AIRPORT CAPACITY ANALYSIS
A SYSTEMS APPROACH

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ABSTRACT

Existing quantitative models for analysis of the capacity of various components of the airport system are presented. Procedures for utilizing these models in a system analysis are discussed. Recommendations are made concerning possible modifications of existing models, and priorities for these modifications are assigned according to the necessity for improvement.

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CHAPTER 1. INTRODUCTION

BACKGROUND

This report presents the results of a research study on airport capacity, sponsored by the Bureau of Engineering Research of The University of Texas at Austin. The purpose of this study was to develop a systematic approach to analyzing airport capacity. The approach taken was to first define the parameters which affect airport capacity, then to investigate existing capacity models, and finally to describe methods for tying these models together for a systems analysis of airport capacity.

In the past, airport capacity was analyzed in terms of capacity of individual components and little concern was directed toward balancing the capacity of the components. There are two major drawbacks to using this approach. First, use of this approach to the design of a new facility can result in an unbalanced system, with some components having excessive capacity, and some components underdesigned. If this occurs, then time, money, and manpower may be wasted. The second problem with a "component approach" to analysis occurs when an engineer is trying to analyze an existing facility to determine where future problems might occur. Without a systematic approach, the analyst might have great difficulty in finding the weakest link in the system.

There are several benefits to using a systems approach to airport capacity. First, as mentioned earlier, it provides a rational approach toward the design of airports, in that by using a systems approach, a balanced airport system can be designed, where all the components have approximately the same capacity. Secondly, a systems approach provides a rational method for analyzing existing airports to insure that all components which affect capacity are considered. The third benefit is that once a systems analysis has been performed, a sensitivity analysis can be performed to find the most critical capacity components. Research priorities can then be set up to find methods of maximizing flow in these components.

OVERVIEW

This report contains eight chapters. Chapter One is an introduction. Chapter Two discusses the flow through the airport system and contains flow charts outlining this flow. Chapter Three discusses the problem of analyzing the ground access subsystem of an airport. Chapter Four presents methods of analyzing the terminal building subsystem. Chapter Five discusses methods for analyzing the aircraft handling subsystem. Chapter Six discusses the problem of analyzing the interface between the three subsystems. Chapter Seven presents a method for analyzing the "noise capacity" of airports. The final chapter presents the summary, conclusions and recommendations.

SCOPE

There are three basic limitations to this study. First, general aviation is not considered in this report. Second, the boundaries of the airport system were set at the gates of the airport on the ground side, and the airspace was limited to airspace under the control of the approach/departure control facility assigned to the airport. The third limitation is that there was insufficient time to develop new models for analyzing capacity. Therefore, this study was restricted to discussing existing models.

Sources of information, used in preparing this report, ranged from textbooks, to FAA and other government publications, to Ph.D. dissertations. A list of these sources is presented at the end of this report.

CHAPTER 2. COMPONENTS AFFECTING AIRPORT CAPACITY

In any logical attack of a problem, the first task is to identify the significant parameters of the problem. Therefore, the purpose of this chapter is to identify the important parameters which affect the capacity of an airport system. An airport system can be broken into three major subsystems; they are the access/egress subsystem, the terminal building subsystem, and the aircraft movement subsystem. The relationship of these three subsystems is shown in Fig 2.1.

Currently, the capacity of many airports is being limited by aircraft noise problems. Since this problem is not part of the physical airport system, it will be dealt with in a later chapter. The chapter on noise problems covers methods for estimating community response, and techniques for calculating how changes in operational characteristics will affect community response.

The remainder of this chapter deals with individual components of the subsystems as they pertain to capacity. The summary contains a final flow chart which contains all of the airport system components, identified in this chapter.

AIRPORT ACCESS/EGRESS SUBSYSTEM

Airport access/egress is possibly the most critical and most difficult problem facing the airport designer. Figure 2.2 shows the components of the airport access subsystem. The egress portion of this subsystem would be simply the reverse of the access portion.

The flow chart shows that there are two major modes of airport access/egress, mass transit and personal transit. In this analysis, limousines are considered as mass transportation, since they usually accommodate several passengers. Taxicabs are considered as personal transit because they usually accommodate only a single passenger.

The parking area indicated in the flow chart actually represents several types of parking. These are long-term passenger parking, short-term passenger and visitor parking, metered parking, parking for delivery and cargo vehicles,

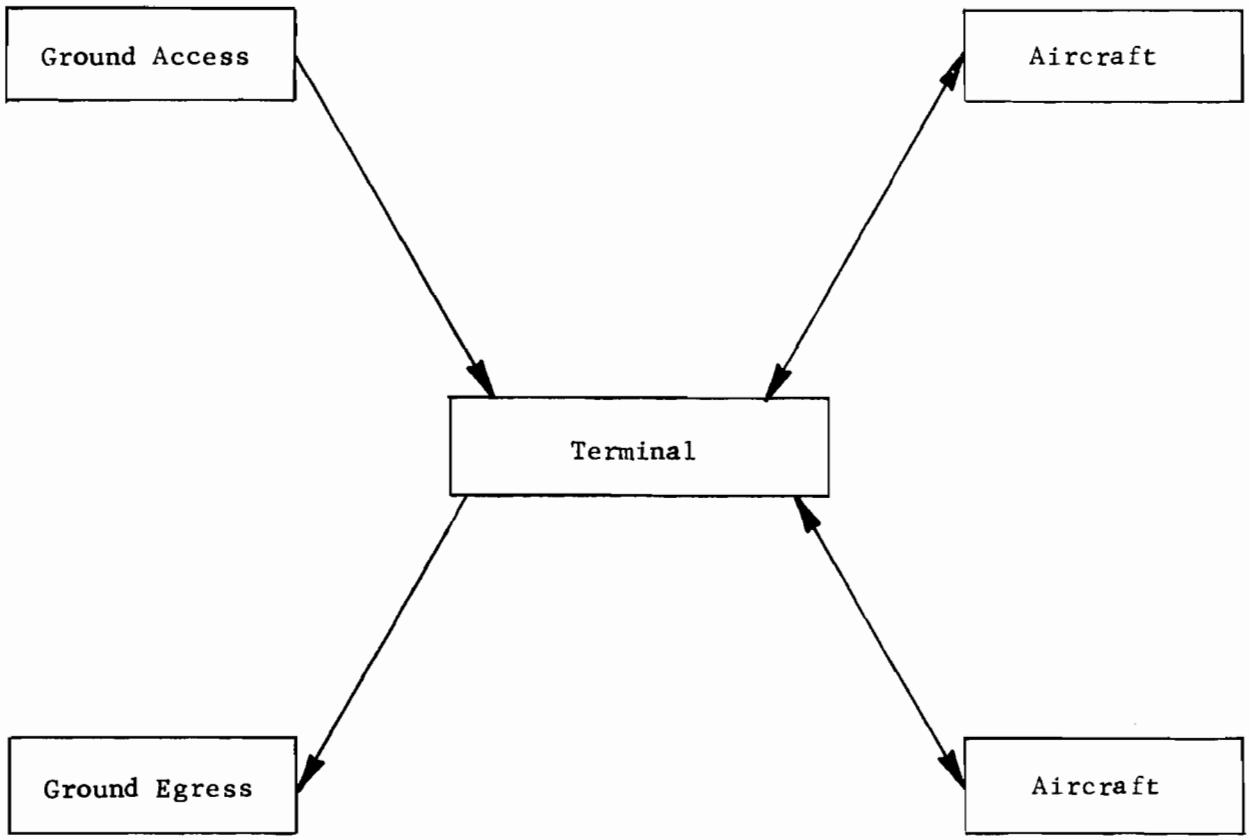


Fig 2.1. General flow chart for passenger flow.

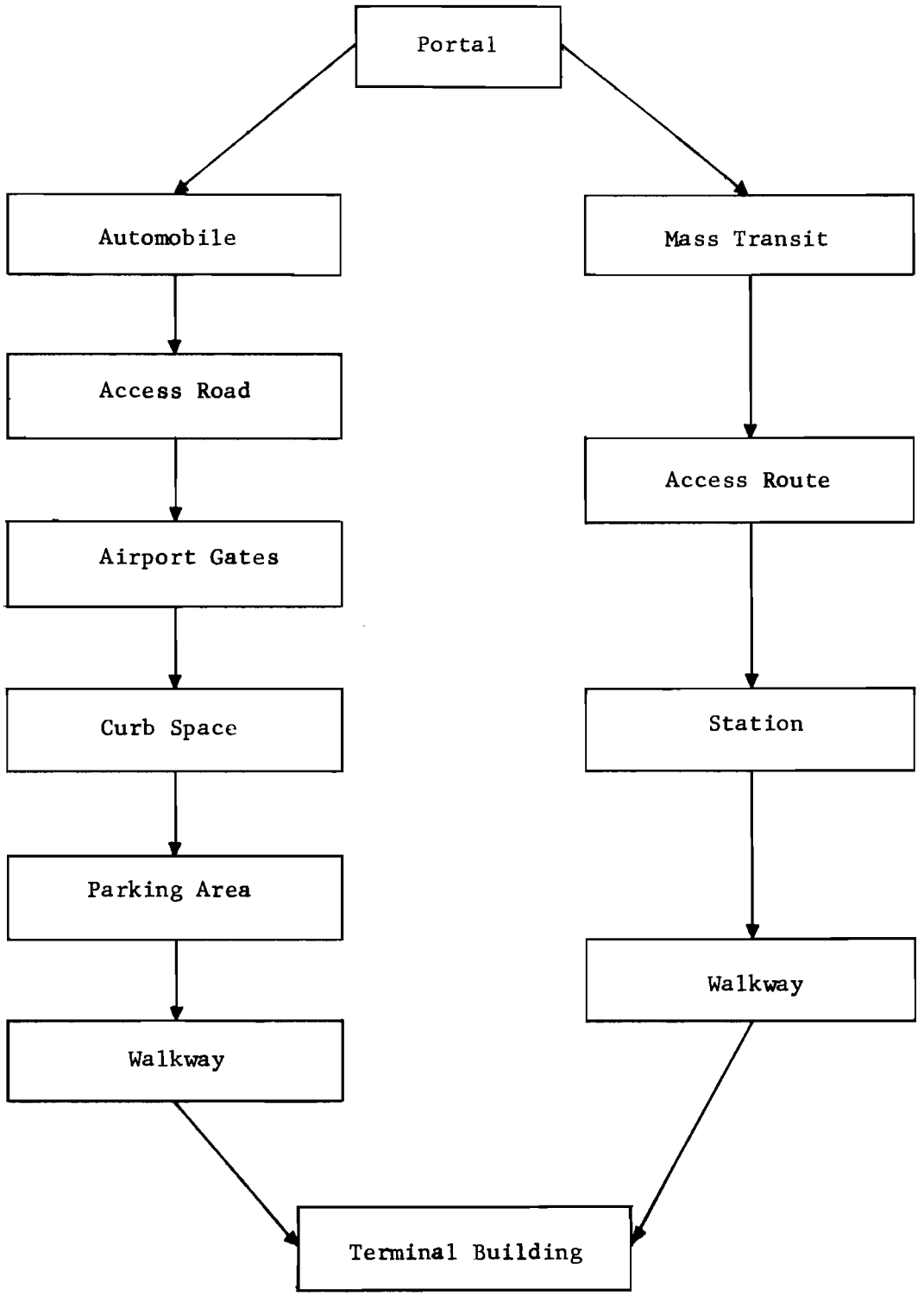


Fig 2.2. Flow chart of ground access.

and employee parking. These types of parking are all combined into one block in the flow chart because an individual driver is only concerned with one parking area. Therefore, these parking areas function independently of each other.

AIRPORT TERMINAL BUILDINGS SUBSYSTEM

In this report, three types of terminal buildings are defined with respect to passenger movement. This was done in order to simplify discussion of the flows of the three types of passengers which are served by an airport.

Figure 2.3 shows the movement of the enplaning passengers. The chart shows the first movement is directly to the ticket counter. At the ticket counter, passengers deposit baggage and buy tickets. Then passengers move into the passenger movement area to await their flight. A security check may be made between the ticket counter and the passenger movement area (labeled Type 1 Security) or the security check may be made as the passengers go from the passenger movement area to the boarding area (labeled Type 2 Security). Advantages and disadvantages of these two types of security checks will be discussed later. Before entering the boarding area, the passenger must have his boarding pass checked; this may be a point of congestion. The final segment of the enplaning passengers' trip is the walk from the boarding area to the aircraft.

The path of the deplaning passenger is shown in Fig 2.4. Most major airports have enplaning and deplaning operations on separate levels of the terminal building. This reduces conflicts between inbound and outbound passengers. Conflict may still exist in traffic flows in the concourses connecting the passenger movement area and the boarding area. Deplaning passengers move from the aircraft, through the departure lounge and the baggage pickup area. In the case of international flights, passengers need to be processed through customs. In small, single level terminals, the passengers would walk through the passenger movement area on the way to the terminal exit. In larger, multi-level airports, deplaning passengers would not necessarily walk through the passenger movement area on the way to the terminal exit.

Figure 2.5 illustrates the path of the transfer passenger. The major problem for the transfer passenger is the great distance from the departure lounges to boarding areas in some of the larger airports, such as Chicago's

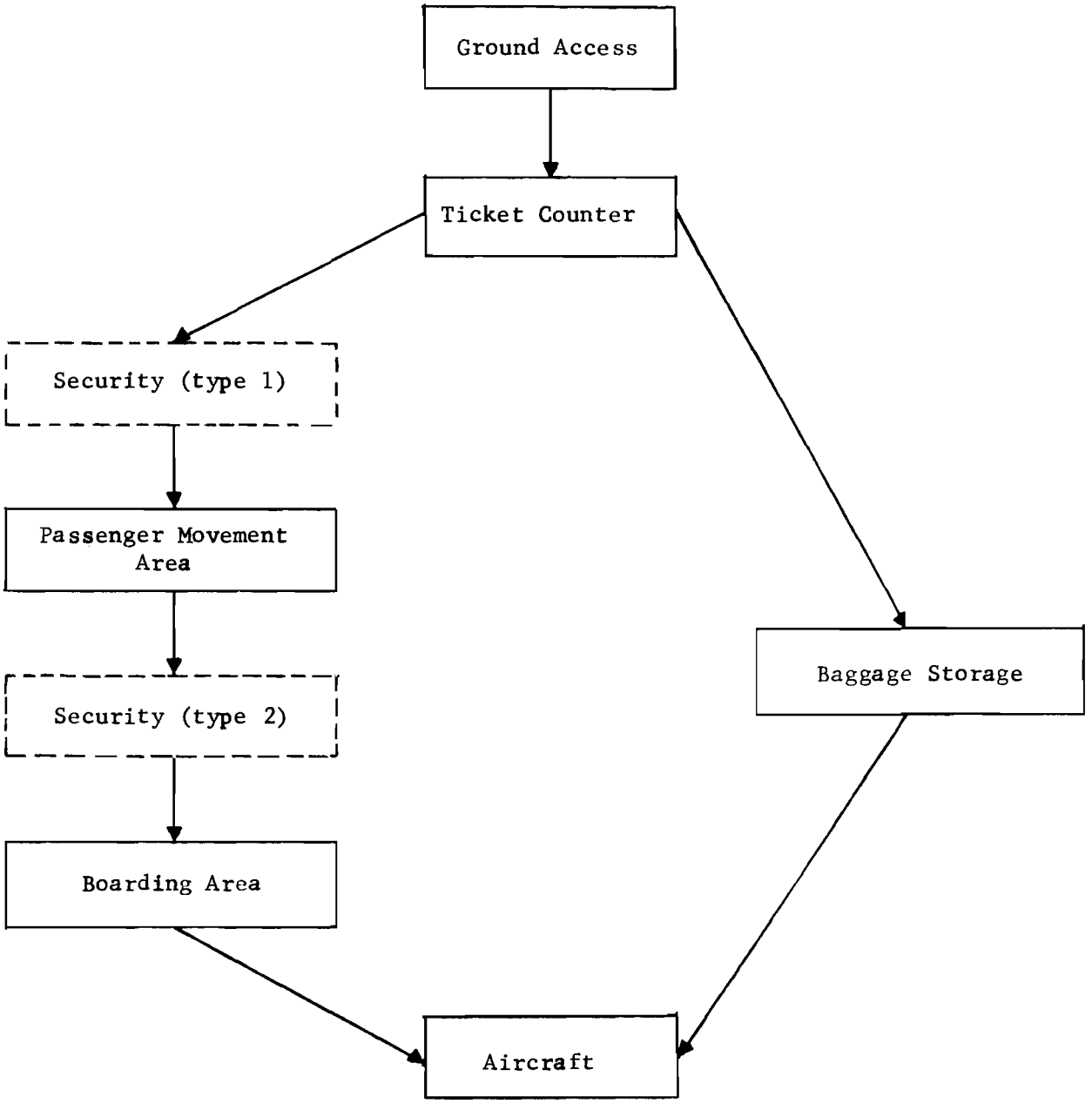


Fig 2.3. Flow chart for Terminal Building No. 1 (enplaning passengers).

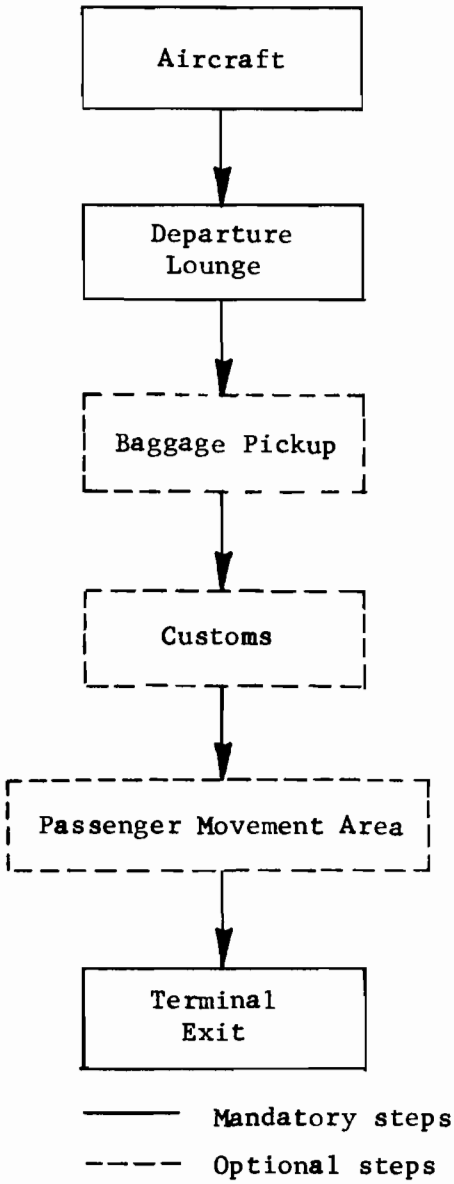


Fig 2.4. Flow chart for Terminal Building No. 2 (deplaning passengers).

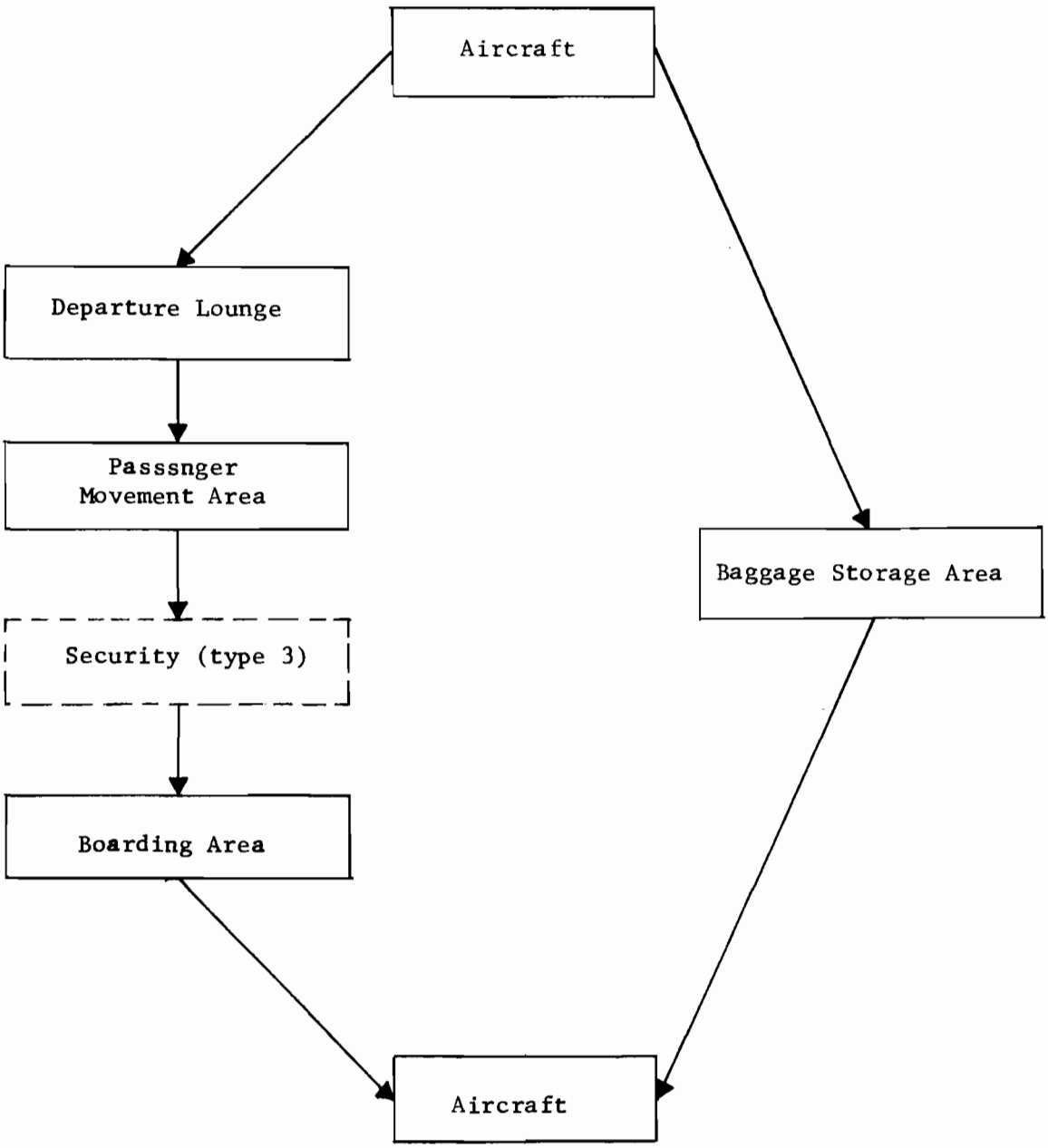


Fig 2.5. Flow chart for Terminal Building No. 3 (transfer passengers).

