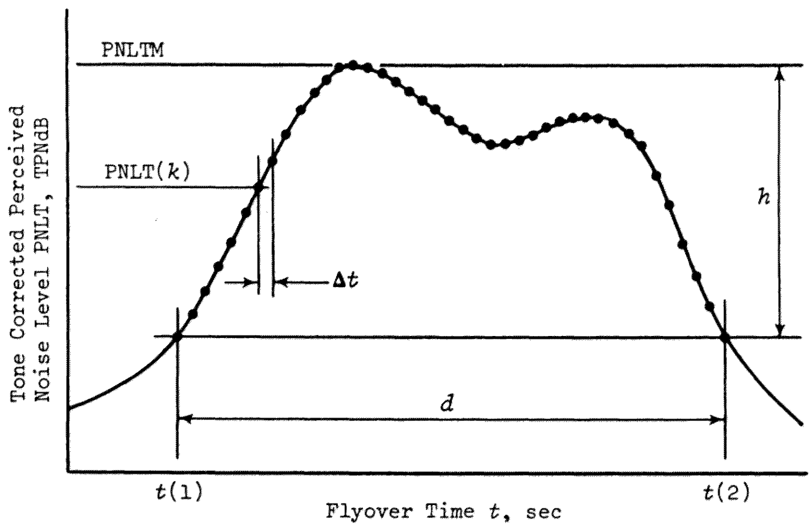


FIGURE 15.3 Typical pattern for 20-sec aircraft flyover. (*Source*: Reference 6)

Step 7. Compute the EPNL by adding the duration correction factor D to the maximum value of the tone-corrected perceived noise level PNLTM:

$$\text{EPNL} = \text{PNLTM} + D, \quad \text{PNdB} \tag{15.7}$$

The resulting value of EPNL represents the effective perceived noise level for a single noise event such as a flyover. One is normally interested in evaluating the total noise exposure level (TNEL) produced by a succession of n aircraft. This can be determined by employing the following equation:

$$\text{TNEL} = 10 \log \sum_{i=1}^{n} \text{antilog} \frac{\text{EPNL}(n)}{10} + 10 \tag{15.8}$$

The ICAO (6) has recommended that the total noise exposure level be adopted internationally for land use planning purposes and that the measure be referred to as the International Noise Exposure Unit.

In a report (10) presented to the British Parliament in 1963, a rating technique called the *noise and number index* (NNI) was introduced to account for the average peak noise level as well as the number of aircraft heard in a given period of time:

$$\text{NNI} = \bar{L} + 15 \log_{10} N - 80 \tag{15.9}$$

where

N = number of aircraft heard
$\bar{L}$ = the average peak noise level (PNdB or EPNdB)

The average peak noise level is computed by the following equation:

$$\bar{L} = 10 \log_{10} \frac{1}{N} \sum_{i}^{N} 10^{L/10} \tag{15.10}$$

where L = peak noise level (PNdB or EPNdB) for a single noise event. The constant 80 was included in the NNI equation so that zero NNI would correspond to zero public annoyance due to aircraft noise, as determined by a social survey around Heathrow Airport.

In the late 1970s, the FAA adopted the day/night average sound level (L_{DN}) procedure (11) as the preferred method of measuring noise resulting from aircraft operations. The L_{DN} is a measure of the noise environment at a specified location over a 24-hour period. In terms of sound energy, it is equivalent to the level of a continuous A-weighted sound level with nighttime noises increased by 10 dB to account for the undesirable effects of night noise disturbances. The L_{DN} may be directly measured by a sophisticated integrating noise measurement meter, or it may be calculated in several ways.

With the L_{DN} method, the contribution of an aircraft operation is described in terms of the sound exposure level (SEL). The SEL is the A-weighted sound level integrated over the entire noise event and normalized to a reference duration of 1 sec. In other words, the SEL gives the level of a continuous 1-sec sound