O'Hare Field. This problem is complicated further when Type 2 Security is used at the air terminal. The importance of the problem of handling transfer passengers varies according to the classification of the airport. At the 22 hub airports, such as O'Hare and Atlanta, handling transfer passengers is a major function of the airport. Conversely, at the smaller municipal airports, there are very few if any transfer passengers.

Baggage handling at the airport is an important operation, which when handled poorly may have an adverse effect on the airport's capacity and convenience. Enplaning passengers may deposit their baggage at the curb at some large airports when they have prepurchased their ticket. Otherwise, baggage is deposited at the ticket counter when the passenger checks in or is purchasing a ticket. Due to airport security problems, very few people carry any luggage onto the plane. Deplaning passengers usually pick up baggage at one central location in the airport. Transfer passengers usually do not need to handle their baggage; however, the airport baggage handling system must have sufficient capacity to transfer their bags between planes.

Security is a new and hopefully temporary constraint on airport terminal capacity. There are two basic types of security checks being used today. Type one is a sterile terminal concept. With this type of security, everyone, including visitors, is checked; they are then free to go to any part of the terminal. The open terminal type of security has the passenger movement area open to the public. The security check is performed near the boarding lounges. Under this system, only passengers are allowed into the sterile area. The sterile terminal concept has advantages over the open terminal concept in the following ways:

(1) Visitors and passengers are allowed to remain together until boarding time.

(2) Transfer passengers may go to any part of the terminal without having to be checked by security before boarding.

(3) There will be a more even flow of people through the security check. This is due to the fact that under the open terminal concept, all the people on the flight must be checked between the time their flight is called and boarding time.

(4) There is less congestion near the boarding area with the sterile terminal concept.

Disadvantages of the sterile terminal concept include:

(1) Since visitors as well as passengers must be searched, a larger security force is required.

(2) The sterile terminal concept can cause congestion at the terminal entrance.

In summary, there are advantages and disadvantages in both types of security. The governing factor as to which system is used, depends upon the layout of the terminal as to where the security check can be carried out causing the least congestion in the traffic flow system of the airport.

The passenger movement area is usually a major part of the main terminal area. This area contains all the various consumer conveniences which should be provided in the terminal building. Generally, there is no specific path which can be assigned to passengers in the passenger movement area; therefore, Fig 2.6 shows flow between the various components as unrelated activities within one boundary.

With the implementation of the jumbo jets into the aircraft fleet, the volume of air cargo has been dramatically increased. This means that the airport planner must now make accommodations for handling greater cargo loads. The usual practice is to provide a separate terminal to handle cargo.

AIRCRAFT HANDLING SUBSYSTEM

In the past, the capacity of the aircraft handling subsystem was considered the capacity of the airport. In this paper the aircraft handling subsystem is considered as only one of the three major airport subsystems. The basic movements of the aircraft are shown in Fig 2.7.

The first box of Fig 2.7 shows the aircraft in flight. This represents the plane in the holding stacks waiting for its turn to use the runway. The plane then lands and taxies to the apron. The dashed boxes represent an arrival.

The activities on the apron have been expanded in Fig 2.8 to show some of the major activities. These activities include parking the aircraft, connecting the walkways, discharging the passengers, servicing the aircraft, enplaning the passengers, disconnecting the walkway, unloading and reloading baggage and cargo, and taxiing away from the terminal building. The solid portion of Fig 2.7 shows the plane moving back out onto the taxiway, on the runway, and finally back in flight.

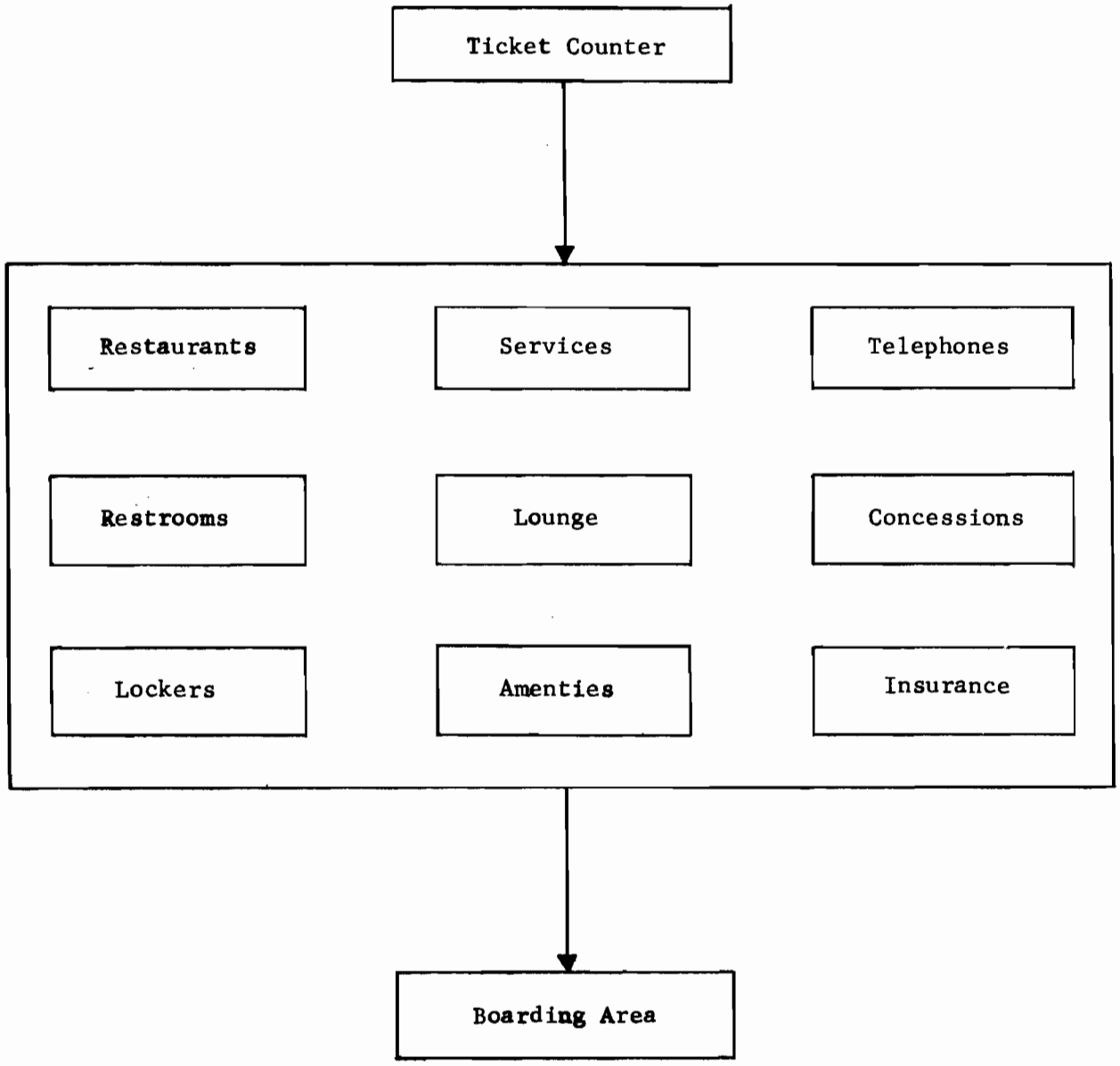


Fig 2.6. Flow chart of passenger movement area.

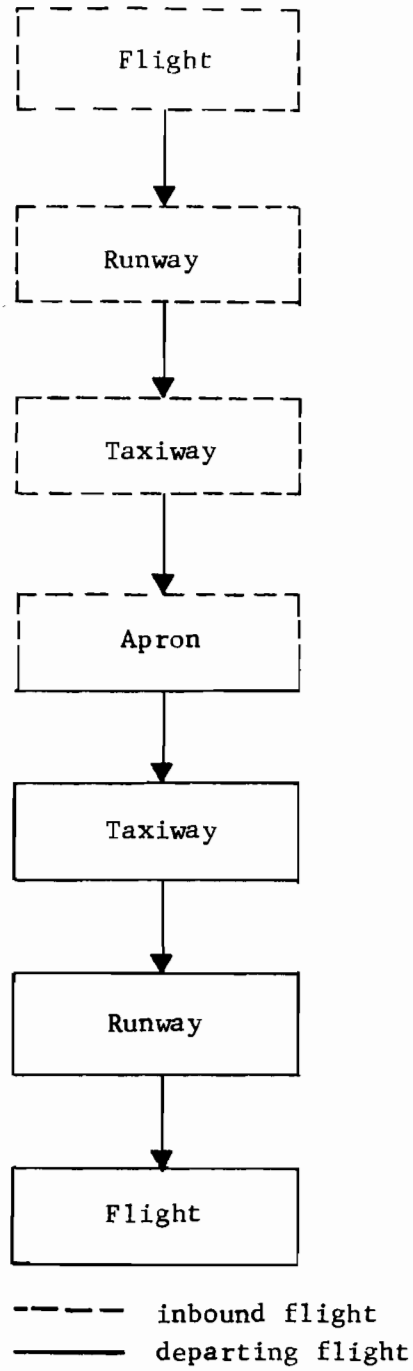


Fig 2.7. Flow chart of aircraft movement.

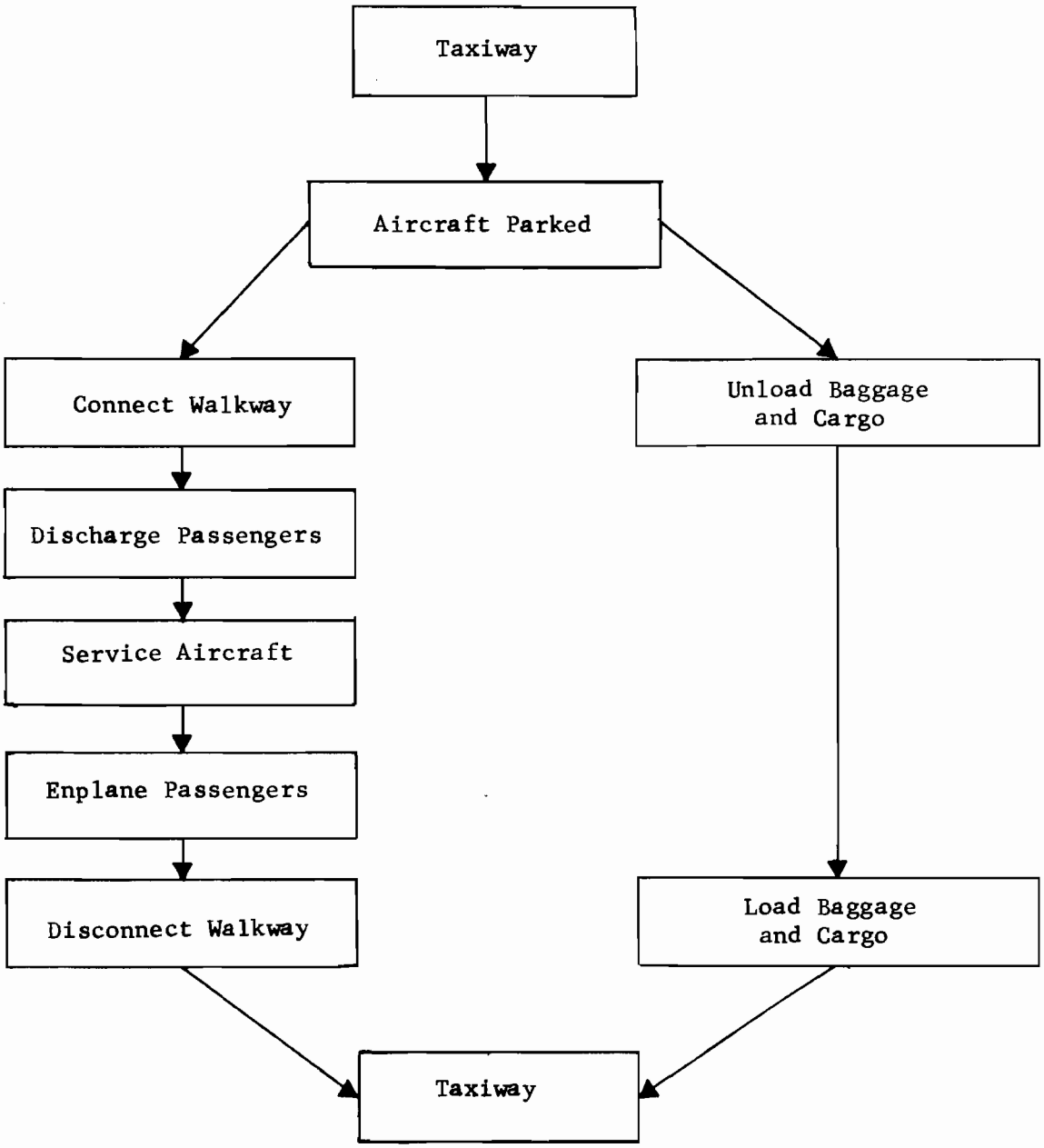


Fig 2.8. Flow chart of apron area.

SUMMARY

Now that all the components of the airport system have been identified in their respective subsystems, an overall flow chart of the airport system can be established. This will enable the planner to look at the system as a whole. Figure 2.9 presents such a flow chart. Baggage flows are shown by the dashed lines. The blocks labeled "Flight in Approach Control Area" represent the air boundary of this project. This boundary is the flight under the control of the approach/departure controller rather than the regional controller.

By establishing this final flow chart, we can now proceed to quantify each of these components. After all the components are quantified, they can be compared to each other, for any given airport, to find the weakest link in the system.

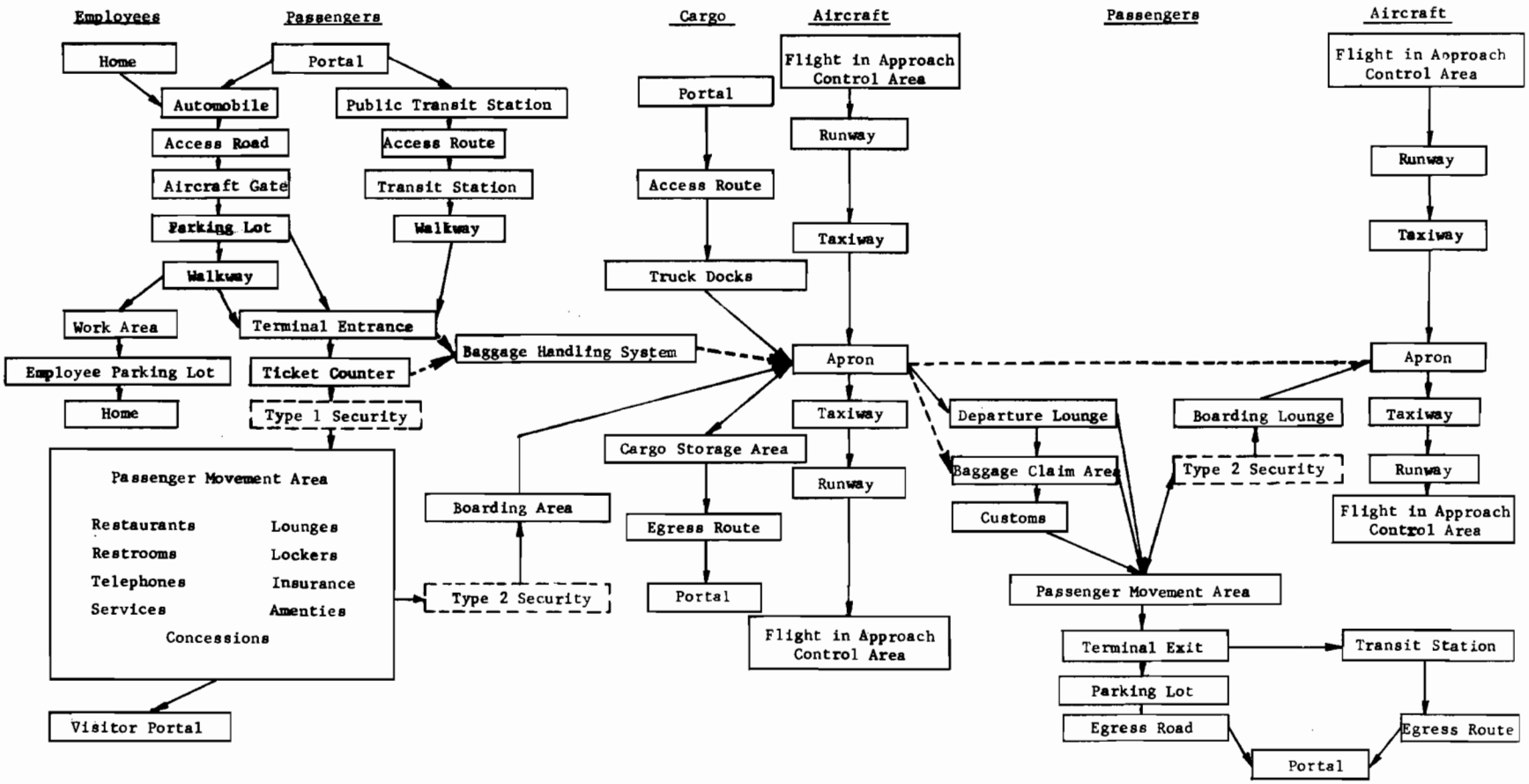


Fig 2.9. Overall flow chart.

CHAPTER 3. AIRPORT ACCESS/EGRESS

> There is a dichotomy of the problems which an airport planner must consider; this dichotomy is established by the physical airport boundary. The problems outside of the airport are related to noise and airport access. The airport planner's degree of control over the aspects of noise and access is limited due to jurisdiction. Such control must be effected primarily through rapport with community and governmental entities (Ref 44).

This chapter will deal with the airport access; the noise problem will be covered in a later chapter. The access problem will be broken into two major parts, "the off-airport section" and "the on-airport section" of the trip. The discussion on the first section will be limited to a general discussion of the factors which the airport planner must know and be able to convey to the local governments, which have the control over this portion of the system. The second section of this chapter will present a specific, detailed method for analyzing or planning the "on grounds" section of the airport access trip.

OFF THE AIRPORT GROUNDS

This section of the report is limited to a general discussion of the factors which affect airport access and the methods available for analyzing these factors. Such a discussion is adequate for the purpose of this report, because as mentioned earlier, the airport planner is not the person responsible for decisions in this area. Decisions on the type of access, the quality of service, and the level of service which needs to be provided, are made by the political process. Because there can be no analytical relationship between the relative importance of human values, choices must be made by political leaders where government funds are involved. The major question to be resolved by the political process is the emphasis to be placed upon the economic return (physical resources) as opposed to social return (human resources).

Characteristics of People Visiting Airports

The first factor which needs to be studied in any transportation study is the people making the trips. The factors which need to be known are demand,

geographic distribution, trip purpose, access modes, socio-economic characteristics, and length of flight. These figures have been well documented and average or typical figures are given here as a basic guideline for the planner, but it should be emphasized that the planner needs to study and determine accurate numbers for any specific area.

Demand - Air Transport Growth. The projection for air transport shows an enormous rate of growth. The number of enplanements is expected to increase from 84.6 million in 1965 to 435.5 million in 1980 (515 percent growth), air cargo to increase from 1.3 million tons to 19.7 million tons (1400 percent growth) over the same period (Ref 9).

Geographic Distribution. The largest concentration of all trips to the airport during weekdays is usually between the airport and the central business district. The percentage of these trips to the total number of trips to the airport, however, is not large. It is nine percent for San Francisco and Indianapolis, and 11 percent for Washington, D.C. (National). The percentage of passenger trips between the central business district and the airport is higher; 15 percent for Philadelphia, 20 percent for San Francisco, and 28 percent for Washington, D.C. (National). The remainder of the trips are widely distributed throughout the urban areas (Ref 45).

Distribution of Trip Purpose. Of all the trips to the airport, roughly one third are for air travel. The distributions of trips, by purpose, vary over a wide range. Excluding the more extreme values, the distribution of persons traveling to the airport by trip purpose is as follows: air passengers range from 23 percent at Providence to 43 percent at Philadelphia; employees represent 23 percent at Buffalo to 47 percent at Minneapolis-St. Paul; visitors and others make up 15 percent at Washington, D.C. (National) and 38 percent at Providence. As an approximation, the number of trips can be divided equally among: (1) air passengers, (2) employees, and (3) visitors and others (Ref 42).

Distribution by Access Mode. By far, the greatest number of trips to airports is by private automobile. In San Francisco, 85 percent of 67,000 out-bound person trips on a weekday of 1967 were by private automobile. The percentage of air passengers using automobiles was somewhat less, 72 percent. For the New York City airports, the use of the private automobile is one of

the lowest in the country, ranging from 38 percent at Laguardia to 54 percent for Newark.

The number of inbound automobiles is about two per enplaned passenger, varying from 1.6 for Washington, D.C. (National) to 2.8 for Seattle-Tacoma. Access by automobile has been greatly helped by Interstate Highway Systems which provide service within one mile of many major airports.

Socio-Economic Characteristics. The median family income of travelers in the Washington, D.C. area is $16,000, a high income compared to the average income of the area. Most of the travelers (86 percent) have had some college education and a large majority (81 percent) are males. About two thirds are part of the professional or managerial working force. Of all air travelers to the Washington, D.C. area (National and Dulles), 41 percent are on business related to the Federal Government (Ref 43).

Length of Flight. In the Washington, D.C.-Baltimore area, four percent of the air trips were less than 200 miles, 48 percent were between 200 and 500 miles (including New York City and Boston), 30 percent were between 500 and 1,000 miles, and 19 percent were over 1,000 miles (Ref 43).

Characteristics of Urban Areas

The second factor the transportation planner needs to be aware of is the physical features of the urban area. The items included under this subject are land use distribution and transportation facilities. Facts must be known about the existing and projected characteristics of each of these two items. Because these items vary widely for each urban area, there is no point in trying to give an "average" or even a typical city.

There are certain characteristics of land use that the airport planner should concentrate on. As noted earlier, certain groups such as high income college educated persons constitute a large proportion of the air passengers. Therefore, special care should be taken in locating their residential areas. Other factors the airport planner should observe are the locations of businesses, and government offices which are high passenger generators. Care should also be taken to identify industries which use air cargo. This will become increasingly important as air cargo grows.

Characteristics of the transportation facilities which the airport planner needs to characterize are similar to those which any urban transportation

planner needs to quantify. As reported earlier, the major mode of access is the private automobile. Cleveland is presently the only city with rapid rail service to its airport. Except for this one case, all access to the airport is on the surface streets, road and highway systems. An important point that the airport planner should keep in mind is that while traffic to and from the airport is relatively small in terms of the overall urban traffic, the total urban traffic has a large effect on the airport access. This is especially true since the peak hour trips to the airport coincide with the peak hour traffic of the city. A measure of this congestion can be taken as the ratio of travel time at peak hours to off-peak hours. Some examples of this ratio are Atlanta 1.9, New York-Newark 1.7, New York-Laguardia 1.6, Boston 1.6, Houston-William P. Hobby 1.6, Chicago-Midway 1.4. The highest ratio is for Los Angeles to Van Nuys 2.3 (Ref 43).

Social Factors

The third factor that the airport planner must be aware of concerns the relatively new field of social factors. The three major items of this factor are social accounting, level of service desired, and environmental concern. Value judgments in this area have to be made by political process. The engineer is restricted to analyzing how these judgments affect the system he is studying.

In analyzing what effect social accounting will have upon the airport system, the airport planner needs to do the following analysis:

(1) Analyze the need of major social programs, such as health, education, etc., for improved transport services.

(2) Analyze urgent concerns of urban areas, such as poverty, racism, education, etc., to determine what contributions and types of air transport or airport access services would contribute to the solution.

(3) Analyze and identify specific society functions that could be improved by air transport and airport access services, such as emergency services in urban areas, etc.

Level of Service

The level of service is a measure of the quantity and the quality of the system. The characteristics of this item are:

(1) Level of service describes output only, not the means.

(2) It has two major categories to describe the quality of service, direct and indirect.

(3) The level of service measurement must provide an accurate, useable representation of the performance of the system.

(4) The specific elements defining level of service of a transport system are:

(a) purpose,

(b) quantity,

(c) direct effect, cost, time, safety, comfort,

(d) indirect effects, physical, psychological, and

(e) resources consumed.

The third item which needs to be analyzed in this category is the environmental impact of the airport access system. This means that the planner must consider what impact the access system has on the noise and air pollution of the surrounding area. He must know if this impact is within the allowable limits set up by the political process.

With this background into access, an urban transportation model will now be presented which can be adapted by an airport planner in order to determine the capacity of the airport access subsystem.

The Gravity Model

The gravity model is based upon the theory that the attraction between two components is an inverse function of the distance separating these two components. In the area of transportation planning, the components are defined as zones and distance is defined as the minimum driving time path. Basically, the gravity model can take several forms based upon the number of trip types the planner is interested in, travel time factors, and zone adjustment factors.

Definition of Parameters

Trip Production and Trip Attraction. Two of the important parameters required in the gravity model are the number of trips produced, and the number of trips attracted to each traffic zone in the study. These parameters are related to the land use and socio-economic characteristics of the people who make the trips. The gravity model distributes trips from production zone to the attraction zone. For the purpose of an airport access analysis, one could

assume that all trips would be produced at the airport, and attracted to the portal.

Spatial Separation Between Zones. The usual measurement of spatial separation between zones is total travel time. Total travel time includes the minimum path driving time, plus the "terminal" (walking and parking) times at both ends of the trip.

Travel Time Factors. Travel time factors or friction factors indicate the impedence to interzonal travel due to spatial separation between zones. Basically, these factors measure the probability of trip making at each one-minute increment of time travel.

Zone-to-Zone Adjustment Factors. These factors reflect the effect of social and economic characteristics of a certain zone on the travel patterns to the study area. Very few cities find that quantifying these values is necessary for a general transportation study. However, it should be noted that the persons coming to an airport generally have special characteristics, and therefore, identification of these characteristics and locating communities with high densities of these characteristics should prove useful for improving the accuracy of an airport access study.

The data needed to determine the parameters required by the gravity model for airport access are essentially the same as those for any transportation study. The data needed from the trip makers could best be determined from origin-destination studies. Airline passengers could be surveyed during their flight. Employee records would provide the needed home address. Surveying visitors would be more difficult, but perhaps a system would work where the visitor received a form along with his parking stub and returned the completed study when paying for parking. Data on the travel facilities could be obtained from the proper authorities within the city.

The gravity model can be used to predict either person trips or vehicle trips. Generally, it is much simpler to determine the number of vehicle trips. Vehicle trips should be an adequate tool for the airport planner to use in analyzing the capacity of the airport access.

The gravity model is also flexible in the number of trip purposes and the types which can be handled. Five trip purposes would give the airport planner very good detail about the trip types. These types are passenger based trips, work trips, visitor trips, cargo delivery trips, and airport and airline

delivery trips. The gravity model has been used to analyze up to nine trip types, and eight trip types is a common number in studies of large urban areas; therefore five trip types could be easily handled.

The purpose of discussing the gravity model in this section is to provide a basic insight into the capabilities of this model and offer suggestions on handling the parameters. It is recognized that the airport planner probably would not have the funds to make any revisions to the off-airport grounds portion of airport access. However, the airport planner might be able to persuade other agencies to make improvements, if he could show where improvements are needed.

VEHICULAR PATTERNS ON THE AIRPORT GROUNDS

Vehicular movement within the airport boundaries should all be done on one-way uncongested access routes. Intersections should be as few as possible. Parking should be adequate and very close to the terminal building. Adequate curb space should be provided for the convenience of loading and unloading passengers. These general statements about the facilities that should be provided in an airport are generally well accepted. However, there is a lack of information on how to achieve these goals.

Generally, the internal airport roadways in the United States are formed in a one-way counter-clockwise loop(s) pattern, with the terminal on the outside of the loop(s) and parking on the inside. The quality of the access which this type of system provides depends directly upon the number and type of intersections involved, the roadway characteristics, and the destination of the driver.

Capacity of the Internal Roadways

Due to the nature of a one-way operation and because of the special situation at an airport, it is assumed in this report that there will be no signalized intersections on the internal road of an airport. Also at any intersection, it is assumed that there will be no yield or stop signs restricting the flow of the main roadway. By making these assumptions, maximum capacity will be achieved on the main access routes.

Analysis of this capacity may be done by the use of the Highway Research Board Special Report 87, The Highway Capacity Manual. The steps presented in this manual have been modified for application to analysis of internal airport

roadway systems in this report. The capacity manual stresses that these calculated capacities are approximations and if greater accuracy is required, then field observations should be made and the maximum observed values should be accepted as the correct values.

The Highway Capacity Manual presents a series of curves for different roadway situations. The curves used in this report are for signalized intersections. Therefore, the units are given in terms of vehicles per hour of green time, and to obtain the final results, the user needs to multiply the values by the ratio green time to total cycle length. This ratio will be assumed equal to one for an unsignalized intersection. It is a conservative approximation to use these curves to analyze the capacity of an unsignalized intersection. The justification for assuming these curves can be used is that the major factor which affects an intersection's capacity is the turning movements. Therefore, we are assuming that the effect of turning movements will be the same for a signalized intersection and an unsignalized intersection. It is realized that more refined techniques for calculating intersection capacity have been developed and these should be implemented into the systems analysis during an improvement interaction.

The factors which affect approach capacity of a roadway leading to an intersection are:

(1) width of approach,
(2) load factor (based upon the level of service),
(3) peak hour factor,
(4) metropolitan area population,
(5) parking,
(6) percentage of trucks,
(7) location within the metropolitan area, and
(8) number of left and right turns.

The width of an approach is one of the basic inputs which the airport planner must use in this analysis. This is the total width from curb to curb, even when there is parking along the sides of the street. If there are separate turning lanes, then the width of these lanes is subtracted from the width of the street and the number of turning movements is input as zero. The capacity of the turning lanes is then calculated separately.

The load factor is an indicator of the level of service which the facility provides to the drivers. A true level of service indicator would need to be based upon the whole system, rather than just one intersection. Two levels are considered in this report due to the fact that there is an actual capacity and a design capacity. The design capacity is assumed to represent a level of service "C." For this level of service, the driver is somewhat restricted, but not objectionably so. Capacity is defined as level of service "E." This represents the most vehicles that a particular intersection can accommodate for the given conditions. Under this condition there is unstable flow.

The peak hour factor is a measure of the consistency of the flow. It is the ratio of the maximum peak hour flow and four times the number of vehicles counted during the highest consecutive fifteen minutes. The closer this ratio is to one, the more uniform the flow. Where an approach is expected to carry high loads for most of the hour, a peak hour factor of 0.85 is a reasonable estimate. This value also is a reasonable estimate to use in the absence of any knowledge about the conditions at the intersection. Therefore, a peak hour factor of 0.85 is assumed in this report.

Location within the metropolitan area is another input which affects intersection capacity. The Highway Capacity Manual gives four breakdowns of this parameter, the central business district, the fringe area, the outlying business district, and residential areas. Since airports are generally outside of city limits, it is assumed in this report that conditions at the airport are most closely approximated by the values given for the fringe area.

The basic capacity curves used to arrive at capacity are shown in Fig 3.1. From these curves, the following mathematical equations were derived.

One-way street, no parking, level of service "C":

$$V_1 = -110 + 85.5\ W$$

One-way street, no parking, level of service "E":

$$V_2 = -350 + 112.5\ W$$

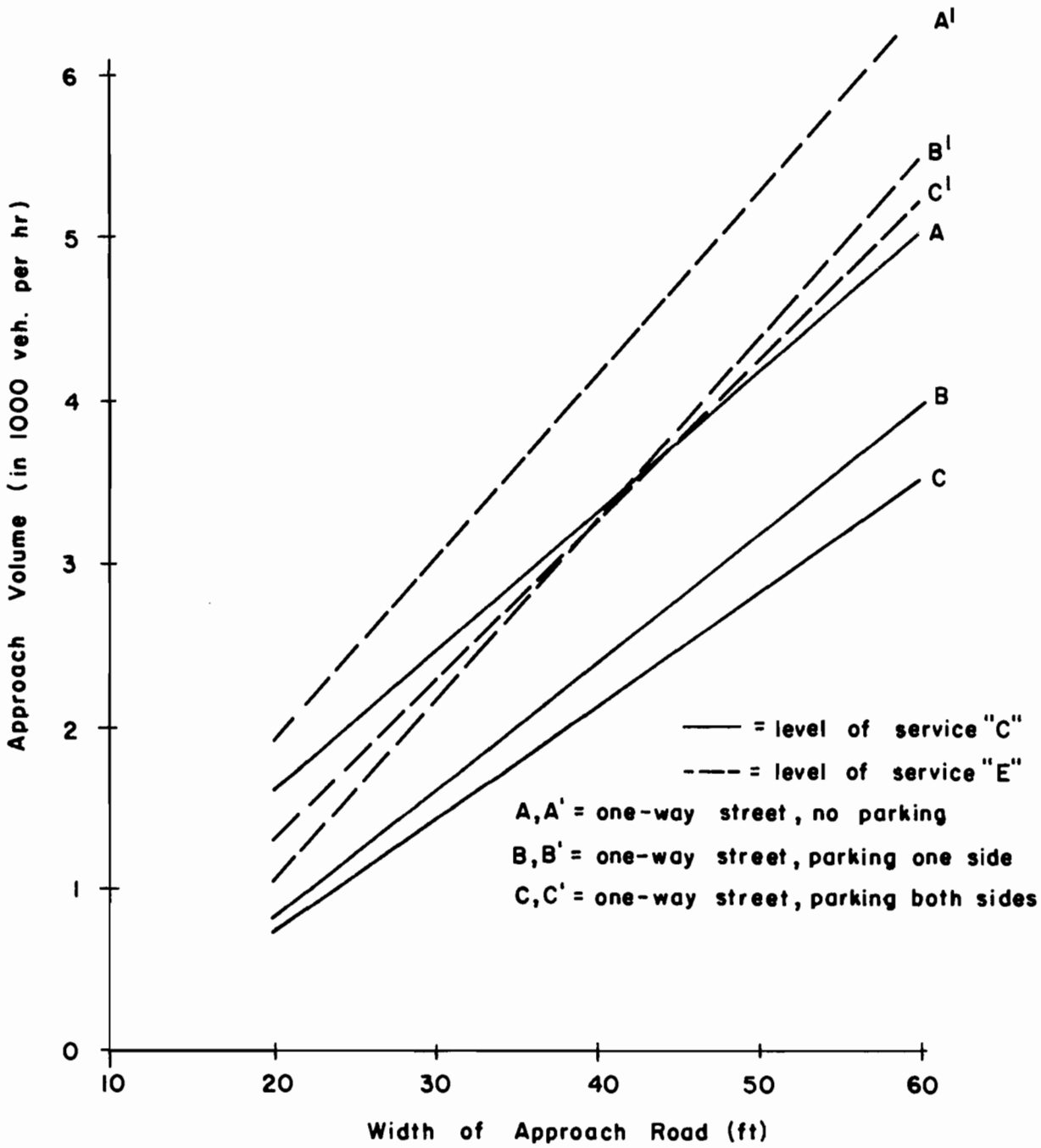


Fig 3.1. Urban intersection approach, service volumes (Ref 25).

One-way street, parking on one side, level of service "C":

$$V_3 = -790 + 7915\ W$$

One-way street, parking on one side, level of service "E":

$$V_4 = -1190 + 111.5\ W$$

One-way street, parking on both sides, level of service "C":

$$V_5 = -675 + 69.8\ W$$

One-way street, parking on both sides, level of service "E":

$$V_6 = -670 + 98.5\ W$$

where

V = approach capacity of roadway, vehicles per hour,

W = width of roadway, feet.

These basic capacities must now be corrected for metropolitan area population, number of turning movements, and special turning lanes. The width of the roadways should be within the limits of the graph, and the value should be between 20 and 60 feet.

The corrections for the size of the metropolitan area are based on the equation:

$$CP = 0.14 + 0.16 \times \log (Pop)$$

where

CP = correction factor for population,

Pop = population of metropolitan area.

This equation is based upon Fig 3.2, which is a graph of the correction values given by the Highway Capacity Manual. This equation is good for populations between 75,000 and 1,000,000. The correction factor for populations greater than 1,000,000 is a constant 1.14 .

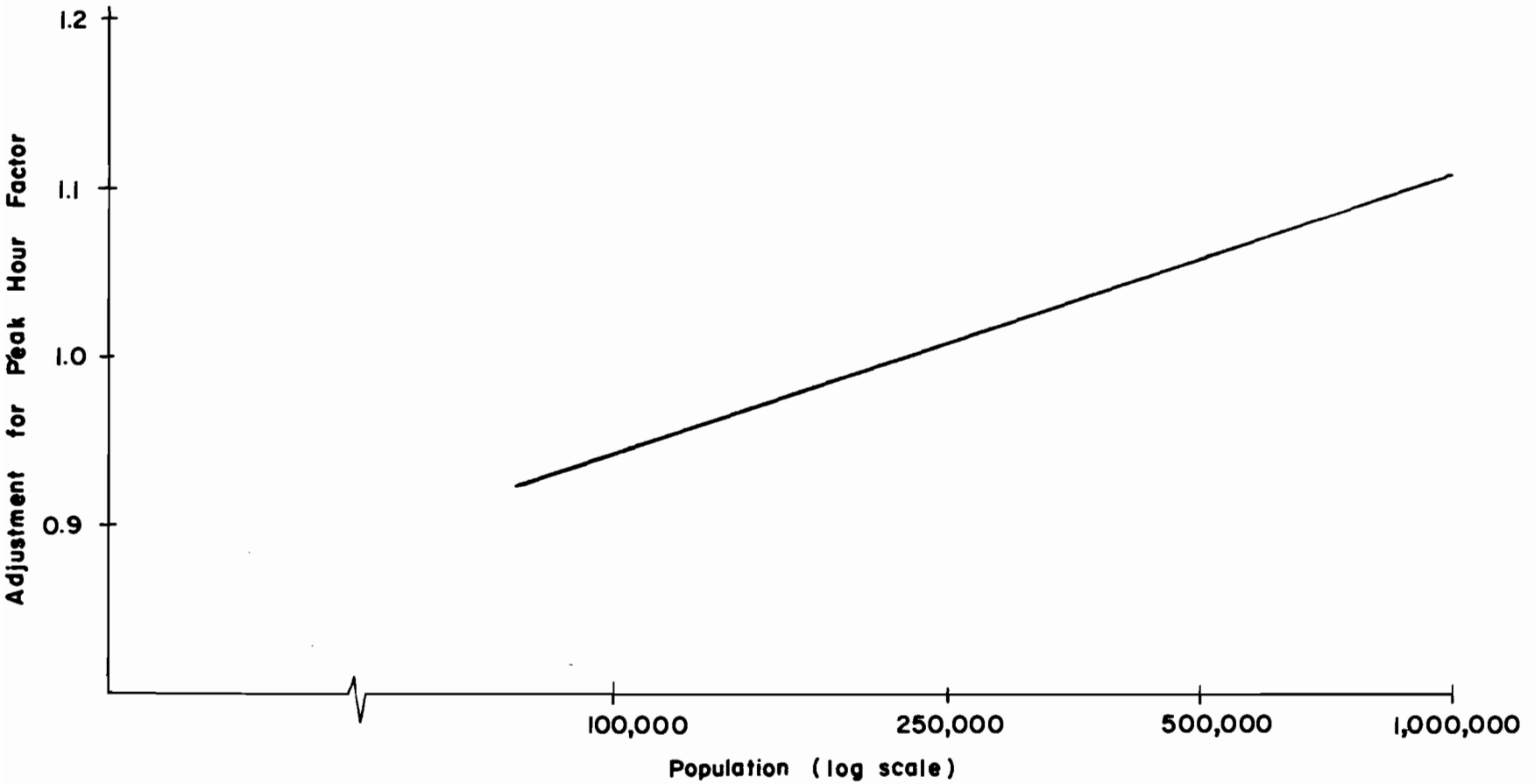


Fig 3.2. Intersection capacity corrections for peak hour factor.

The correction factors for turning movements are shown graphically in Fig 3.3. It has been found that the effect that turning movements have varies with the roadway width and the number of turns being completed. The following equations are derived from Fig 3.3.

$W = 15$ feet no parking or $W \leqq 20$ feet with parking

$CT_{0-10} = 1.2 - 0.02\ T$

$CT_{10-20} = 1.1 - 0.01\ T$

$CT_{20-30} = 1.0 - 0.05\ T$

$CT_{30+} = 0.85$

$16 \geq W \geq 24$ no parking or

$21 \geq W \geq 30$ with parking

$CT_{0-20} = 1.025 - 0.0025\ T$

$CT_{20-30} = 0.925 + 0.0025\ T$

$CT_{30+} = 1.0$

$34 \geq W$ no parking or

$40 \geq W$ with parking

$CT = 1.0$

where

W = width of roadway,

T = percentage of vehicles turning,

CT = correction factors for turning.

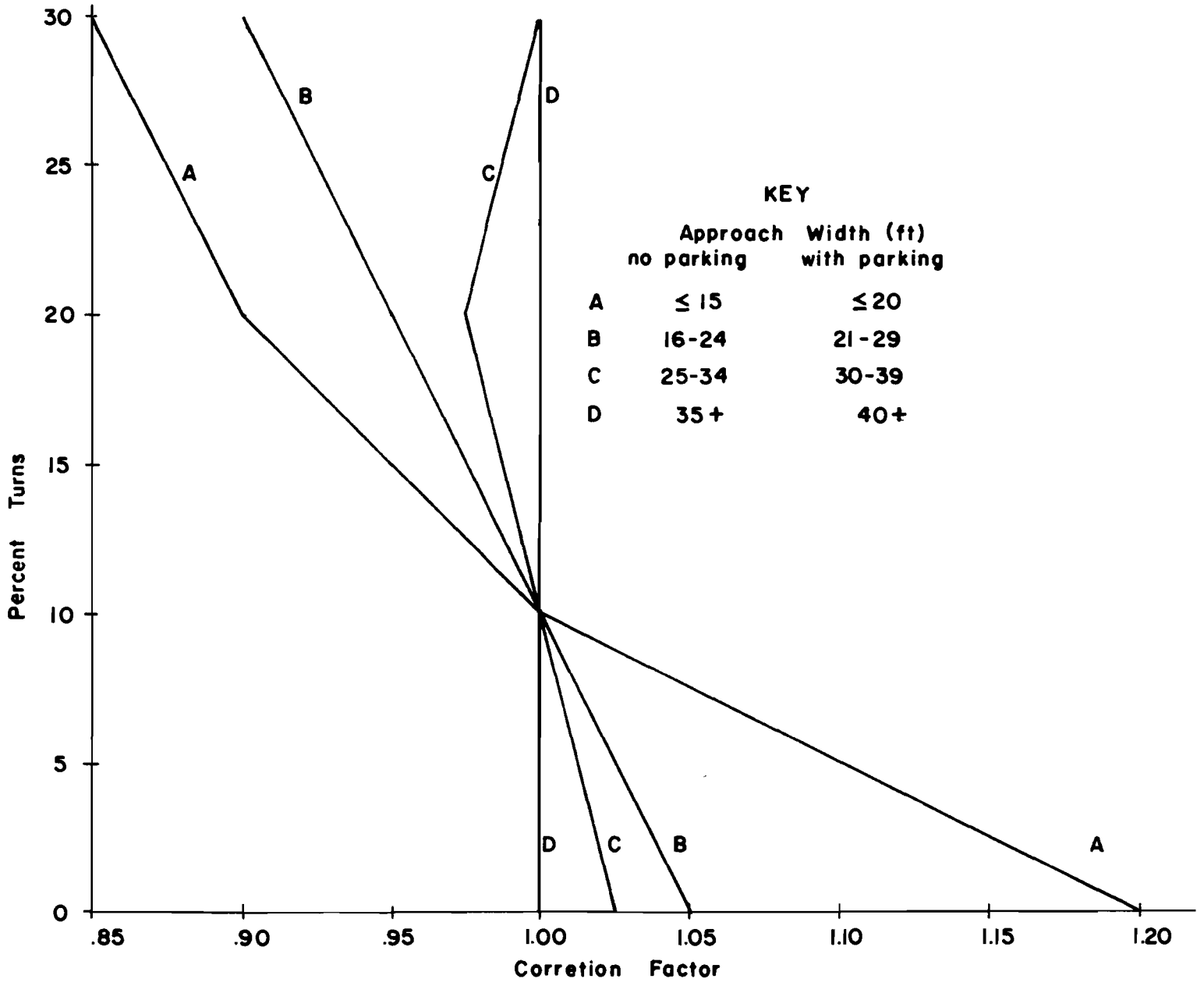


Fig 3.3. Adjustment factors for right and left turns on one-way streets.