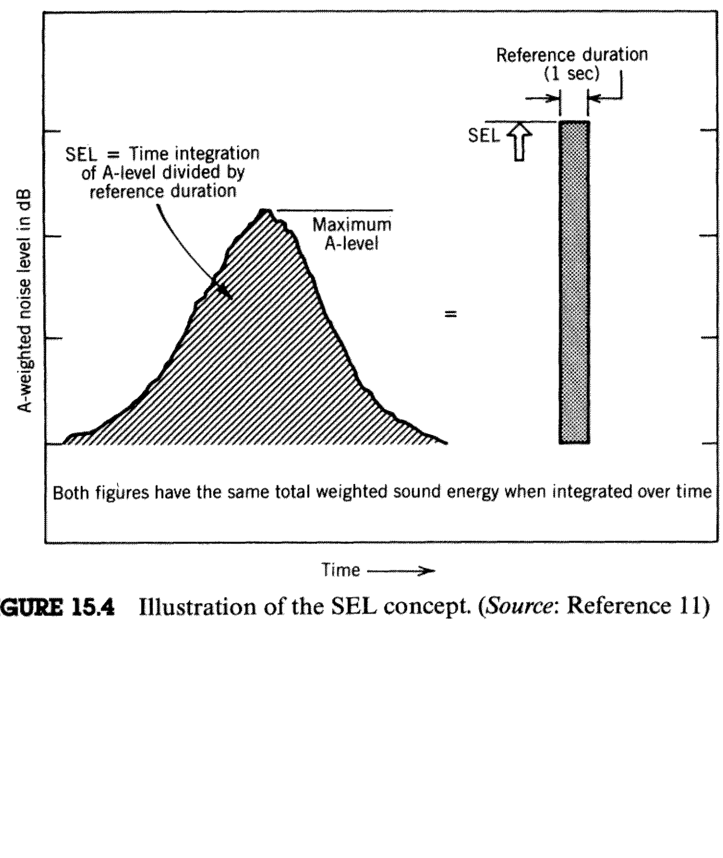


FIGURE 15.4 Illustration of the SEL concept. (*Source*: Reference 11)

that contains the same amount of energy as the noise event (see Figure 15.4).

Empirical graphs, typified by Figure 15.5, have been published (11), giving SEL values in dB for different classes of aircraft, mode of operation, and locations with respect to the flight path. The "partial" L_{DN} value for those conditions can then be calculated by equation 15.11, which accounts for the number and time of day of such operations. For aircraft class i, and operation mode j,

$$L_{DN}(i, j) = \text{SEL}(i, j) + 10 \log(N_d + 10 N_N) - 49.4 \qquad (15.11)$$

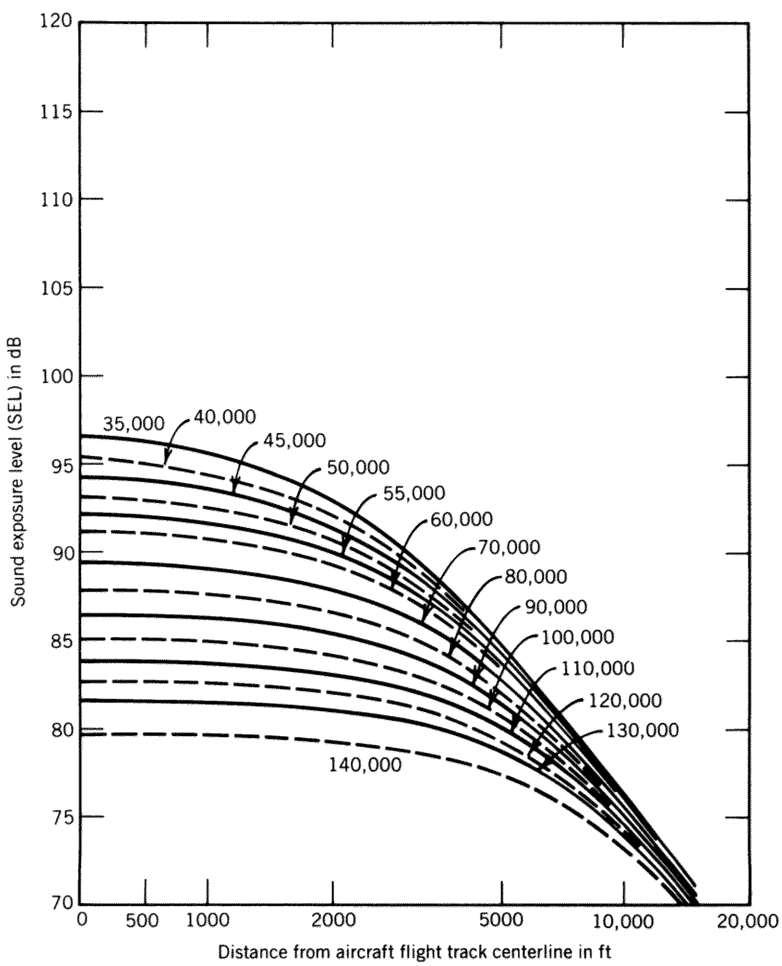


FIGURE 15.5 Example of empirical graph for estimating sound exposure level. (Four-engine HBPR Turbofan Transport (747); landing—3 glide slope; flight tract distance range—35,000–150,000 ft from runway landing threshold.)

where

N_D = number of daytime operations for given conditions
N_N = number of nighttime operations for given conditions

Daytime is taken as the period from 7:00 A.M. to 10:00 P.M., and nighttime is the remainder of the day.

After the "partial" L_{DN} values have been calculated for each significant noise intrusion, they may be summed on an energy basis by Equation 15.12 to obtain the total L_{DN} due to all aircraft operations.

$$L_{DN} = 10 \log \sum_i \sum_j 10^{\frac{L_{DN}(i,j)}{10}} \qquad (15.12)$$

Figure 15.6 shows the relationship between the L_{DN} and the percentage of people highly annoyed by exposures to the aircraft noise. The curve represents the mean of 11 surveys performed by a contractor for the U.S. Department of Housing and Urban Development.

A computer tool for measuring the impact of aircraft noise, known as the Integrated Noise Model (INM), was released by the FAA in 1978. Version 3 of the model was made available in 1982 (12). It is written in ANSI FORTRAN machine-independent code, which is highly portable across major computer

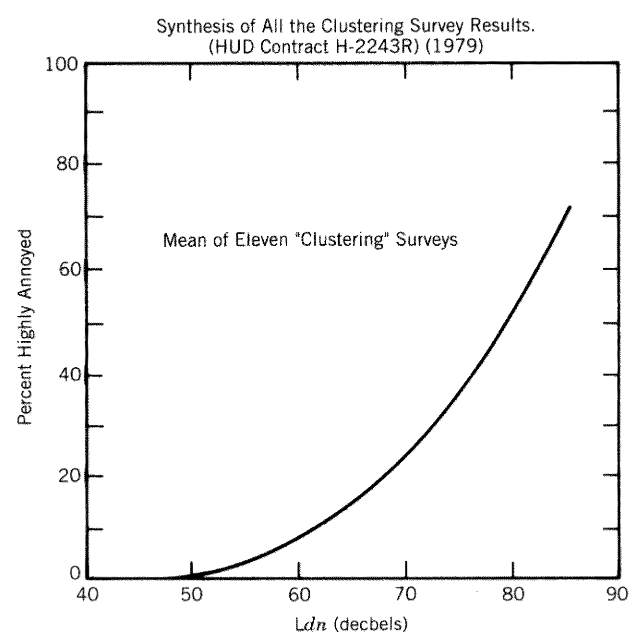


FIGURE 15.6 Percentage of highly annoyed persons in relation to noise. (*Source*: Department of Housing and Urban Development Contract H-2243-R, 1979)

systems. The model includes a standard data base of individual aircraft noise and performance. The data base contains representatives of commercial, general aviation, and military aircraft, which are powered by turbojet, turbofan, or propeller-driven engines. Each of these aircraft is associated with an aircraft category, a set of departure profiles for each applicable trip length, a set of approach parameters, Sound Exposure Level (SEL) versus distance curves at several thrust settings, and Effective Perceived Noise Level (EPNL) versus distance curves at several thrust settings (12).

The model gives the noise impact in terms of contours of equal noise exposure.

The Integrated Noise Model can be obtained from the FAA on a 9-track magnetic tape of 5 and 1/4-inch, 360k floppy diskettes. A contour plotting program has also been developed for the PC version of the model (13).

Noise Abatement

There are a number of techniques and procedures that can be employed to lessen the undesirable effects of noise in the vicinity of airports. These countermeasures can be grouped into four classes, relating to:

1. Aircraft design or modification.
2. Aircraft operation and use.
3. Airport planning and design.
4. Land use in the airport vicinity.

As a part of the certification process, the FAA places limitations on noise from all new subsonic turbojet aircraft. The noise certification process involves making noise measurements at specified locations along the approach and takeoff paths and to the side of the runway. Maximum noise levels in EPNdB are specified for landings and takeoffs as a function of the aircraft gross weight. Manufacturers have made significant advances in recent years in the design of quieter aircraft, primarily through design of quieter engines and improved aerodynamic design, which permits steeper and quicker ascents and descents.