It is expected that on the airport main access route, there will be no parking, except in front of the terminal building where there may be parking and people will be using the curb space to unload bags and passengers. The capacity of the area in front of the terminal will be further reduced due to pedestrians walking between the terminal building and the parking lot. This reduced capacity is somewhat offset by the fact that a majority of the vehicles will not pass in front of the terminal building because they will have exited the access route to enter the parking area. The airport planner should keep these factors in mind when looking for the point of lowest capacity in the access system.

Parking Lot Capacity

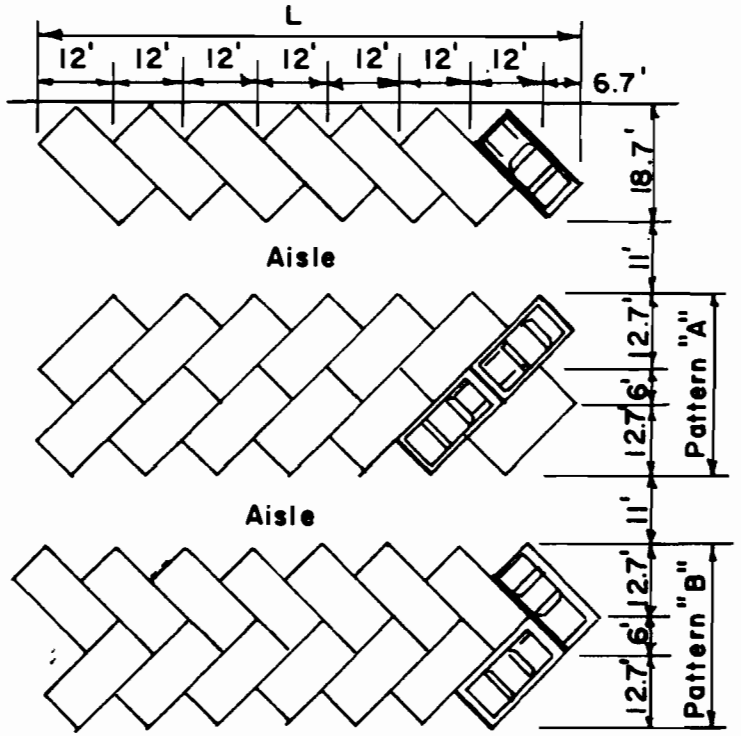
Parking lots are one of the most important features of a well planned airport. An important consideration in the layout of the parking area is to limit the walking distance to an absolute minimum.

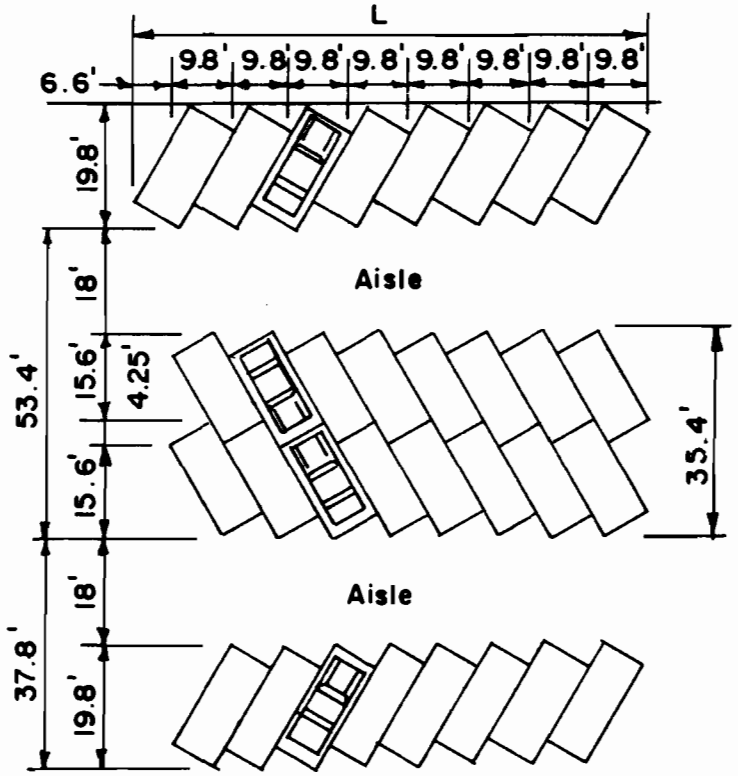
An airport requires several different types of parking. Long-term parking needs to be provided for the passengers who must leave their automobiles for extended periods. Long-term lots can be located further from the terminal than short-term lots and the cost should be somewhat less than the charge for short-term parking. Short-term parking needs to be provided for passengers who are taking commuter flights and for visitors.

Very short-term parking is sometimes offered at a very high fee for those who are coming to the airport to pick up or drop off a passenger. Employee parking must be provided as well as parking for delivery and cargo trucks.

The need for parking varies greatly between airports. The FAA recommends that 1.2 spaces be provided per peak hour passenger, but some airports have reported needing up to five spaces per peak hour passenger. Therefore, no recommendations or assumptions are made in this report about the quantity of parking which is required or how the parking should be distributed between the various types of parking lots.

The capacity of a parking lot is basically a function of the arrangement of the stalls. Figure 3.4 is taken from Airport Terminal Buildings, published by the FAA in 1960. It is recommended that the length of each row of cars (L) be limited to 200 feet in order to allow cars to maneuver easily through the parking lot.

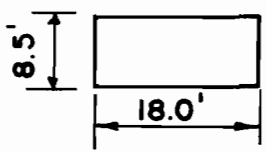




45° Parking Angle
Number of Spaces = $\frac{L - 6.7}{12}$
* Approximate number of cars per acre = 158

60° Parking Angle
Number of Spaces = $\frac{L - 6.6}{12}$
*158 = Approx. number of cars per acre

* includes parking space and parking aisle only



Recommended Parking Space Size

Parking Data Basis: Four-door automobile 216" long by 78" wide

Fig 3.4. Passenger car parking requirements (Ref 8).

The system of charging and collecting parking fees at most airports is handled through the use of an automatic ticket distribution stall at the parking lot entrance and manual collection of the fees as the automobile exits the lot. This is potential "bottleneck" to the parking lot. Observations of this activity were made at the Austin Municipal Airport (as reported in Appendix 1) and from this data it is assumed that the average service time for an automobile entering the parking lot is 5.8 seconds, and that the average service time for an automobile exiting is 16.0 seconds. Based on these service times, the hourly capacity of the entrance ticket distribution system is 620 automobiles per stall per hour. The hourly capacity of the parking fee collection system is 225 automobiles per man per hour.

Curb Requirements

Adequate curb space for picking up and dropping off passengers is important for smooth operation of the internal roadway system. Inadequate curb space will result in double and triple parking which can cause a severe "bottleneck" in front of the terminal building. When this occurs, the capacity of the internal roadway will approach zero.

Figures 3.5 and 3.6 are curves which can be used to estimate the amount of curb space required at a given airport (Ref 51). In order to use these curves, the number of peak-hour vehicles and the percentage of vehicles in each class must be known. The sum of the foot-minute units per vehicle equals the total foot minute required for a group of vehicles. These units are obtained from the charts by entering the modal split of vehicles on the internal roadway system. The number of units is then multiplied by the number of peak-hour vehicles. This product is then divided by 60 to determine the amount of footage which is required (Ref 51).

SUMMARY

The airport access/egress subsystem is perhaps the most important portion of the airport system with respect to user acceptance of the airport. For example, Southwest Airlines recently won a court decision which allows them to continue using Love Field in Dallas for commuter flights from Houston and San Antonio. Southwest Airlines believed that they would lose much of the commuter market between these two cities if the patrons had to commute from the new Dallas-Fort Worth airport to downtown Dallas. As a result of

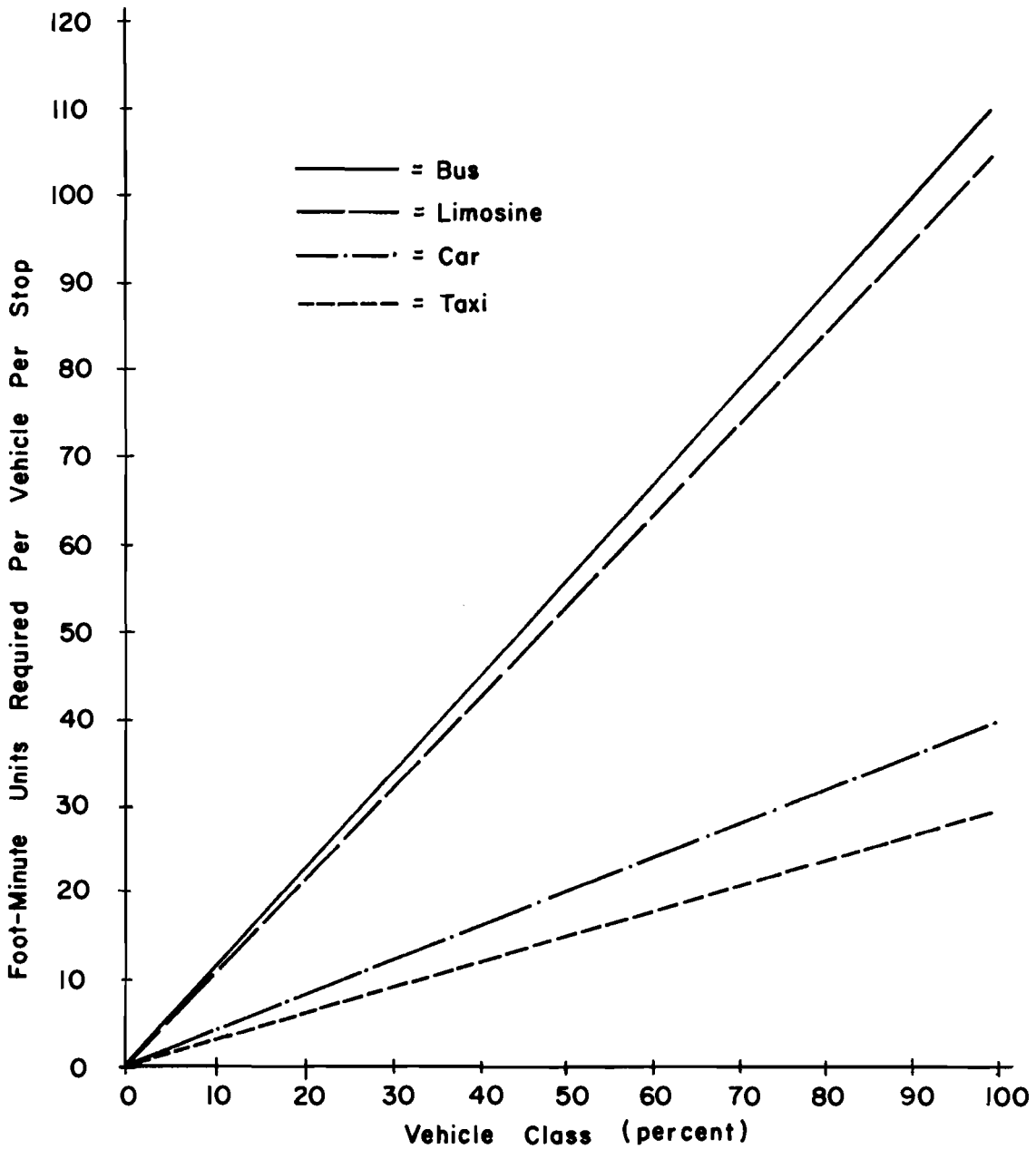


Fig 3.5. Curb usage for vehicles using enplaning curb (Ref 51).

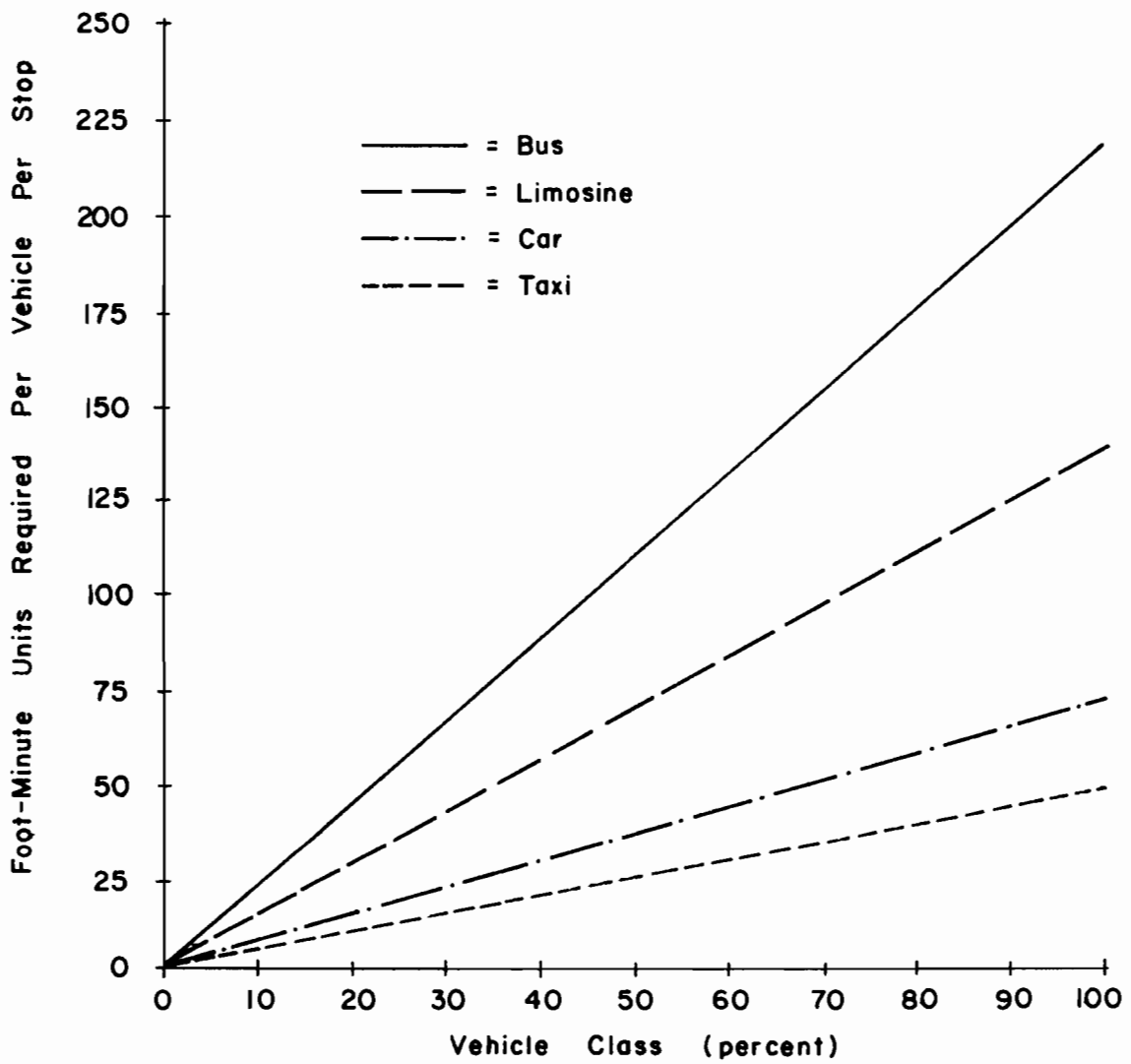


Fig 3.6. Curb usage for vehicles using deplaning curb (Ref 51).

Southwest Airlines' victory in court, two other airlines are now offering commuter flights to Love Field, rather than to the new regional airport. This is a typical case of an expensive new airport losing business to the old facility due to the fact that the old facility is more accessible to the major downtown market.

A second factor showing the importance of the access/egress subsystem is that present-day aircraft fly close to the sound barrier and in the United States, research on supersonic commercial aircraft has been stopped due mainly to environmental considerations. Therefore, it is unlikely that the flying time for a trip will be reduced much further. On the other hand, access times to airports have been increasing in the past few years due to heavier congestion on the access routes. With these two factors in mind, it is obvious that any improvement in the total air trip time must come from improvements in airport access times.

With these factors in mind, the airport planner can see the need for a comprehensive study of the access/egress subsystem of an airport. Furthermore, using the methods presented in this chapter, the planner has a means of supporting his request to the city, county, or state government for improvements in the access/egress system under their jurisdiction.

CHAPTER 4. THE TERMINAL BUILDING SUBSYSTEM

The terminal building subsystem at airports is usually made up of a complex of buildings, each handling specific functions. At large airports, this complex generally consists of the main terminal building, a separate general aviation building, a cargo building, aircraft maintenance hangers, a control tower, and airport equipment buildings. The FAA and other government agencies will have office space in the main terminal building. While all of these buildings contribute to the capacity of the airport, only the main terminal building and the cargo building will be discussed in this chapter.

Unfortunately, there has been very little research done on the terminal subsystem. According to Robert Horonjeff:

> In terms of research, the effort devoted to the flight and access subsystems has been much greater than that devoted to processing at the airport. The reasons for this are understandable. All of the activities related to flight are under the jurisdiction of, or are of direct interest to, the Federal government, hence, there has been substantial Federal support in this area. Likewise, a good share of the access to airports has been by automobile, and the entire street and highway program has received substantial support for research from the Federal and State governments. But, between those two areas, lies the relatively unexplored area of passengers and baggage flow through the terminal building. The prime responsibility for the design of the terminal building rests with the airport owner, who does not have the resources to invest in research (Ref 28).

This chapter is divided into seven sections. The first section is a review of several definitions of passenger flow. The second section reviews the various types of terminal buildings. The third section presents the FAA method for analyzing terminal buildings. The fourth section presents a method of analysis developed by Robert Horonjeff. The fifth section is a discussion of intraterminal people moving systems. The sixth section reviews the FAA method for analyzing cargo areas. The final section is a summary of the important concepts presented in this chapter.

DEFINING PASSENGER FLOW

One of the difficulties in determining the capacity of terminal buildings is the lack of a concise, uniform term for describing passenger flow. To demonstrate this, several of the definitions which have been used in the past are presented as follows:

(1) Horonjeff: "Unlike similar analysis made for highways, which establish volumes for the thirtieth highest hour as a basis for design, for airports there is no specific criterion. Peak-hour volumes are examined and a reasonable value chosen as a basis for design."

(2) FAA (Airport Terminal Buildings) defines peak-hour volumes as "the highest number of passengers enplaning and deplaning during the busiest hour of a busy day of a typical week. Thus, the figure for typical peak-hour passengers (TPHP) represents a plane of high activity, but not necessarily the absolute peak number of passengers that could be expected during a given day of the year."

(3) R. Dixon Speas Associates, in preparing input for the Calgary study defined peak-hour as "the hour during which the level of passengers or aircraft activity represents a high proportion (95 to 100 percent) of the maximum recorded hourly volume."

(4) The Canadian Ministry of Transport defines peak-hour activity as "the total number of enplaned and deplaned passengers in a selected clock hour. The passenger traffic volume during this selected peak is chosen for use in planning and is generally less than the absolute peak."

(5) In England the term "Standard Busy Rate (SBR) or Standard Busy Hour (SBH)" is used rather than peak-hour. It is defined as "the traffic volumes during each hour of a month are ranked in descending order. The top 30 hours are discarded, the 31st hour is called the SBH. This is a method for eliminating extreme peaks from calculations."

(6) Bernhaker and Elek (Ref 36) define design peak-hour as the passenger volume of an hour in the year which is exceeded not more than 15 times.

One deficiency common to all of these definitions is that they fail to mention visitor and airport employee flows. Therefore, it is necessary to assume that visitor flows are included in the definitions and employee flows are excluded.

The concept of using passenger volumes somewhat below the maximum volume, is common to all of these definitions. Definitions 5 and 6 are perhaps the best definitions, because they actually indicate the amount of time the airport will be operating beyond its design capacity. The FAA definition will

be used in this paper unless otherwise stated, because the FAA method of analysis is the major analytical method discussed.

TYPES OF TERMINAL BUILDINGS

There are several basic designs of terminal buildings currently in use. Each basic design has advantages and disadvantages from a capacity viewpoint. Capacity factors which are affected by the design of the terminal building are (1) aircraft parking arrangement, (2) automobile parking arrangement, (3) passenger walking distance within the terminal building, and (4) layout of the passenger services within the terminal building. Basic designs fall into two major categories, centralized and decentralized designs.

Centralized Terminal Buildings

Centralized terminal buildings process all passengers and baggage in one building. There are several types of centralized terminal buildings in use.