A number of controls on aircraft operations can be imposed to minimize noise exposure. Perhaps the most dramatic operational control has been the FAA's decision to prohibit civilian aircraft from flying at supersonic speeds over the United States. Where multiple runways are available, aircraft may be assigned to takeoff or approach paths over sparsely populated areas, weather, wind, and other such circumstances permitting. Similarly, turns may be specified for takeoff movements, and steeper approach glide paths may be employed. Aircraft speeds may be varied during the takeoff to achieve higher elevations and more rapid movements over noise-sensitive areas. In some cases, pilots may be required to cut back on power after achieving a specified elevation, to lessen noise exposure to heavily populated areas. These and other operational controls can be particularly beneficial during evening hours when people are more sensitive to aircraft noise.

Airport planners and designers should consider possible undesirable noise exposures when choosing runway orientation and placement. Once a runway is built, displaced thresholds may be employed to reduce perceived noise levels under the approach and at the end of a runway. Extensive landscaping can also help to shield airport surroundings from aircraft ground operations.

Perhaps the most fruitful countermeasure against aircraft noise is land use planning and control, that is, taking advantage of available land use control techniques to ensure that the land surrounding the airport is used in a manner compatible with the airport environment. With the possible exception of certain outdoor recreational activities, almost all types of land use are compatible with airports, provided the L_{DN} values do not exceed 65. Land that has values between 65 and 75 may be used for commercial and industrial purposes and for offices and public buildings. If the buildings have special insulation, the land may also be suitable for hotels, motels, and apartments. Where the L_{DN} values exceed 75, there are few compatible land uses. Such land can be suitably used for hotels, motels, offices, and public buildings if acoustic insulation is installed.

Table 15.4 provides land use guidance for various levels of noise exposure. By means of the Integrated Noise Model or by objective noise studies conducted in the vicinity of airports, it is possible to define areas exposed to noise levels of a specified magnitude. The results of such studies may be displayed in the form of noise contour maps, such as that shown as Figure 15.7. Such maps must be used judiciously, recognizing the complexity and variability of the public's reaction to noise.

The Public's Reaction to Noise

The most important factors to influence the public's annoyance with noise relate to the characteristics of the noise itself, namely, its sound level, frequency, and variation over time. It should be emphasized, however, that many other factors are correlated with public annoyance with aircraft noise, and there are wide variations in tolerance to noise among people and communities.

Studies of community reaction to aircraft noise have shown that a variety of factors may contribute to the total impact of aircraft operations on a neighboring community, including:

1. Fear of aircraft crashing the community.
2. Perceived importance of the airport to the local economy.
3. Income, occupational status, and other social factors.

Furthermore, the number of complaints about airport noise may not accurately reflect the extent or intensity of annoyance experienced in a community.

TABLE 15.4 Land Use Guidance Chart for Various Levels of Airport Noise

Land Use Guidance Zones (LUG)	Noise Exposure Class	L_{DN} Day-Night Avg. Sound Level	HUD[a] Noise Assessment Guidelines	Suggested Noise Controls
A	Minimal Exposure	0 TO 55	"Clearly Acceptable"	Normally Requires No Special Considerations
B	Moderate Exposure	55 TO 65	"Normally Acceptable"	Land use Controls Should Be Considered
C	Significant Exposure	65 TO 75	"Normally Unacceptable"	Noise Easements, Land Use, and Other Compatibility Controls Recommended
D	Severe Exposure	75 & HIGHER	"Clearly Unacceptable"	Containment Within Airport Boundary or Use of Positive Compatibility Controls Recommended

[a]Department of Housing and Urban Development.
Source: *Airport-Land Use Compatibility Planning*, FAA Advisory Circular 150/5050-6, 1977.

Factors such as the degree of community organization and the availability of institutional mechanisms for voicing complaints may bear strongly on the number of persons who complain. It is not surprising, therefore, that forecasting the impact of aircraft noise on nearby neighborhoods is an inexact process that must be applied with considerable attention to its subjective aspects.

15.7 IMPACTS ON LAND USE

Because of its size and nature, an airport can have profound effects on land use in the vicinity. These impacts may be economic, developmental, or visual. Airport planners and designers should endeavor to employ available land use controls and design techniques to minimize undesirable land use impacts in