Frontal and Linear Terminal Buildings. The frontal and linear terminal buildings are the most basic types of design. They use an open apron concept which allows aircraft to park in the most convenient manner. The level of service of these types of terminal buildings is very poor when compared to the other types of terminal buildings. Therefore, these types of terminals are used only at low-volume airports where it is economically unfeasible to construct one of the other types of terminal buildings. The layouts of these airports are illustrated in Fig 4.1 and Fig 4.2.

Pier-Finger Terminal Buildings. Pier-finger terminal buildings are one of the most common types of terminal buildings currently in use. These terminal buildings commonly result from extending a frontal or linear type terminal building as passenger volumes increase. By building the pier fingers, as shown in Fig 4.3, more aircraft can park close to the departure gates. Some of the problems which arise are

(1) aircraft manuevers into and away from the gate positions become more complicated;

(2) automobile parking can not be readily expanded;

(3) passenger walking distances can become extremely long, especially for transfer passengers; and

(4) the central building can become very crowded since all the passengers must pass through it.

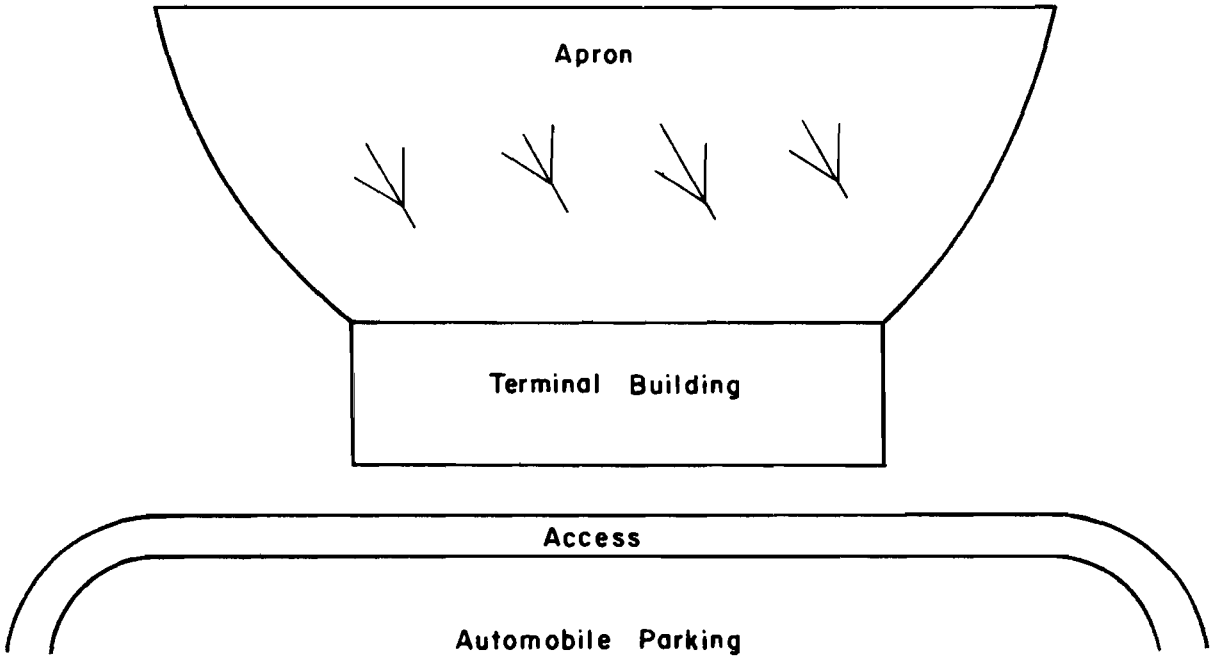


Fig 4.1. Frontal terminal building.

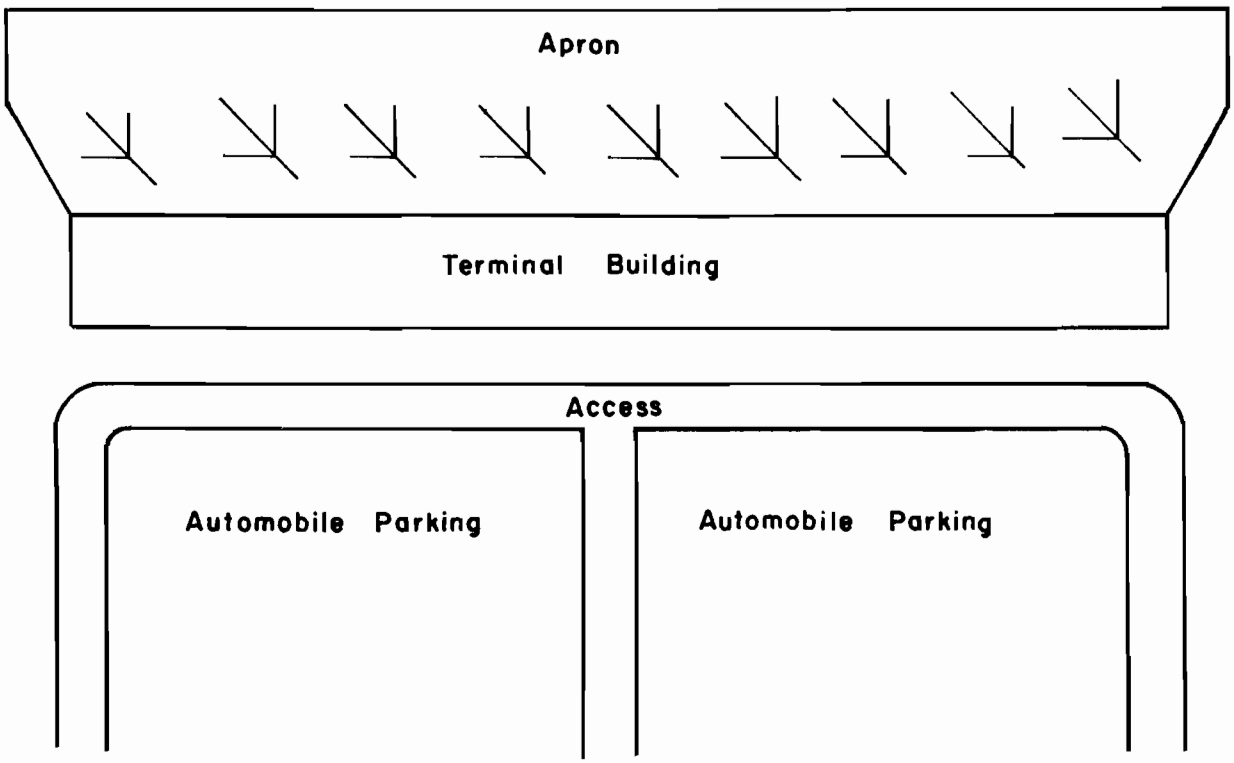


Fig 4.2. Linear terminal building.

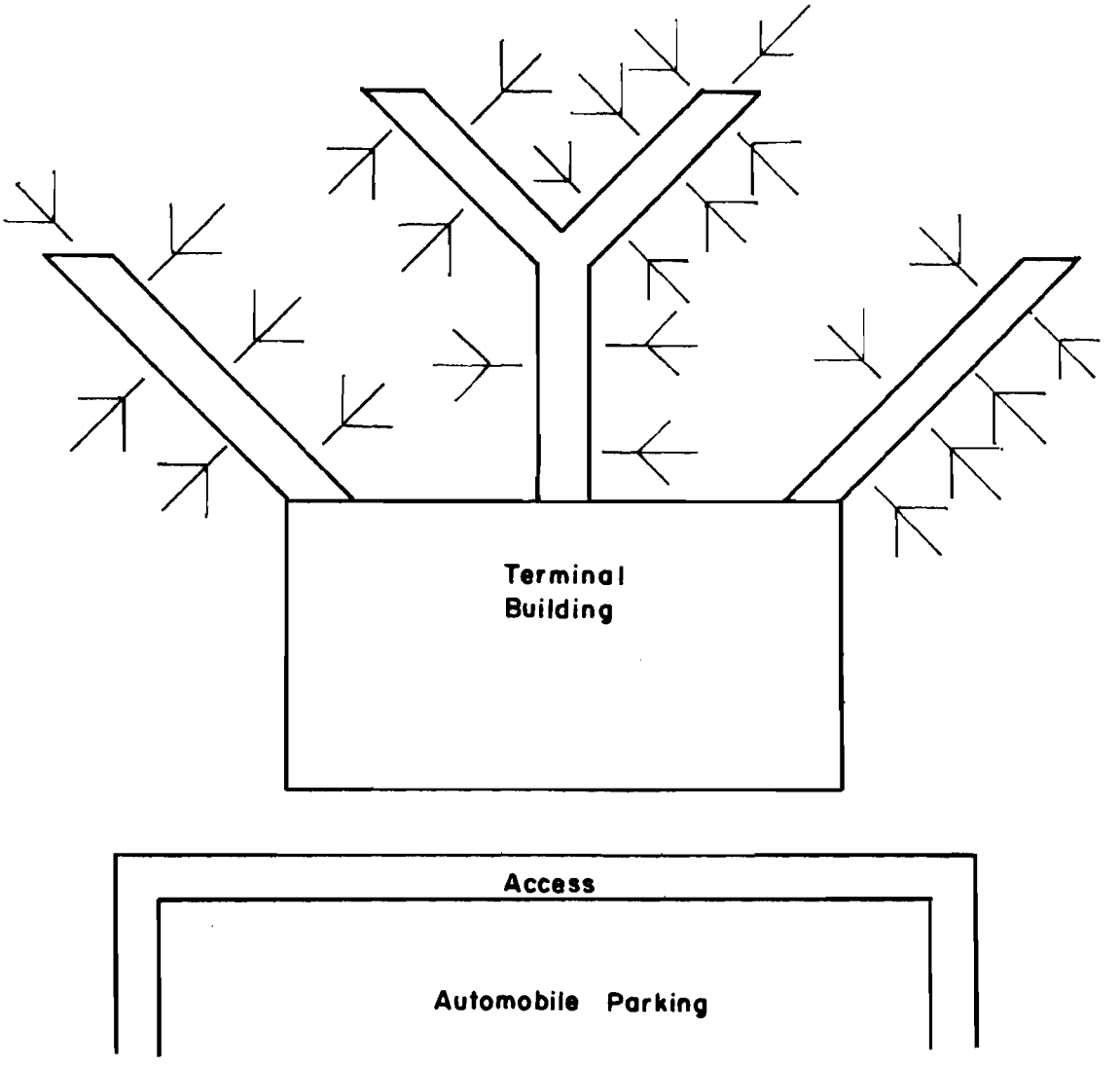


Fig 4.3. Pier-finger terminal building.

Satellite Terminal Buildings. In the satellite terminal design, there is one main building for processing passengers, and several smaller satellite buildings used as departure lounges. The satellite buildings are connected to the main building by a system of tunnels. This concept is illustrated in Fig 4.4.

The major advantage of the satellite concept over the pier-finger concept is that aircraft can maneuver into parking position much more easily, resulting in fewer conflicts in the apron area. The disadvantages of this system are that tunnels are expensive to build and passengers must change levels several times as they move from the terminal building to the aircraft doors.

Remote Terminal Buildings. This unique approach to the design of terminal buildings is used at the Dulles Airport in Washington, D.C. The remote terminal building concept uses a single main building and an open apron for aircraft parking. Passengers are transferred from the terminal buildings to the aircraft on mobile lounges. This concept is illustrated in Fig 4.5.

The advantages of this system are (1) it is very flexible and can be readily expanded, (2) aircraft can park easily, (3) it offers a good level of service to the passengers, and (4) depending upon the design of the mobile lounges, this system can be very economical. A disadvantage of this system is that all passengers must pass through the main terminal building, which can cause extensive conflicts.

Decentralized Terminal Buildings

In the decentralized terminal building concept, each major airline or a group of minor airlines each operates its own terminal building. The advantages of this concept are (1) the passengers are distributed to several buildings, (2) aircraft maneuvering on the apron area is simplified, (3) automobile parking can be conveniently located near each terminal building, allowing for short walking distances for the enplaning and deplaning passengers, and (4) the airport can be easily expanded. The disadvantages of the decentralized terminal concept are (1) some type of transportation system must be provided to move passengers and baggage between the various terminal buildings, (2) a great deal of land area is required, and (3) the system is expensive to build due to duplication of facilities within the various terminal buildings.

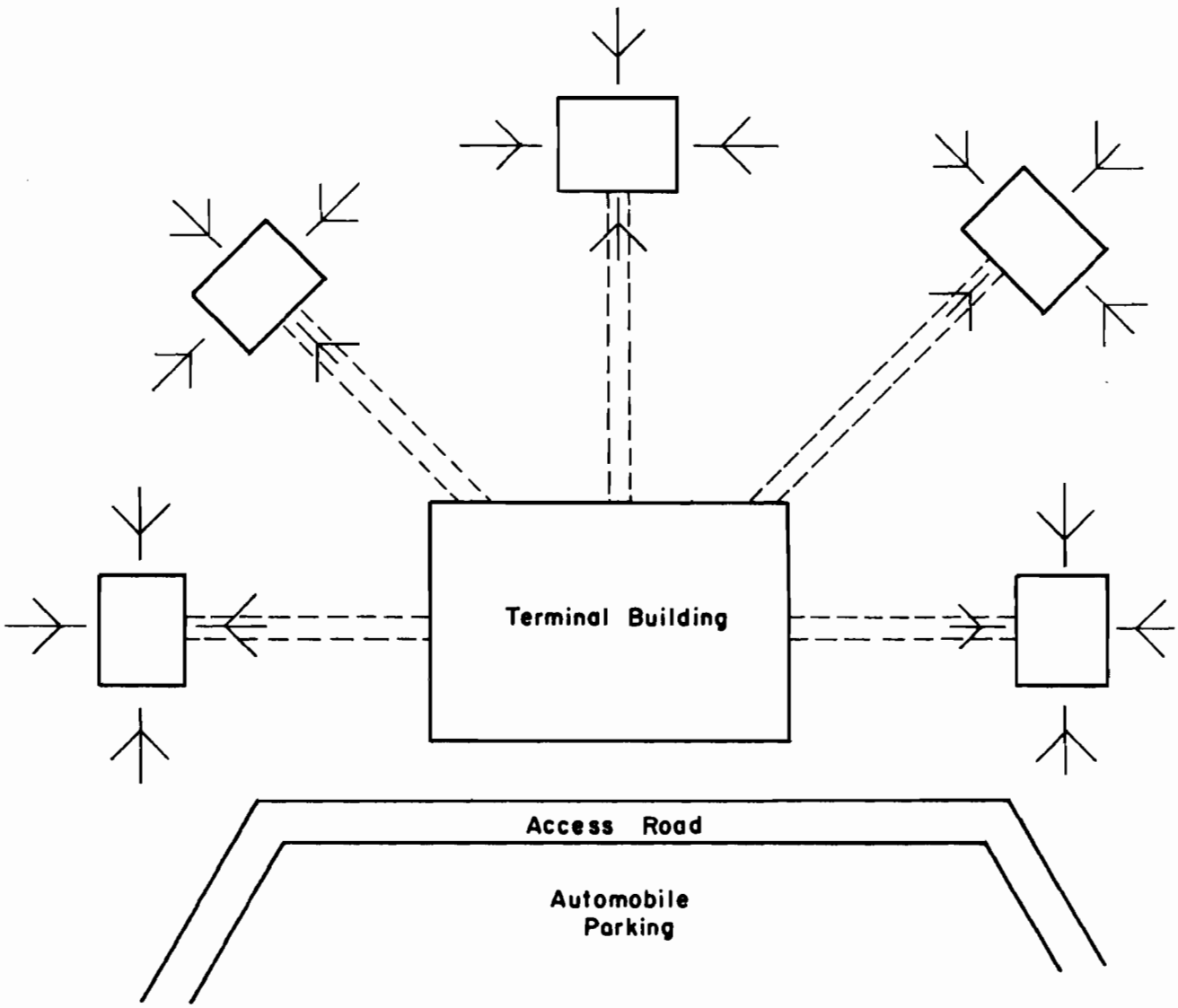


Fig 4.4. Satellite terminal building.

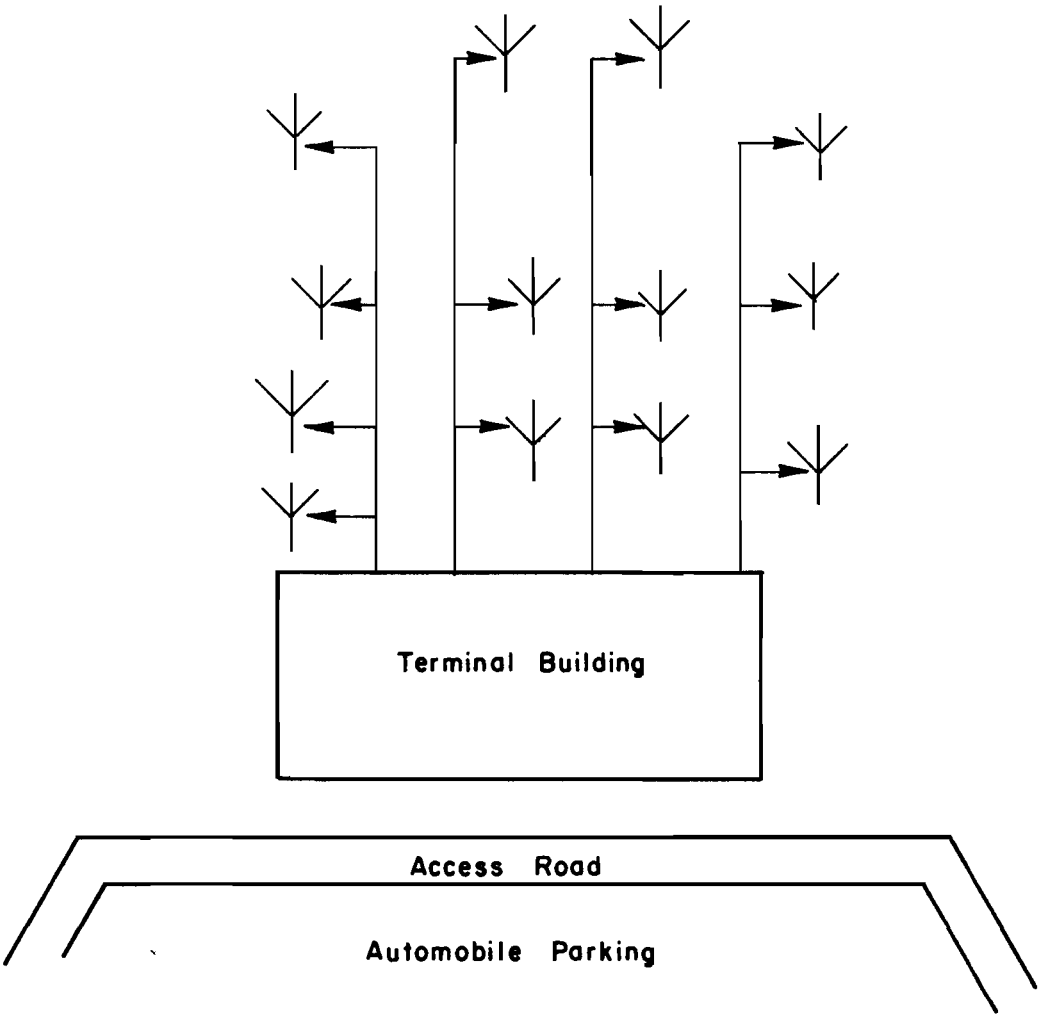


Fig 4.5. Remote terminal building.

Unit Terminal Buildings. The unit terminal concept has several terminal buildings in either a circular or linear arrangement. Each terminal building has either a pier-finger or satellite arrangement of aircraft gates. This concept is illustrated in Fig 4.6.

Spinal Cluster Terminal Buildings. The spinal cluster concept is the newest concept in airport design and is used in the Dallas-Fort Worth Regional Airport. As shown in Fig 4.7, access to the airport is along a single road through the middle of the airport. Parking is provided at each of the terminal buildings.

Summary of Terminal Building Concepts

This section has presented several of the basic types of terminal building designs. Many of the designs in use presently are combinations of these basic designs. It is interesting to note that the only major airport opened in the United States during the sixties, and the newest major airport completed in the seventies, are both designed as decentralized terminal buildings.

Walking distance has become a major problem at large airports. As an example of the walking distance for different airport designs, Table 4.1 summarizes walking distances at some of the major airports. The table shows that decentralized terminals offer the shortest walking distances for the originating passenger, but the walking distance for transfer passengers is excessive.

FAA METHOD OF TERMINAL BUILDING ANALYSIS

In 1960, the FAA published Airport Terminal Buildings, which has become the standard method for analyzing space requirements regarding terminal buildings. This reference contains graphical relationships for analyzing several basic functions of the terminal building. For this report, a regression equation was generated for each FAA relationship. In these equations the independent variable is passenger flow rate, measured as typical peak-hour passengers (TPHP).