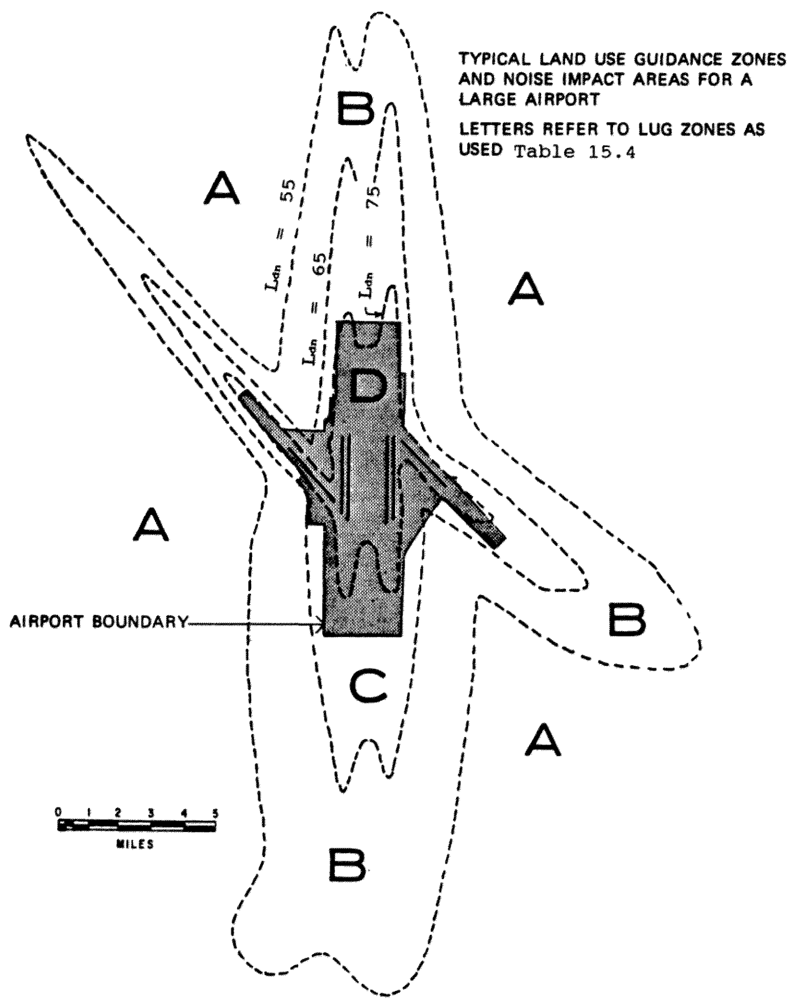


FIGURE 15.7 Typical noise contour map. (*Source*: *Airport-Land Use Compatibility Planning*, FAA Advisory Circular 150/5050-6, 1977.

the airport environs and within its boundaries. The following subsections briefly describe airport land use impacts. Chapter 4 covers specific land use planning procedures and controls.

Economic and Developmental Impacts

A large airport may encompass 20,000 or more acres of land and may overlap several political jurisdictions. In large urban areas, tens of thousands of persons may be employed in air transportation activities. The annual payroll for airport employees may total hundreds of millions of dollars, and indirect effects of purchase of local goods and services by airlines and air transport service industries may equal or exceed that amount. Additional benefits to the local economy derive from the purchase of goods and services by business from tourists or convention participants made possible by the airport. Other impacts that may be equally important but more difficult to quantify include increasing the attractiveness of the area to desirable industries, facilitating commercial transactions, and improving access to recreational, social, and cultural opportunities.

Visual Problems and Controls

Unless carefully planned and designed, airports can have a negative visual effect on the community. Outside the airport boundary, uncontrolled motels, car rental establishments, and other airport-related commercial developments can create a garish and ugly visual impression on airport visitors, employees, and nearby residents. Such problems are the responsibility and concern of local governments, which can improve the appearance of the airport neighborhood in a number of ways (e.g., by use of zoning regulations and building codes, by well-planned location and design of airport access facilities, and by careful design and construction of public buildings in the airport area).

Within the airport proper, positive planning and design controls must be employed by the airport operator to provide a functional and visually pleasing environment.

> The visual environment should provide clear orientation for the different segments of population that use or work at the airport, enabling them to find their destinations with relative ease. Ease of orientation on the airport should be considered at the design phase by adopting a functional and readily identifiable terminal area layout; by using the control tower or other tall buildings as landmarks by which persons may orient themselves; by permitting views of destinations from the roadway; by designing a clear sign system; and by differentiating directions of travel on the roadways.
>
> The environment should provide a clear visual image so that persons at the airport can better understand the sections of the airport that they use. . . . The layout of the entire airport may be more easily grasped by designing a clear and simple layout of the entire airport; by reinforcing the layout by use of simplified maps; by visually differentiating between areas on the airport; and by making clear connections between different parts of the airport (1).

The airport operator can also control the location, height, and appearance of private buildings on the airport, and can enhance the airport appearance further by judicious planning and design of parking lots, access roads, fencing, and landscaping.