Table 4.2 presents the equations which were found to fit the FAA relationships. The R^2 value is a measure of the quality of fit between the FAA curves and the prediction equations. The value R^2 varies between one and zero; an R^2 value of one indicates perfect correlation between the input

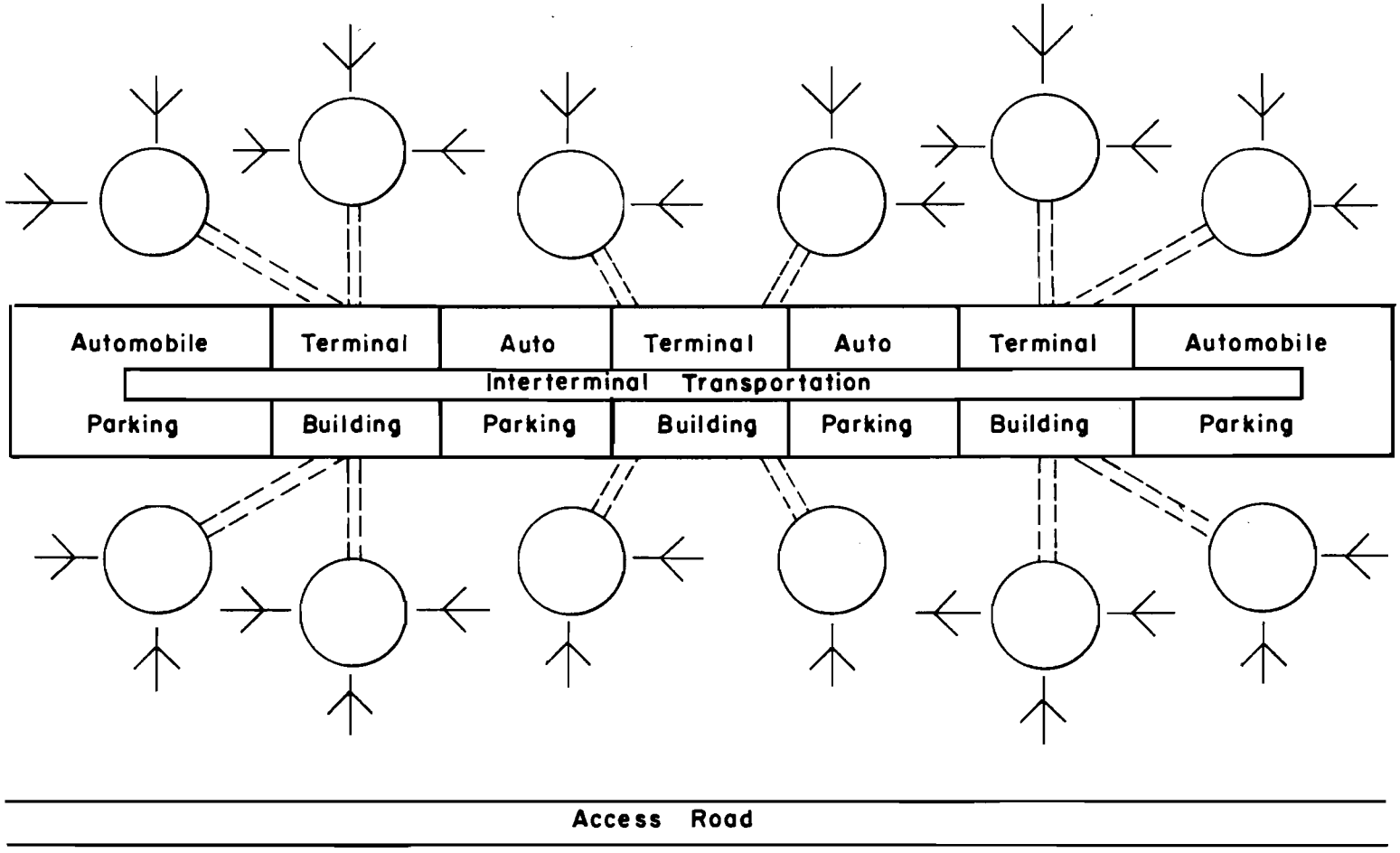


Fig 4.6. Unit terminal building.

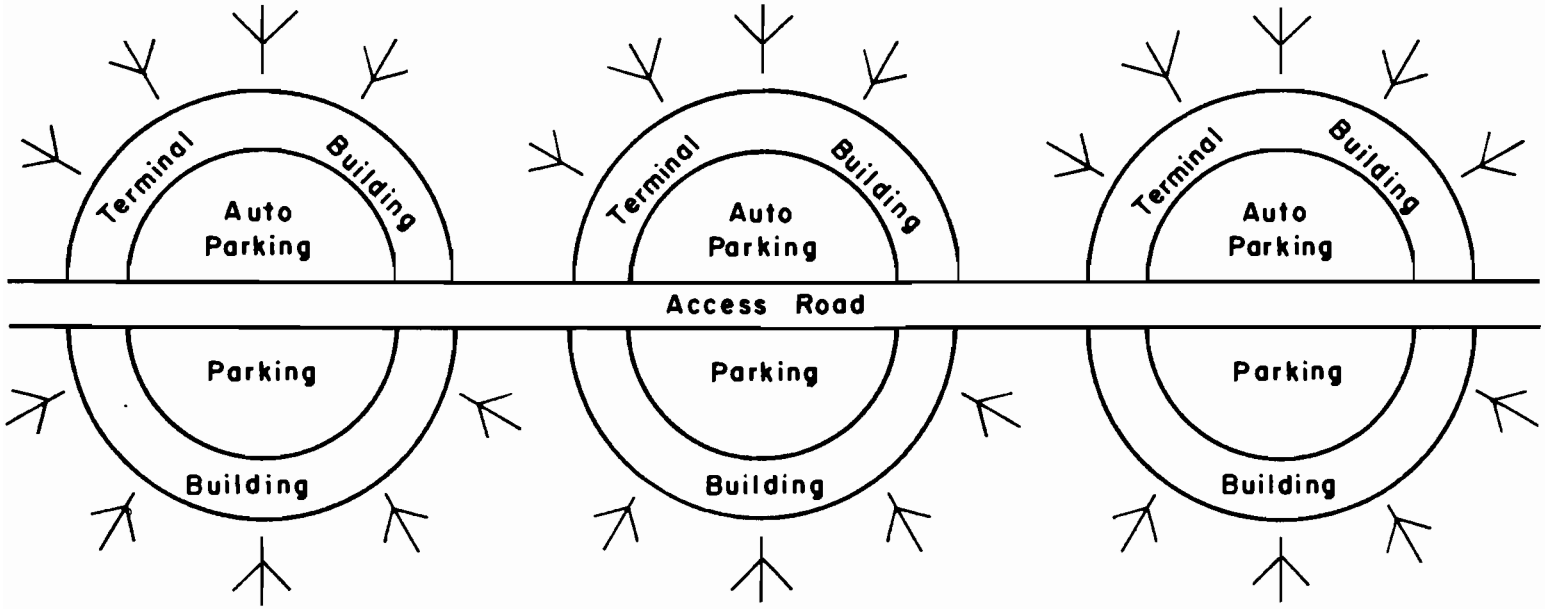


Fig 4.7. Spinal cluster terminal building.

TABLE 4.1. PASSENGER WALKING DISTANCES (FEET) AT MAJOR AIRPORTS

Airport	Passengers		
	Originating		Transfer
	Minimum Nearest Gate	Maximum Farthest Gate	Maximum
Chicago (O'Hare)[a]	580	1735	4720
New York (JFK)[b]	200	1130	7780
Los Angeles International[a]	836	1020	6640*
Atlanta[a]	630	1730	2680
Dallas (Love)[a]	730	1650	1990
Dallas-Fort Worth[b]	400	600	*
Dulles[c]	160	600	600
Houston Intercontinental[b]	550	550	*

*Intraterminal transportation used

[a]Centralized terminal

[b]Decentralized terminal

[c]Remote terminal, mobile lounges used

TABLE 4.2. REGRESSION EQUATIONS BASED UPON FAA RELATIONSHIPS

Component Analyzed (x =)*	Passengers		Equation	R^2
Ticket counter, ft	TPHP	=	$-80 + 3.378x$	.9991
Waiting area, ft^2	TPHP	=	$-31 + 1.751x$	.9990
Operations area, ft^2	TPHP	=	$-24 + 13.5x + .15(x/1000)^2$	.9999
Eating facilities area, ft^2	TPHP	=	$-71 + 41.9(x/1000) + .73(x/1000)^2$	.9989
Women's rest rooms (both closets and lavatories)	TPHP	=	$-2.6 - 28x + 1.27x^2$	.9994
Men's rest rooms (closets and urinals)	TPHP	=	$132 + 1.56x$	.9997
Men's rest rooms (lavatories)	TPHP	=	$13 + 15.27x - 11.6 \log (x) + .76x^2$	1.0000
Concession area, ft^2	TPHP	=	$9 + .306x$	1.0000
Lobby area, ft^2	TPHP	=	$-39 + .101x$	.9997
Baggage area, ft^2	TPHP	=	$-33 + .190x$	.9988
Annual Passengers**	AP	=	$22.9 + .0004P + 3.02 \log P + .00002 (P/1000)^2$	1.0000

*Column 1 is the factor which can be analyzed by the corresponding equation to determine the capacity of that component in units of typical peak-hour passengers.

**This equation calculates annual passengers as a function of TPHP.

data and the regression equation. The regression equations are derived for a minimum passenger flow of 200 TPHP.

The FAA method of calculating typical peak-hour passengers is to use a graphical relationship between typical peak-hour passengers and total annual passengers. An equation for the relationship is included in Table 4.2 with total annual passengers as the independent variable.

There are two problems with using the FAA method of terminal building analysis. First, there are some functions in the terminal building which are not described by the FAA model, such as customs and security. The second problem with the FAA model is that the FAA book was published in 1960. This indicates that the data for these relationships had to be collected in 1958 and 1959. Since the first commercial jet airliners were entering service at this time, it is likely that a majority of the data collected in developing the FAA model was from propeller aircraft. This raises a serious question about the current validity of extrapolating the FAA curves for analyzing passenger flow rates generated by the new wide-bodied jets. Because of these shortcomings of the FAA model, it is desirable to investigate an alternate approach to analyzing flow in terminal buildings. One alternate is the approach used by Robert Horonjeff for analysis of passenger flows in departure lounges.

HORONJEFF'S METHOD OF ANALYSIS OF PASSENGER FLOWS IN TERMINAL BUILDINGS

The introduction of the large, wide-bodied jets has created new space requirements in terminal buildings. Because of this, a comprehensive understanding of the flow process in the terminal building is needed. One approach toward an understanding of the flow process is to develop analytical methods for analyzing passenger flow. This is the approach taken by Horonjeff for the analysis of passenger flow in departure lounges (Ref 28).

For the analysis of passenger flows in departure lounges, Horonjeff developed two analytical models; one model describes the flow of passengers into the departure lounge and the other describes the flow of passengers into the aircraft. The first step in this procedure was to collect data about the flow of passengers into the departure lounge and from the departure lounge. This data was then plotted on cumulative flow versus time before departure curves. Figure 4.8 shows the cumulative flow of passengers into the departure lounge $F(t)$. The total number of passengers waiting in the departure lounge

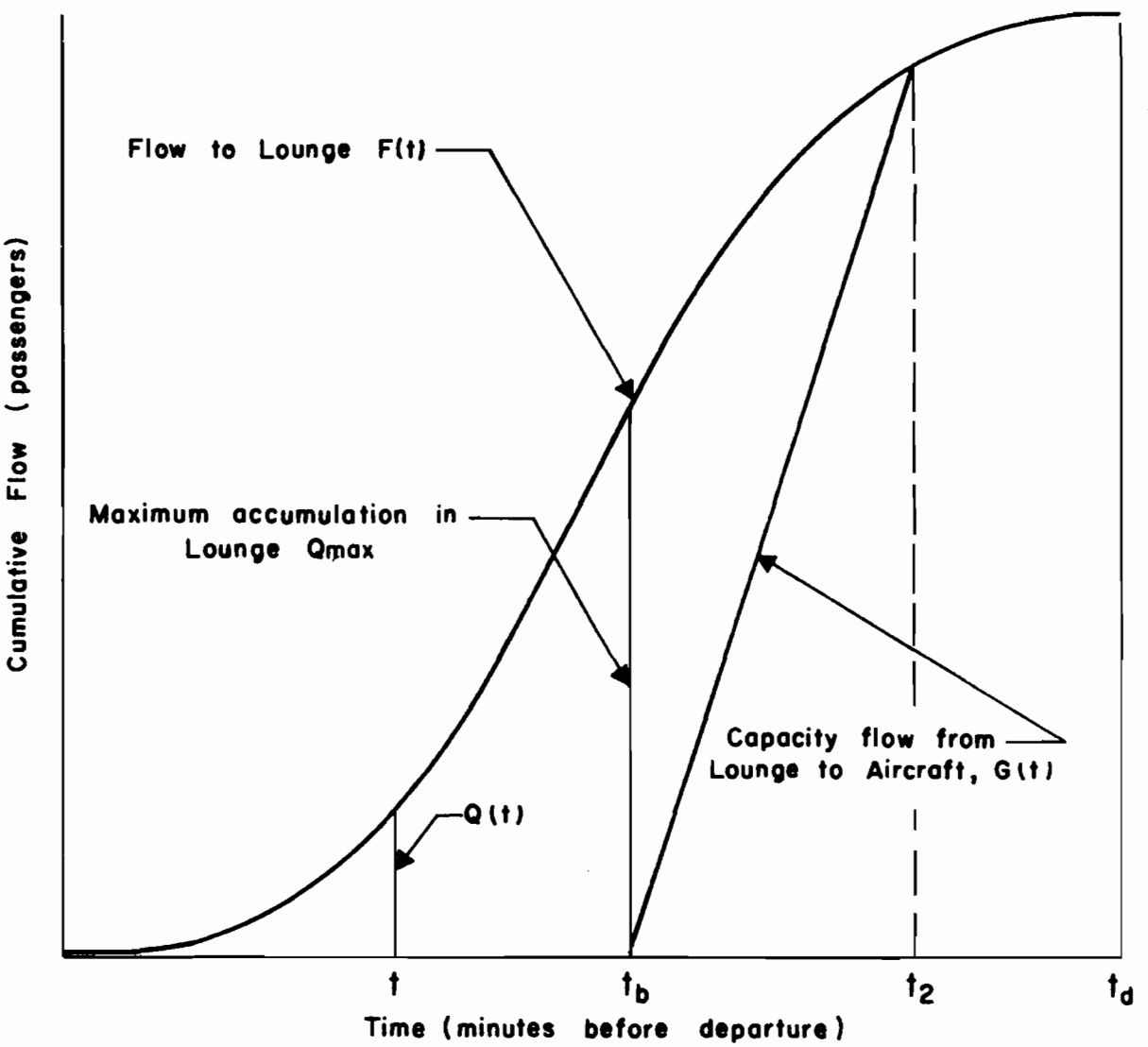


Fig 4.8. Departure lounge passenger flow (Ref 28).

at time t is $Q(t)$. The time the aircraft doors are opened is shown as t_b. At time t_2, the queue dissipates and the flow rate into the aircraft equals the flow rate into the lounge.

An equation of the form

$$F(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4$$

where:

$F(t)$ = percent of passengers boarding a flight,

t = the minutes before departure, and

a_n = regression constants, $n = 0, 1, 2, 3, 4$

was written based on a least-squares regression analysis of the data. It was found that the flow rate of passengers from the departure lounge into the aircraft was nearly constant from the time the aircraft doors were opened (t_b) until the queue dissipated (t_2). Thus, the equation for flow into the aircraft can be expressed as:

$$G(t) = b(t - t_b), \quad t_b < t < t_2$$

where:

$G(t)$ = the total cumulative flow into the aircraft,

b = capacity flow rate into the aircraft, passengers/minute, and

t = minutes before departure.

From these relatively simple calculations, the number of passengers in the departure lounge can be calculated based upon airline operating procedure and aircraft characteristics. The airline operating procedures which have an effect on the number of passengers in the departure lounge are the time the departure lounge is opened prior to departure and the time before departure that the aircraft doors are opened. The aircraft characteristics which are important are number of doors used for boarding and the seating capacity of the aircraft.

Horonjeff has developed similar procedures for analyzing flow of arriving passengers, baggage flow and flow in pier-finger corridors. The important concept is relatively simple; calculations can be used to determine theoretical flows based on the variables at each airport, rather than using the relatively gross and perhaps outdated FAA capacity relationships. Another advantage of using an analytical method of analysis is that this basic procedure can be used at any point in the airport where passenger queues occur and these analyses can be tied together, through the airline schedules, for analysis of flow through the entire terminal building subsystem.

INTRATERMINAL BUILDING PASSENGER TRANSPORTATION

As pointed out in the first section of this chapter, one of the major problems at large airports, is intraterminal walking distances. With decentralized terminal buildings, such as the new Dallas-Fort Worth Regional Airport, some form of intraterminal transportation is absolutely essential. Two basic types of transportation systems can be used: in centralized terminal buildings, a moving walkway concept is usually considered; in a decentralized terminal building, some form of "people mover" system needs to be provided.

Moving Walkways

Moving walkways have been used in some of the large terminal buildings as one method of reducing passenger walking distances. There are two basic types of moving walkways, the pallet type, a continuous system of flat grooved treads, using basically the same machinery as an escalator, and the belt type, a continuous conveyor-like, grooved rubber belt supported on rollers.

Capacity of Moving Walkways. The capacity of moving walkways is usually based on the assumption of standing pedestrians. It has been found that when pedestrians walk on moving walkways, the capacity is decreased because the additional area a pedestrian requires when walking more than offsets the higher relative speed of the walking pedestrians. However, such walking does substantially reduce the time required to move through the terminal.

The capacity of moving walkways is a function of the area each pedestrian occupies, and the operating velocity of the unit. The rated capacities supplied by one manufacturer are shown in Table 4.3. The theoretical capacity of these units is based on the spacing of two feet between pedestrians and single occupancy on the 24-inch unit, and double occupancy on the 42-inch

TABLE 4.3. MOVING WALKWAY CAPACITY
(SPEED 120 FEET PER MINUTE)
(REF 21)

	Lane	
	Single	Dual
Item		
Hip width (inches)	30	42
Belt width (inches)	24	36
Theoretical Capacity		
Persons per hour	4800	9600
Persons per minute	80	160
Nominal Capacity (75 percent theoretical)		
Persons per minute	60	120

unit. The nominal capacity figures are based on a spacing of 2.7 feet. The average pedestrian occupancies are 5.4 square feet and 4.0 square feet for the 24-inch unit and the 42-inch unit respectively.

Features of Moving Walkways. The three principal features of a moving walkway are its width, operating speed, and length. The width of moving walkways is usually a minimum of 24 inches; commonly used widths are in the range of 36 to 48 inches. The length of the moving walkway, of course, depends upon the individual situation, but extremely long walkways should be avoided because a failure in any part of the system causes the complete system to shut down.

The operating speed of moving walkways is limited by the entrance/exit capability of pedestrians. This generally means the operating speed of the moving walkways is in the range of 90 to 180 feet per minute. There is a significant amount of research underway on the development of variable speed walkways. These units would have a boarding velocity in the range of 90 to 120 feet per minute, then accelerate the passenger to speeds as high as 880 feet per minute.

People Movers

The decentralized terminal building concept requires that some form of transportation be provided between the terminal buildings. At two of the newest major airports, the Dallas-Fort Worth Regional Airport and the Houston Intercontinental Airport, people moving systems were included as part of the original design of the airport. The system at the Dallas-Fort Worth Airport has been designed as a complete intra-airport transportation system. Functions served by this system include carrying passengers, employees, interline baggage and mail, all trash, and commissary supplies (Ref 19).

The capacity of a people moving system is a function of the size of cars used, the length of the routes, the operating velocity, the frequency of stops and the length of the stops, and the minimum headway. The procedure used in a capacity analysis of a people moving system is too lengthy to be presented in this report.

THE FAA METHOD OF CARGO AREA ANALYSIS

In 1960, slightly more than 600 million-ton miles of cargo were flown, and by 1970 almost 5000 million-ton miles of cargo were flown. This is an 850 percent increase in the amount of air cargo flown in ten years. With the introduction of the new wide-bodied jets, this increase should continue. Therefore, the airport analyst or designer needs to give consideration to the cargo capacity of the airport. There are three basic steps in the handling of air cargo at the airport, receiving, processing, and distributing. The receiving and distributing steps can be receiving a shipment for air distribution or the receiving of air cargo for either ground distribution or for transfer to another air carrier. The capacity of the cargo handling subsystem depends upon the layout of the cargo area, the procedures used for handling cargo, and the layout of the airport terminal buildings.

Layout of the Cargo Handling Subsystem

The layout of the cargo terminal is an important factor in determining the capacity of the facility. There are four major functional elements to consider in the design of the cargo terminal, (1) freight handling areas, (2) administration area, (3) personnel and customer accommodations, and (4) service facilities.

For receiving air transportation cargo, there must be a sufficient number of truck bays. To determine the optimum number of bays requires detailed analysis of truck arrival rates during peak hours, service time required at the bay, and an acceptable waiting time for those experiencing delays. The minimum number of bays can be calculated by dividing an average unloading rate of 5000 pounds of cargo per hour per dock into the average of arriving cargo. For example, if 30,000 pounds of cargo arrived per hour, then six bays would be required (Ref 7).

The processing area of the cargo terminal must have sufficient room for receiving, sorting, weighing, labeling and temporary storage of the cargo. The cargo turnover rate, density of the cargo, and characteristics of the cargo all have a profound effect on the type of storage needed as well as the total space required. Figure 4.9 gives FAA suggestions on space requirements for receiving and processing areas.

Adequate administrative space must be provided for the efficient management of cargo operations. Functions of the administrative space include

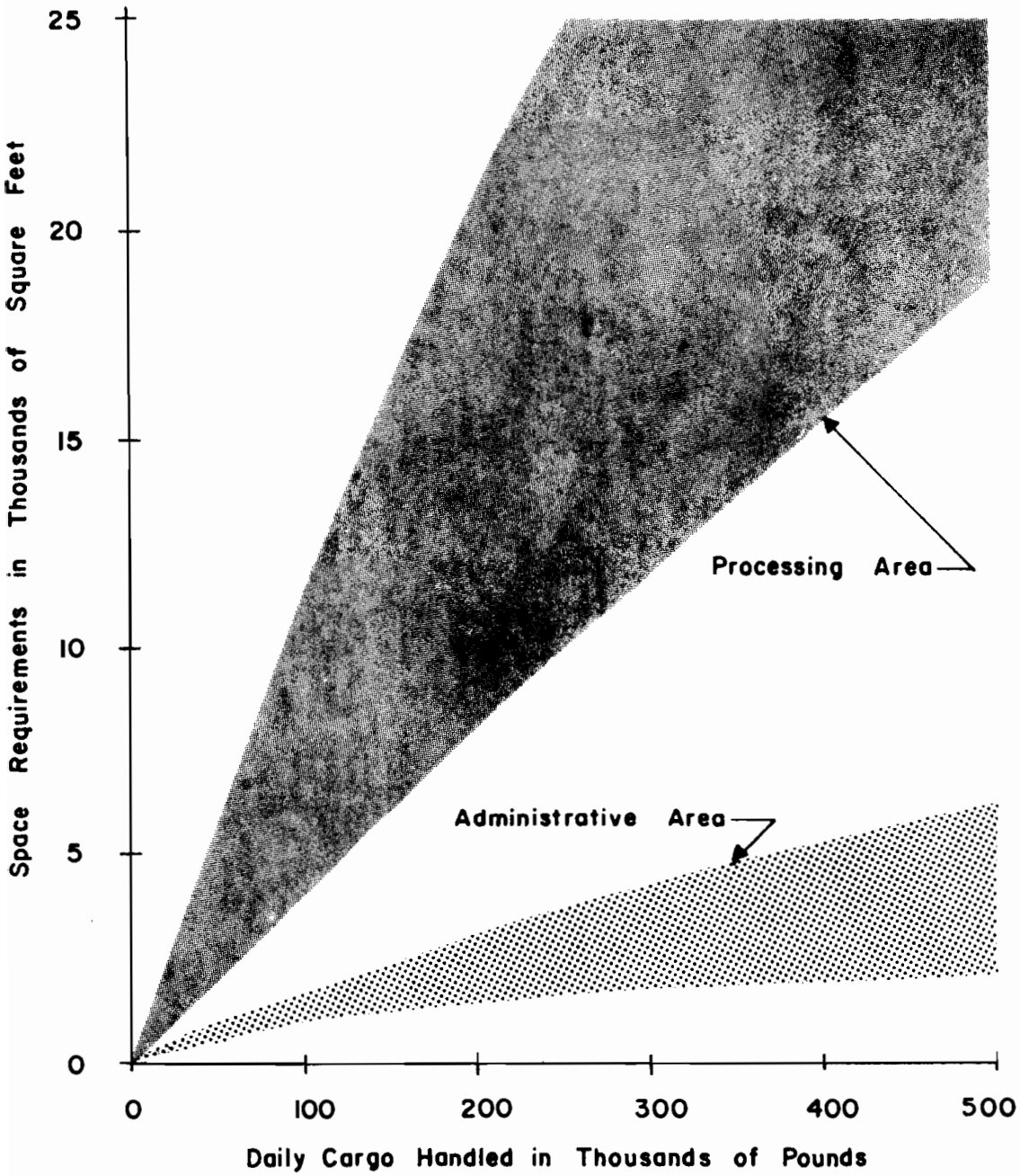


Fig 4.9. FAA cargo building space requirements (Ref 7).

(1) reception area for handling customers, (2) communication center, (3) management and general office space, (4) aircraft space control offices, and (5) sales offices for the cargo-carrying airlines.

Procedures for Cargo Handling

Several procedures can be used for the handling of the cargo. The cargo handling capacity depends directly on how well these procedures function together. For small packages, the most efficient procedure is to consolidate several packages into one unit. This unit can be either a normal pallet or a special "belly" container designed to fit the cargo area of the aircraft.

These consolidated units should then be weighed, and then stored in a manner which facilitates loading onto the aircraft. Methods for the transporting of cargo in the terminal building include handtrucks, forklifts, scissor lifts, overhead hoists, and conveyor lines.

Layout of the Airport Terminal Buildings

The capacity of the cargo handling subsystem is affected by the layout of the terminal buildings because much of the air cargo is carried on regular passenger flights. The means that the cargo must be transferred from the cargo terminal to the passenger gate positions. Therefore, the cargo terminal should be centrally located within the terminal building complex, and vehicles carrying cargo between the cargo terminal and the aircraft should not have to cross active runways or taxiways.

SUMMARY

Little research has been done in the area of terminal building capacity analysis. One indication of this, is the lack of an accepted definition of passenger flows within terminal buildings. Another indication of the lack of research is the great variety in terminal building concepts. If more research were done in the analysis of terminal buildings, then probably the design of terminal buildings would become more standardized.

There are two basic methods available for analyzing passenger flow in the terminal building subsystem. The FAA method relates passenger flows to empirically derived relationships. Horonjeff's method of analysis uses analytical models to relate passenger flows to the variables present at the airport. The

disadvantage of Horonjeff's method is that it has been developed only for flows in departure lounges, baggage flows, and flows within pier fingers.

The size of today's larger terminal building subsystems dictates that some form of intraterminal building transportation be provided. In centralized terminal buildings, moving walkways may be provided. In decentralized terminal buildings, people mover systems need to be provided.

Air cargo is becoming an increasingly important function at the airport. The designer needs to plan cargo facilities to accept these high cargo loads.

CHAPTER 5. THE AIRCRAFT HANDLING SUBSYSTEM

Historically, the capacity of the aircraft handling subsystem of the airport has been considered the capacity of the airport. For this reason, more research has been done on this subsystem than on either the airport terminal building subsystem or the access/egress subsystem. There are three major components of the aircraft handling subsystem, the apron component, the terminal airspace component, and the runway component which includes the gluide slope, the runways, and the taxiways.

This chapter is divided into four sections. The first section is a review of the models which can be used for analyzing the capacity of the aircraft handling subsystem. The term "capacity" will be defined as it applies to the different models in this section. The second section is a detailed presentation of a model which can be implemented into the computer program accompanying this thesis. The third section presents suggestions for modifying and using this model to increase its usefulness as a tool for analyzing runway and apron capacity. The final section reviews the important concepts presented in this chapter.

REVIEW OF EXISTING CAPACITY MODELS

At the present time, there is no model available with the ability to analyze the three components of the aircraft handling subsystem as a unit. The capability of the available models to analyze capacity may be divided into three categories. Some models can handle only the runway component of the aircraft handling subsystem. Other models have the ability to handle the runway and apron components as a unit. Models for analyzing the capacity of the terminal airspace make up the third category.

Models for Analyzing the Runway Component

There are two types of models available for analyzing the runway component of the aircraft handling subsystem. The first model was developed by the Airborne Instruments Laboratory under contract with the FAA. This is an

analytical model based on empirical relationships. The second type of model was developed by the Mitre Corporation. The Mitre model is based on a combination of mathematical and simulation models.

The Airborne Instruments Laboratory Model. Although the Airborne Instruments Laboratory model only analyzes capacity of the runway component, it has become the most widely accepted method for calculating "capacity." This is due to the fact that the Airborne Instruments Laboratory model is in handbook form and it has been available since 1963 (revised in 1969). This handbook is the basis for the FAA advisory circulars for calculating "airport capacity."

The Airborne Instruments Laboratory model defines capacity as the level of aircraft operations where average delay to aircraft reaches a maximum acceptable delay. This definition of capacity is sometimes called the operating capacity.

The Airborne Instruments Laboratory capacity model is based on two mathematical models (Ref 37). A spaced arrival model (SAM) is used to predict departure delay for a specified movement rate. The main elements of the SAM model are:

(1) It assumes random (Poisson) distribution of departures at the "ready to takeoff" point.

(2) It assumes modified Poisson distribution for arrivals at the "commitment" point.

(3) It assumes arrivals have priority over departures and departures are scheduled on a first come first served basis.

(4) Service times are required for the following parameters:

   (a) T: time between two consecutive departures.

   (b) F: time required to release a departure in front of an arrival.

   (c) C: commitment interval for arrivals.

   (d) R: runway occupancy time for arrivals.

The second mathematical model in the Airborne Instruments Laboratory "capacity" model is a first come first served model (FIM). The FIM model predicts either arrival delay for a specified arrival rate or departure delay for a specified departure rate, where departure operations are assumed independent of arrival operations. The main elements of the FIM model are:

(1) It assumes a Poisson distribution for arrivals as they enter the runway gate, or in the case of departures only, it assumes a Poisson distribution at the "ready to takeoff" point.

(2) It assumes that no one aircraft has priority over another aircraft.

(3) It requires the following service times:

(a) A R + C where A equals time between two consecutive arrivals (R and C are defined in the description of the SAM model), or

(b) T: time between two consecutive departures.

These models were computerized and the output from many computer runs were combined in the development of the Airborne Instruments Laboratory handbooks.

The Mitre Model. The Mitre model consists of a family of mathematical and simulation models for the calculation of single runway capacity operating under instrument flight rules. A statistical model is used to calculate the "basic saturation" capacity of the runway for the cases of arrival only, or departure and arrival operations. The basic saturation capacity is defined as the total number of aircraft which can be forced through the system, regardless of delay. The model has been modified to handle the less than saturated demand through the use of a queueing model (Ref 24).

The basic theory used in the Mitre model is that the minimum time separation between aircraft can be calculated based upon the FAA regulations. The capacity of the runway is simply the inverse of the weighted average minimum time separation between aircraft. For example, if the minimum time separation between aircraft is two minutes, then the capacity of the runway would be 60 minutes per hour divided by two minutes per aircraft or 30 aircraft per hour.

Table 5.1 shows the basic factors which the Mitre model uses in analyzing runway capacity. Each element in the table represents a parameter used in the overall calculations of the minimum separation of aircraft.

Models for Analyzing the Runway and Apron Components

Computer simulation models have been developed to analyze runway and apron area capacity. Computer simulation is a technique that provides a means of testing and evaluating a proposed or an existing system, under laboratory conditions. The system's behavior is modeled by a computer program to various operating conditions in a manner similar to the system itself. There are two

TABLE 5.1. FACTORS USED IN THE MITRE MODEL TO DETERMINE AIRCRAFT SPACING (REF 24)

	Region of Control		
	Approach to ILS gate (sequencing/delivery)	Gate to threshold (final)	Runway occupancy (rollout)
Approach geometry and rules	Physical safety Separation of aircraft (altitude and/or distance) Ordering (first-come-first-served or speed-class sequencing)	Common path length Safety separation standard Allowed probability of violation of separation	Single occupancy rule Exit locations and speed limitations
Characteristics of demand	Mix of approach speeds	Precision of aircraft Speed control on approach or Ability to fly a time mark Separation required by wake turbulence	Touchdown speed, braking capacity, and maximum ground/turn rate
Approach control	Precision with which aircraft can be (time) delivered to the gate	Passive controller Monitoring of approach (Blunder detection) or Active monitoring and speed control (feedback)	Controller detection of threshold crossing, touchdown and exiting of aircraft
Environment	Winds aloft Noise abatement Requirements	Wind shear Wake turbulence Dissipation	Runway surface condition

basic types of computer simulation models: real-time and fast-time simulation models.

Real-Time Simulation Models Versus Fast-Time Simulation Models. Real-time simulations operate at the same rate as the actual system. With this type of simulation, the human elements in the system can interact with the program. This type of simulation has the advantage in that actual human decisions and reactions are used in the simulation process. This avoids the problem of estimating the human elements of the system. The disadvantage of real-time models is that they are expensive, lengthy to operate, and require qualified people to operate the human link in the model.

Fast-time models have the advantage of speed of operation. Their disadvantage is that an estimate must be made of the human element in the system. This disadvantage may be overcome when the human elements in the system are governed by a strict set of rules which minimize the variability of individual performance. This situation exists when airports are operating under instrument flight rules (IFR). Therefore, the human element, i.e., pilots and air traffic controllers, can be adequately modeled for use in fast-time computer simulation at airports. Recent studies by the Airborne Instruments Laboratory have shown that most airline operations use IFR, even during visual flight rules weather conditions. Therefore, the assumption of IFR procedures being used at airports appears to be appropriate.

One factor which distinguishes simulation models from the Airborne Instruments Laboratory and the Mitre models is that simulation models require that the schedules of arriving and departing aircraft are inputs to the simulation model. The simulation models use the schedule information to simulate the flow of the aircraft through the runway, taxiway, and apron components. As the flow of the aircraft is simulated, the delay encountered by each aircraft is calculated. By varying the schedule of the aircraft, the analyst can find the flow rate which corresponds to a maximum allowable delay. This flow rate would then be the capacity of the runway and taxiway components.

Overview of Fast-Time Simulation Models. While the different fast-time computer simulation models vary in the exact method they use to handle the various details of aircraft movement, many of the basic assumptions and features of the models are essentially the same. Some of the basic operational parameters which are common to a majority of the models are:

(1) Aircraft performance characteristics are approximated by grouping aircraft with similar approach speeds into a few classes. This greatly reduces the amount of input data required and simplifies the calculations within the program.

(2) Airline scheduling often causes a bunching of departures which causes delays. Airline policy regulates the method of aircraft parking. This can have an effect on the amount of time spent parking and "unparking" the aircraft.

(3) The airport's physical parameters are the basic elements being examined in the model. The important parameters are:

   (a) runway length, number and location of exits, and the type of exits,

   (b) taxiway length, curvature, and number of intersections, and

   (c) apron/gate area aircraft size, type of layout, and the number of gates.

(4) Human factors, such as efficient, intelligible communication and the ability of the local and ground controllers to coordinate the flow of aircraft, are very important in minimizing delay. Therefore, the ability of the controllers to follow FAA regulations in a repeatable manner is one very important assumption made by the simulation models.

(5) FAA regulations for IFR conditions are used in the simulation models to determine the aircraft spacing for landings and departures. For an arrival following an arrival, minimum separation is three nautical miles. If the lead aircraft is slower than the following aircraft, this requirement is assumed to be met at the runway threshold. If the lead aircraft is faster than the following aircraft then the three nautical mile separation must be satisfied at the runway gate. When an arrival precedes a departure, the departure must be released before the arrival is within two nautical miles of the runway threshold. When a departure follows a departure, the amount of separation required depends upon the path of the two departures. (It should be noted that these rules are currently being revised due to the problem of wing tip vortexes.)

These operating procedures are then organized in the simulation models in a manner which allows the program to calculate the delay encountered in the runway, taxiway, and apron components of the aircraft movement subsystem. The output from the different models varies. Some models give only the total amount of delay, while other models give the arrival or departure time of each aircraft and the delay incurred by each aircraft.

Models for Analyzing Terminal Airspace

The terminal airspace is the component of the airport system which connects the enroute airspace to the runway gate. The terminal airspace is

usually defined as the area within a radius of 20 to 50 miles from the airport. There are two jurisdictions within this area, the approach and departure control facility and the control tower. The control tower controls all aircraft within a five-mile radius of the airport.

Aircraft outside of the five-mile radius are under the jurisdiction of the approach/departure facility. The radius of the control area for the approach/departure facility varies between 20 and 50 miles based upon the number of airports in the area, the volume of the traffic, the topography, etc.

Again, as in the case of the ground components of the aircraft handling subsystem, it is useful to define capacity in terms of ultimate capacity and operating capacity. The ultimate capacity of the terminal airspace component during a specified period of time may be defined as the total number of aircraft which can be processed through the component under sustained demand during that period of time. This definition of capacity is often inadequate because typically as the number of aircraft processed builds up, the average delay to aircraft in the component may reach intolerable levels. Therefore, another definition of capacity is needed, which includes a consideration of the amount of average delay. Thus the operating capacity of the terminal airspace component is defined as the number of aircraft which can be handled without exceeding an acceptable amount of average delay to the aircraft in the component.

Factors Affecting Terminal Airspace Capacity. The principal factors affecting the capacity of the terminal airspace component are:

(1) Aircraft performance characteristics such as speed, maneuverability, climb rate, and navigation accuracy all have an effect on the capacity of the terminal airspace. The mix of aircraft with different characteristics affects the way in which aircraft interact and therefore, the capacity is affected.

(2) The size and topography of the airspace available affects the capacity by limiting the number of routes that can be used and by influencing the number and location of potential conflicts.

(3) There are several environmental considerations which affect the capacity due to physical and operational constraints on the component. Weather conditions affect aircraft performance characteristics, thereby affecting the capacity. Wing tip vortexes can become a limiting factor on aircraft separation. Noise considerations can restrict the use of certain routes, restricting the capacity of the system.

(4) The communication and radar used to control and detect aircraft movement influence the speed, accuracy, and reliability when processing flights. Therefore the method and viability of communication can have an important effect on the capacity of the terminal airspace.

(5) The accuracy of the navigation equipment affects the pilot's ability to adhere to designated routes.

(6) The FAA flight rules, based on safety considerations, specify separations which must be maintained between the aircraft. These rules govern the rate at which aircraft can be processed through the available airspace.

(7) The ability of pilots to react to directions from the controllers limits the amount of control work which can be performed during a given period of time.

Of the factors listed above, the two most important and the most variable factors are the ability of the controllers to communicate with the pilots and the ability of the pilots to carry out the commands of the controllers. Therefore, the capacity models available for analyzing the capacity of the terminal airspace component are based on the concept that the controller's ability is the limiting link in the terminal airspace component.

Based on this criteria, two basic approaches have been used to model the terminal airspace component and to analyze capacity. These two methods can be classified as the workload approach and the complexity rating approach.

The Workload Approach to Analyzing Terminal Airspace Capacity. The major assumption of the workload approach is that the workload of the controllers consisting of communications with the pilots and the associated decision making time is the factor which limits the number of aircraft which can be handled during any given period of time. This model is based on observations of air traffic controllers indicating that during a given period of time, there is a maximum total time that a controller can spend on decision making and communication with the pilots. Measured in seconds, this total time is naturally less than 3,600 seconds per hour. In any one control jurisdiction, as the aircraft rate increases, so does the total workload time on the controller. Capacity of a control jurisdiction is defined as the aircraft movement rate corresponding to the maximum controller workload time.

The FAA simulation model is based on the controller workload approach. This model was developed by the FAA's Systems Research and Development Service and its National Aviation Facilities Experimental Station (NAFES). This model was developed by using a real-time simulation of the New York Metropolitan

Area airspace system. Total workloads were computed for various levels of aircraft demand. Also, with the use of the simulation, an assessment was made of the maximum levels of communication workload time that controllers could sustain.

The FAA model is a simple relationship which can give an estimate of the workload time given the number of aircraft and the number of potential conflicts. The equation for the FAA model is:

$$WLT = N\ (K_1) + N\ (K_2) + C\ (K_3)$$

where

WLT = total workload time

N = number of aircraft per hour

C = number of potential conflicts per hour. The value of C is determined from the total demand by considering the physical layout of the airspace and applying a stochastic queueing model.

K_1 = the routine communications workload. Measured in seconds per aircraft. This variable is the workload time spent on routine communications work such as identification, position, speed, and acknowledgement.

K_2 = the non-conflict control and control support communications workload measured in seconds per aircraft. This is the time spent transmitting control commands in non-conflict situations. Usually, this workload time constitutes the major part of the controller's workload.

K_3 = the conflict control workload measured in seconds per conflict. This is the time required to resolve potential conflicts which may arise between aircraft.

The FAA model may also be used in the form,

$$N = \frac{WLT - C\ (K_3)}{K_1 + K_2}$$

in order to calculate capacity. This would require an iterative solution process since C is dependent on N . Typically, the value of WLT will be in the range of 2,160 - 2,880 seconds per hour.

Another model which uses the workload approach for estimating airspace capacity was developed by the Stanford Research Institute (SRI) for the FAA. This model is similar in concept to the FAA model, but has several important differences.

The SRI model estimates the number of "ATC events" associated with a given pattern of traffic. An ATC event is defined as conflicts, handoffs, pilot requests, etc. The estimated number of events was determined using an analytical model of the air traffic operating within a sector of the approach airspace. A minimum decision making time is associated with each type of event. Field observations and interviews with air controllers were used in determining estimates of the decision making time. Only observations of controllers operating at or near capacity were used in making the estimates of the various decision times. Hopefully, this procedure results in minimum decision making times. The observations found decision making times of one minute, six seconds, and five seconds for conflicts, handoffs, and pilot requests respectively for the present ATC system.

The total time required for decision making per hour, based on a given traffic pattern, is then computed from:

$$T_{DM} = \sum_{i=1}^{n} E_i \, T_i$$

where

T_{DM} = total time required for decision making in man-minutes per hour

E_i = expected number of type i events per hour

T_i = decision time in man-minutes required for each type i event.

The capacity estimating procedure used in the SRI model is to plot the total decision making time versus the hourly number of aircraft through the sector. The capacity is then determined graphically by finding the number of aircraft corresponding to the specified upper limit on total decision making time.

The Complexity Rating Approach to Analyzing Terminal Airspace Capacity. The second basic method for analyzing airspace capacity, the complexity rating approach, is similar to the workload approach. The difference is that in the workload approach, the number of aircraft movements is related to the controllers' workload, while in the complexity rating approach, the number of aircraft movements is related to a set of relative numbers called the complexity ratings. These complexity ratings represent the relative complexities of controlling various types of aircraft interactions such as climb, descent, level flight, and crossing paths.

The complexity rating approach has the advantage of considering the pilot workload, the equipment involved, the aircraft capability, and the geometric aspects of the airspace, as well as the controller workload.

A complexity rating approach model called the Transair model was developed by the Airborne Instruments Laboratory (AIL) under an FAA contract. In computing complexity ratings for the different sectors within the terminal airspace, the Transair model uses a set of figures called complexity weighting factors. A complexity weighting factor is assigned to each type of aircraft interaction. The complexity weighting factors represent the relative complexity of different types of controller-initiated aircraft interactions. Table 5.2 summarizes the values of the complexity weighting factors associated with various types of aircraft interactions.

The Transair model uses a steady state stochastic model which computes the number of aircraft interactions, of the various types, based upon a given demand level. The physical layout of the airspace component, the aircraft mix, and the performance characteristics of the various aircraft are inputs used by the stochastic model. Once the complexity weighting factors and the number of interactions are known for each type of interaction, the total complexity rating factor can be determined as follows:

$$CR = \sum_{i=1}^{n} N_i W_i$$

TABLE 5.2. COMPLEXITY WEIGHTING FACTORS USED IN THE COMPLEXITY RATING AIRSPACE MODEL (REF 30)

Aircraft Interaction	Same Path	Different Path
Level/level	1.0	3.0
Level/climb	2.5	3.5
Level/descent	2.5	3.3
Climb/climb	1.1	3.3
Climb/descent	4.0	5.0
Descent/descent	1.1	3.3

where

CR = complexity rating

N_i = number of type i interactions

W_i = weighting factor for the type i interaction.