15.8 AIR AND WATER POLLUTION

Air and water pollution may constitute the most serious environmental impacts caused by an airport development. These problems are also probably the most complex, and their evaluation and control may require the assistance of highly trained environmental specialists. Although a detailed treatment of air and water pollution is well beyond the scope of this book, we describe briefly various types and sources of air and water pollutants and ways of controlling and lessening their impact.

Air Pollution

Air pollutants may be grouped into five major classes:

1. Particulate matter.
2. Carbon monoxide.
3. Photochemical oxidants.
4. Nitrogen oxides.
5. Sulfur dioxide.

Particulate matter is any solid or liquid material less than 500 microns (μ)in size and dispersed in the air. An average annual particulate matter concentration of 75 $\mu g/m^3$ may have an adverse impact on human health, as might a maximum 24 hr level of 260 $\mu g/m^3$, which occurred only once a year (1).

Carbon monoxide is a colorless, odorless, highly poisonous gas that results from the incomplete combustion of carbonaceous fuels. Gaseous organic compounds of carbon and hydrogen (hydrocarbons) and oxides of nitrogen are also emitted during combustion. Prevailing concentrations of hydrocarbons do not appear to be detrimental to human health, but certain of these substances may react with nitrogen oxides to produce harmful pollutants.

Ozone and other oxidizing agents are formed when hydrocarbons and nitrogen oxides are exposed to sunlight. These photochemical oxidants can cause irritation to the respiratory and alimentary systems, as well as damage to vegetation, metals, and other materials. There is also some evidence that long-term exposure of humans to nitrogen dioxide even in low concentrations contributes to chronic respiratory diseases.

Sulfur dioxide, which is present in the exhaust gases of aircraft, is a colorless, extremely irritating substance that is especially harmful to the respiratory system. Detailed information on these pollutants can be found in publications of the EPA.

The air pollution at an airport may stem from a variety of sources. Some of the major sources are as follows:

1. Aircraft engine exhaust.
2. Aircraft fuel venting.

3. Aircraft fueling systems.
4. Motor vehicles of passengers, employees, and airport visitors.
5. Ground service equipment.
6. Airport heating plant.
7. Construction operations.

The pollutants contained in aircraft engine exhaust gases consist principally of carbon monoxide, carbon dioxide, hydrocarbons, nitrogen oxides, soot, and other particulate matter. The exhaust gases also contain highly irritating organic acids and carbon and sulfur compounds. The amount of compounds emitted into the atmosphere is a function of the type of aircraft and engine, the phase or mode of operations, and how long the engine is operated in each phase. It is useful to consider the pollutants emitted in the following phases of operation:

1. Taxi or idle.
2. Takeoff.
3. Climbout (from lift-off to 3000 ft altitude).
4. Approach (from 3000 ft altitude to touchdown).
5. Landing.

For most jet aircraft, the pollutant rate of emission of carbon monoxide and hydrocarbons is greatest during the taxi or idle phase, and the rate of emission of nitrogen oxides is greatest during takeoff.

Vaporization of fuel from spillages that occur during fueling and from fuel storage tanks can produce a significant amount of airport air pollution. Virtually all the vapor emissions from these sources are hydrocarbons.

As much as 25% of the pollutants emitted by all sources within the airport boundary may come from motor vehicles of passengers, employees, and airport visitors (1). Additional pollution is caused by the operation of gasoline-powered ground service equipment. The amount of pollution from these sources is directly related to the amount of gasoline burned. Estimates of fuel burned by motor vehicles of passengers, employees, and visitors can be made from traffic counts and estimates of average distances traveled within the airport boundary. Studies made at large airports indicate that ground service vehicles consume approximately 7 gal of gasoline per vehicle per day.

At large airports, the airport heating plant can be a significant source of air pollution. The quantity of pollutants emitted, of course, depends on the type of power plant and the type and amount of fuel used.

Construction operations at an airport may also contribute to the air pollution problem. Clearing and excavation activities, burning of refuse, demolition of old buildings, and other such operations may add dust, smoke, exhaust emissions, and other pollutants to the atmosphere.

The EPA has the overall responsibility for the establishment of national ambient air quality standards. Such standards have been established and published in the *Federal Register* (14). Enforcement of these standards is the responsibility of state air pollution control agencies supported by the EPA.

Three approaches have been used to measure the air pollution impact at an airport: (1) direct measurement, (2) estimation of emission density, and (3) atmospheric dispersion modeling.

Direct atmospheric measurement of the concentrations of various classes of pollutants is a complex undertaking calling for highly specialized and expensive equipment. Methods for measuring various pollutants have been published by the EPA, and assistance for making direct atmospheric pollution measurements may be obtained from state air pollution control agencies.

Estimates of the number of pounds of various classes of pollutants can be based on previous research. For example, using data of the type given in Table 15.6, it would be possible to estimate the number of pounds of carbon monoxide, hydrocarbons, and nitrogen oxide for each phase of an operation of a long-range jet. To estimate total quantities of pollutants, the quantities of pollutants for one long-range jet would be multiplied by the total number of operations per day by each aircraft. Calculations of this type could be made for other classes or aircraft. From similar computations, the quantities of pollutants from fuel spillages, motor vehicles, the airport heating plant, and so on, could be estimated.

Atmospheric dispersion modeling is a highly complex computer simulation procedure that predicts pollutant concentrations at various locations in the airport vicinity. Detailed information is required on emission sources, topography, air temperature, wind speed and direction, and other meteorological variables. From the computer output, it is possible to develop contour maps showing lines of equal pollutant concentration. Such results readily identify areas that may have high concentrations of various pollutants and make it possible to evaluate realistically the available countermeasures.

TABLE 15.6 Example of Available Data for Estimation of Quantities of Pollutants from Long-Range Jets

Phase	Engine Emission Rate (lb/hr) Carbon Monoxide	Hydrocarbons	Nitrogen Oxide	Average Time in Each Phase (min)
Taxi/idle	103	84	1	Variable[a]
Takeoff	10	12	148	1.0
Climbout	10	13	94	2.2
Approach	29	12	20	4.0
Landing	10	13	94	0.4

Source: *Airports and Their Environment*, CLM/Systems, Inc., prepared for the U.S. Department of Transportation, September 1972.

[a] Taxi/idle times should be based on actual operating practices at the airport under study.

Remedial programs to reduce airport air pollution can be grouped in three categories:

1. Modifications to aircraft engines.
2. Modifications to ground operations.
3. Modifications relating to the planning, design, and construction of the airport.

A great deal can be done to reduce aircraft pollution rates by better design, but such modifications are costly and can be implemented only over a long period of time. There are also a number of operational changes that can be inaugurated to reduce air pollution; however, some of the changes can be undertaken only with considerable additional cost or hazard. Apparently, the most desirable operational changes would be to:

Require engines to be shut down at gates.

Use fewer engines, operating at higher rpm when taxiing, to reduce carbon monoxide and hydrocarbon emissions.

Eliminate the problem of fuel venting by providing a means of draining residual unburned fuel at the gate.

Airport planners and engineers may have the greatest success in reducing the impact of air pollution through better airport planning, design, and construction. For example, new airports should be provided with buffer zones between the airport, where pollution concentrations are highest, and the community. To the extent feasible, parking lots, heating plants, and other sources of pollution should be separated and located downwind from locations accessible to the general public. Pollution from vehicular traffic can be lessened by designing access roads to avoid bottlenecks and unnecessary stops. Amounts of water or chemicals used during clearing, grading, and demolition operations to control dust should be minimized, as well as burning activities. These and other measures would decrease the impact of air pollution.

Water Pollution

Water pollution may result directly from the construction and operation of an airport or indirectly from land development induced by the presence of the airport. Removal of natural cover and other airport construction practices can result in unsightly soil erosion and sedimentation. An increase in the sediment load 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. In addition, the construction process may generate various waste materials (e.g., fuels, lubricants, construction debris, and sanitary wastes from construction personnel).

The water pollution that results from the operation of an airport may be grouped into five classes:

1. Sanitary wastes.
2. Storm water pollution.
3. Wastes related to fueling, operation, and cleaning of aircraft.
4. Wastes related to major aircraft overhaul and maintenance.
5. Industrial wastes.

Sanitary wastes are the wastes generated by the people who use the airport. These wastes are produced by such activities as food preparation, washing, and toilet use. It is estimated that 20 gal of water per passenger per day is used at a typical airport and that 90% of this water returns to the collection system (1). This water must be treated to remove inorganic solids and dissolved impurities and to destroy disease-causing organisms.

Storm water runoff may be polluted by chemicals used for insect control and snow and ice removal, by fuel and oil spills on the runways, taxiways, and aprons, and by fire fighting 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.

Even more serious water pollution may be caused by major aircraft overhaul activities. These pollutants consist primarily of the highly toxic chemicals used to remove paint and clean and rechrome engine parts. Similar pollutants may be generated by light industries that are located on or near the airport and use the airport sewage disposal system.

Development induced by the presence of an airport facility also contributes water pollutants and may have a serious impact on the water pollution problem unless suitable countermeasures are undertaken. 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.

Strict regulations have been imposed in the United States to prevent the pollution of lakes and streams. Airport sponsors must consult with the EPA and the appropriate state water pollution agency or agencies about the treatment and discharge of wastes, and the discharge of waste materials into navigable waters must be licensed by the Corps of Engineers. Information on water quality standards may be obtained from these agencies. It is generally necessary to collect, separate, and treat all waterborne wastes, regardless of geographic location. The specific procedures for the treatment of wastes are not within the scope of this book; however, some of the more important measures that may be employed to *prevent* water pollution are listed below.

1. Where feasible, use shallow gradients for backslopes and channels to avoid erosion.

2. Protect slopes from erosion by using appropriate ground cover during and after construction.
3. Establish procedures to keep fuel spills from getting into the storm drainage system.
4. Prohibit dumping of waste oil and grease into the storm drainage system.
5. Avoid flushing of fire fighting foam down storm sewers.
6. Use low phosphate detergents for aircraft washing.
7. Limit the amount and type of chemicals used for insect and vegetation control.

15.9 HYDROLOGIC AND ECOLOGICAL IMPACTS

Now we consider impacts on the life cycles of plants and animals, and changes that can occur to the natural circulation and distribution of water as a result of airport construction. Although these effects may be no less objectionable than those previously described, they may be more insidious.

Hydrologic Impacts

Three of the most common hydrologic problems associated with airport construction are flooding, disruption of water movements by filling and dredging operations, and salinity intrusion.

An airport development typically involves the construction of vast expanses of runways, taxiways, buildings, aprons, and other impermeable surfaces. This decreases the infiltration of rainwater into the ground and increases the quantity of runoff and the likelihood of flooding.

There is an additional but less apparent reason for flooding to be caused by an airport development. Impervious surfaces tend to increase the speed at which water runs off or to decrease its time of concentration at the various drainage structures. This means that the impacts of storms of shorter duration and higher average rainfall intensity are likely to be manifest at each drainage structure during the design period. This flooding tendency may be felt throughout the drainage basin, and the effect may extend far beyond the airport boundaries.

Airports are frequently constructed along coastal lands where original subsurface materials are weak and unstable. In these circumstances, it may be necessary to relocate channels and drain and fill swampy areas. Such changes to the water environment may cause significant local climatic changes, alter the patterns of water movement, and endanger fish and wildlife. Proposed earthwork changes of this nature should be undertaken only after the hydrologic impact has been carefully evaluated and considered. Interference with water movements may be minimized by constructing airport facilities on open substructures.

When airports are located in coastal areas, the decreased infiltration of rainwater is likely to cause a lowering of 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.

Ecological Impacts

"Ecology" is defined as the science of the relationships between living plants and animals and their environments. Impacts of airports on man have been described already. In contrast to those effects, certain ecological impacts on plants and animals are subtle and may be manifest 10, 20 or more years after an airport has been developed. Ecological impacts may result from airport construction practices, from activites related to the daily operation of the airport, or from development induced by the presence of the airport.

Unless carefully controlled, clearing, grubbing, and stripping operations may cause sedimentation and siltation to occur in natural waterways. This may destroy the food sources of small fish, and in extreme cases may smother certain species of marine life. Ecological harm may also result from filling, dredging, draining, and other topographic modifications, and from the construction of roads, fences, pipelines, and natural waterways. Such construction activities may destroy wildlife habitat and food sources, as well as create barriers and corridors that impede or enhance the distribution of organisms.

Use of pesticides and herbicides at an airport may contaminate food supplies of aquatic animals. Excessive withdrawal of groundwater may deplete water supplies for wildlife or contaminate those supplies by salinity intrusion. Aircraft and automobile engine emissions may damage certain plant species and suppress growth and yield of crops. Water pollution may deplete the supply of oxygen in natural waterways so heavily that aquatic life cannot survive.

Construction activities associated with development due to the airport can cause the same types of ecological damage described earlier.

Induced developments may also cause a lowering of the water table and flooding, as well as complicating efforts to control water pollution.

Earlier sections described countermeasures that can help control various types of environmental impact of airports on people. Those countermeasures can be employed with similar success to lessen an airport's impact on plants and animals.

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