The absolute value of the complexity rating has little meaning in itself. Therefore, in order to use the complexity rating approach, it was necessary to estimate the maximum complexity rating which a controller could handle. By consulting with controllers in the New York area, it was determined that a complexity rating of about 1,000 corresponded to the maximum rate at which the controllers could process aircraft. Therefore, the capacity of the airspace system is assumed as the flow rate which corresponds to a complexity rating value of 1,000. If the terminal airspace component is large and has heavy flow rates, the component may be broken up into sectors of airspace. In this case, the capacity of each sector is the flow rate which corresponds to a complexity rating of 1,000.

The disadvantage of the complexity rating approach is that the absolute value of the complexity rating has little value except when calibrated within a given system and environment. The capacity of a sector is defined as the amount of aircraft movement which causes a complexity rating corresponding to the controller's own assessment of the largest amount of traffic that he can handle in a particular sector.

This discussion on terminal airspace models is based on class notes from the University of California (Ref 30). Unfortunately, these notes do not contain the exact details of these models.

THE MADDISON MODEL FOR ANALYSIS OF THE AIRFIELD SURFACE SYSTEM

The model that will be discussed in detail at this point is a fast-time computer simulation model developed by Donald Maddison at the Institute of Transportation and Traffic Engineers, University of California at Berkeley (Ref 34). This model was chosen for detailed presentation because it is more flexible than the Airborne Instruments Laboratory handbook method in that exact runway, taxiway, and apron arrangement can be input into the program, rather than trying to fit the airport's arrangement to one of, or a

combination of, the runway layouts reported in the Airborne Instruments Laboratory Handbook. Another advantage of the Maddison Model is detailed information given concerning the points of conflict in the aircraft handling surface subsystem. This information can be of great benefit to an analyst looking for the point in the system where bottlenecks occur.

A disadvantage of the Maddison Model is that while the model was developed as a general purpose program for analyzing any airport configuration, some of the parameters in the program are related specifically to the San Francisco airport which Maddison used in verification of the model. This was done in the development stages in order to cut down on the amount of input required during the development of the model. Since that time the model has been modified to convert these fixed parameters to input parameters, thereby making the model suitable for general application to any airport configuration.

The remainder of this section will contain discussion of the procedure used in the model, input required, output from the model, and validity of the model.

Procedure Used in the Maddison Model

For description purposes, it is convenient to divide Maddison's Model into two stages, data preparation and model operation.

Data Preparation Stage. The purpose of the data preparation stage is to take the input data and convert it into a form which can be handled by the main program. The main task accomplished in this stage is arranging the departure and arrival schedules into time-ordered arrays of departure aircraft and arrival aircraft waiting to enter the taxiway component. An arrival aircraft time-ordered array is calculated by considering the scheduled time of arrival of the aircraft, positive or negative lateness associated with the arrival, approach speed, touchdown distance, deceleration rate, and the operational speed of the taxiway. The results of these calculations are the estimated time of arrival (ETA) at the runway threshold, runway occupancy time, the exit taxiway to be used, and the time of exit from the runway for each aircraft. Because of the priority rules that exist for runway operations, arrival aircraft are processed up to the point of exit from the runway, irrespective of what is happening in the rest of the aircraft handling subsystem. Based on the runway exit selected and the desired terminal gate position, a route through the taxiway component is assigned to each arriving aircraft.

A departure aircraft, time-ordered array is calculated by adding an assigned lateness to the scheduled departure time. The result of these calculations is an estimated time of departure from the terminal gate for each aircraft. A route through the taxiway component is assigned to each departing aircraft, based upon the terminal gate the departure is leaving from and the departure runway in use.

The distributions used in calculating the values of the various parameters used in the data preparation program are summarized here. For a detailed discussion of how these distributions were obtained, the reader is referred to Ref 34. Approach speeds were found to be normally distributed. The mean and standard deviation of the normal distribution depend on the aircraft class as follows:

(1) Class one: Aircraft Approach Speed Normal (135 knts, 5 knts^2)*
(2) Class two: Aircraft Approach Speed Normal (120 knts, 3 knts^2)
(3) Class three: Aircraft Approach Speed Normal (100 knts, 3 knts^2)

Table 5.3 summarizes the types of aircraft in each class.

Touchdown distance (the distance from the runway threshold to the point where the aircraft touches down) is assumed to have a normal distribution with a mean of 1,000 feet and a standard deviation of 300 feet. The deceleration rate of the aircraft is assumed to be normally distributed with a mean of 5.0 feet per second squared and a standard deviation of 0.3 feet per second squared.

The lateness associated with the arrival of aircraft was found to depend upon the length of the flight. It was found that the proportion of short range flights arriving early was significantly less than the proportion of medium or long range flights arriving early. Thus, a separate distribution is used for short range flights. It was found that three-stage linear curves provided the best approximation of the data for both the short range flight data and the medium and long range flight data. The probability that a short range flight will not be more than T minutes late is given by:

---

*The notation X Normal (K, J^2) indicates that X is normally distributed with a mean of K and a standard deviation of J^2 .

TABLE 5.3. CLASSIFICATION OF AIRCRAFT TYPE

Class	Type of Aircraft
1	Boeing 707 and 770 series
	Douglas DC 8 series
	Convair 880 and 890 series
	BAC VC 10
2	Boeing 727 and 737 series
	Douglas DC-9 series
	Lockheed Electra
3	Fairchild F-27

$$P\left\{T_i < T\right\} = F(T)$$

where:

$$F(T) = \begin{cases} (0.0650T + 0.325, & -5.0 \leqq T \leqq 6.5) \\ (0.0089T + 0.685, & 6.5 < T < 30.0) \\ (0.0007T + 0.937, & 30.0 < T \leqq 90.0) \end{cases}$$

The probability that a medium or long range flight will not be more than T minutes late is given by:

$$F(T) = \begin{cases} (0.0288T + 0.375, & -13.0 \leqq T \leqq 13.0) \\ (0.0083T + 0.639, & 13.0 < T \leqq 30.0) \\ (0.0013T + 0.850, & 30.0 < T \leqq 120.0) \end{cases}$$

For departures, there was no significant difference between the lateness associated with short, medium, and long range flights. A modified log-normal curve was found to best fit the lateness data for departure aircraft. The probability that a departure aircraft will be more than T minutes late is given by:

$$F(T) = \Phi\left[\frac{\log(T) - 1.0}{1.5}\right]$$

where:

$$T = e^x$$

and the values of x are randomly generated from a normal distribution with a mean of 1. and a standard deviation of 1.5 .

Once these parameters have been used in preparing the time-ordered arrays, the data preparation stage of the model is considered complete. Now the operational stage of the model is used to analyze delays encountered by aircraft in the taxiway and apron components.

Model Operation Stage. This part of the model essentially processes each time-ordered aircraft individually, depending on the type of event that is about to occur. At the same time, it takes into consideration the effects of processing on other aircraft.

The aircraft handling subsystem is modeled for use in Maddison's Model as a system of nodes connected by links. Figure 5.1 is an example of the node and link systems used to model the San Francisco airport. In order to simplify the model, terminal gates are modeled as gate sinks. For example, all of the gates along one pier finger of a terminal building would be grouped into one gate sink.

The model simulates flow through the system by moving each aircraft from node to node. As each aircraft moves through the system, its ETA at the next node is calculated and this time is entered into a master time array. This array keeps track of the times associated with aircraft movement and is time ordered. Once an ETA is entered into the master time array, a check is made to find the next event which needs to be considered. Once the next event is identified, the type of event and characteristics of the aircraft are determined. The aircraft characteristics determined are the aircraft's identification number, its route through the network, its present position in the network, and the ETA of the aircraft at the next node.

The final event of interest will be either an arrival exiting the runway or a departure leaving the gate. Once the flow has begun, the events may be any one of the following types:

(1) aircraft exiting the runway,

(2) aircraft leaving the gate,

(3) aircraft arriving at the gate,

(4) aircraft occupying the runway for takeoff, and

(5) aircraft moving from one node to another - this can involve the possibility of a conflict if an intersection is involved.

In order to illustrate how the main program works, an aircraft movement will be traced from the time of arrival until the time of departure. The main program receives the first exit taxiway that an arrival could use, the ETA of the aircraft at that exit, and the aircraft's route through the system from the data preparation program. A check is made at the exit taxiway to establish whether the exit is available for use or if the arriving aircraft must use another exit. If the exit taxiway is available, the aircraft exits and the ETA at the next node is calculated. If the exit is unavailable, the aircraft continues down the runway to the next free exit. A new route is assigned to the aircraft and the ETA at the next node is calculated. At this point, the main program would move to the next event of interest. For this example,

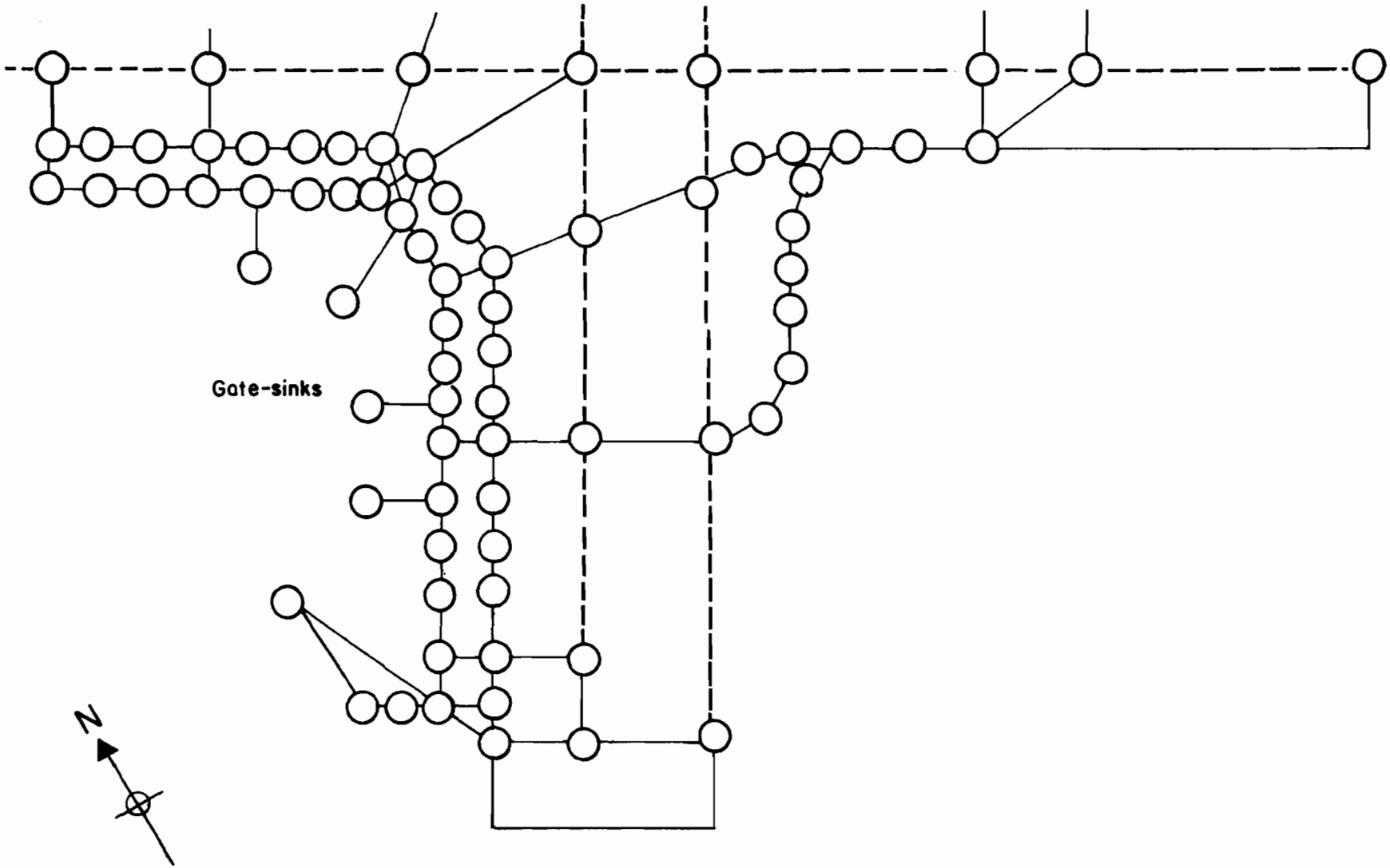


Fig 5.1. Node and link system used at the San Francisco International Airport (Ref 34).

the next event would be the aircraft moving from one node to another. A check is made to determine if the next node is vacant. If the next node is blocked, the aircraft will be delayed until the node is vacant. When the node is vacant, the aircraft's ETA at the node is calculated. If the node involves an intersection, a check is made for possible conflicts. Priority at the intersection is handled on a first come first served basis. Therefore, once an aircraft has established priority, a check is made to see if this causes delay to any other aircraft. If other aircraft are delayed, then a new ETA is calculated for the delayed aircraft and the amount of delay incurred is assigned to the delayed aircraft.

Once an aircraft has travelled through the taxiways, the next event is the aircraft entering the apron and gate area. Once the aircraft is assigned a gate sink area, a time is assigned for the aircraft to maneuver into position. At this point details of the aircraft's movement through the system are printed out.

The next event which will occur in this simplified example is the departure of the aircraft from the gates. It is assumed in this model that arriving and departing flights using the same aircraft can be handled independently. This assumption is invalid only when an arrival is so late that the schedule cannot absorb the lateness.

For departure aircraft, the main program receives the estimated time of departure from the gate and the route through the taxiway system. When an aircraft is ready to depart, the apron area is checked for clearance. If the apron is clear, the aircraft is allowed to proceed from the gate and to taxi to the next node. If the apron is blocked, the departure is held until the apron is cleared. Any delay the aircraft experiences while waiting for the apron to clear is recorded.

While the departure aircraft is on the taxiway it is handled in the same manner as arrival aircraft. The next event for the departure aircraft will be entering the departure queue. Depending on the departure runway to be used and the number of aircraft in the departure queue, the aircraft's ETA at the end of the queue is calculated. The aircraft is then moved up to the runway as the preceding aircraft in the queue take off. The next event is the aircraft occupying the runway for takeoff. Before the aircraft is allowed to depart, the FAA separation rules stated on page 66 must be satisfied. When an aircraft is delayed while waiting for takeoff, all of the aircraft in the

departure queue are assigned this delay. Once the aircraft is given clearance for takeoff, all of the aircraft in the departure queue are moved up simultaneously. At this time, the details of the departure aircraft's movements are printed out.

The model is allowed to run until a specified cutoff time is reached. When the cutoff time is reached a summary of all aircraft processed and their characteristics is printed out.

The parameters used by the main program are the taxiing speed of the aircraft, the maneuvering time into the gate positions, and the distance between the nodes. The methods for assigning values to these parameters are summarized here. For a more detailed explanation the reader is referred to Ref 34.

The separation between two aircraft taking off from the same runway was assumed to be one and a half minutes. The amount of time required for an aircraft to clear an intersection was assumed to be 20 seconds. Aircraft taxiing velocity was found to increase as the length of the aircraft's route through the taxiway network increases. This model assigns an average taxiing velocity for each taxiway section, based upon the section's location within the airport. Figure 5.2 shows the curve used to assign taxiing velocities for various sections. For taxiways next to the apron area, taxiing velocity is assumed to be 15 miles per hour. Average velocities are used in the program to account for the acceleration and deceleration of the aircraft.

Aircraft maneuvering times for arrival aircraft are measured from the time the nose wheel crosses the edge of the apron area until the aircraft comes to a complete stop at the gate position. Departure maneuvering times are measured from the time the departure aircraft starts movement until the nose wheel of the aircraft crosses the edge of the taxiway adjacent to the apron. Table 5.4 gives maneuvering times used in analyzing the San Francisco airport. Because of the many types of gate arrangements used, it is necessary to determine these values for the individual airport being studied.

Maddison recommends that in constructing the node-link network for the airport, the links should be approximately 300 feet long. This length allows one aircraft per link with a buffer length of approximately one aircraft length between aircraft.

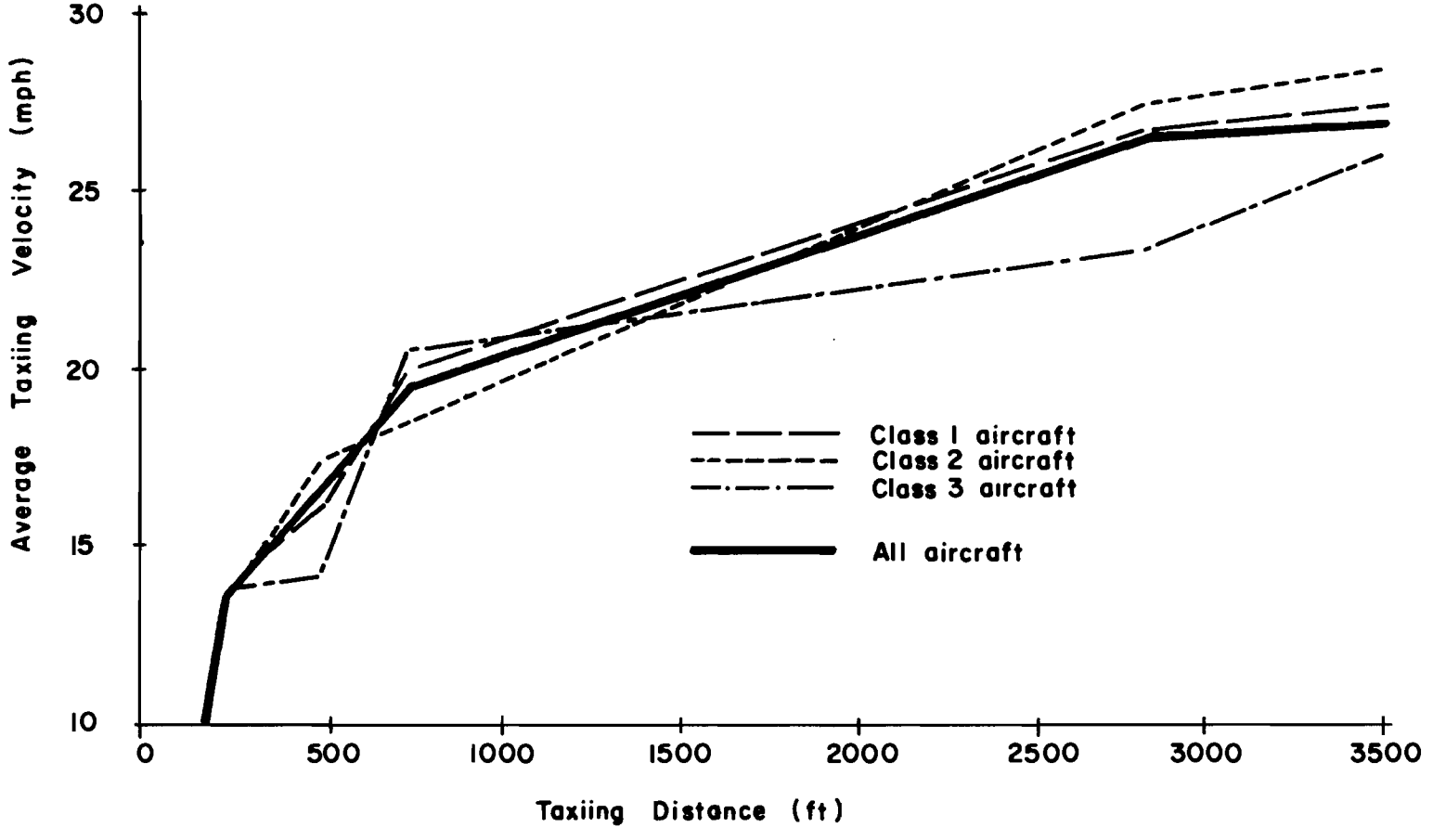


Fig 5.2. Variation of taxiing velocity with taxiing distance.

TABLE 5.4. AIRCRAFT SERVICE TIME IN THE APRON/GATE AREA (REF 34)

Airline	Service Time (Minutes)	
	Arrival	Departure
Air California	0.8	0.8
Air West	0.7	0.6
American	1.0	2.5
BOAC	1.4	3.5
Continental	0.5	2.5
Delta	0.8	2.5
JAL	1.4	3.5
National	0.8	2.5
PSA	0.8	0.8
PAN-AM	1.4	3.5
TWA	1.1	0.8
United	1.2	0.8
Western	0.9	3.0

Inputs for the Maddison Model

Because of the great variation which exists in the layout of terminal buildings, taxiway networks, and runways, Maddison's Model requires a great deal of input data. The input data that are required are as follows:

(1) description of the taxiway and runway network in terms of nodes and links. Each link is described by two nodes.

(2) travel time associated with each taxiway link, to the nearest 0.1 minute.

(3) distance from runway thresholds to each exit taxiway, to the nearest 50 feet.

(4) taxiway operating speeds, to the nearest five miles per hour.

(5) airline gate locations.

(6) aircraft routings between the runways and the terminal gates.

(7) apron area maneuvering times for departures and arrivals for each airline using the facility, to the nearest 0.1 minute.

(8) schedule of departure and arrival aircraft, including times, aircraft type, airline involved, and the origin or destination of the flight.

Output From Maddison's Model

The output from the Maddison Model is divided into information about arrival aircraft and information about departure aircraft. For arrival aircraft model outputs are:

(1) time of arrival at the runway threshold,

(2) time of exit from the runway,

(3) exit taxiway used,

(4) time of arrival at the gate,

(5) total time in the taxiway network,

(6) delay experienced while in the aircraft handling subsystem, and

(7) number of conflicts* with other aircraft.

Output for departing aircraft includes:

(1) time of departure from terminal gate,

(2) time of entering the departure queue and the number of aircraft in the queue,

---

*A conflict occurs when an aircraft must adjust its velocity when approaching an intersection because another aircraft has priority at the intersection.

(3) time of clearance for takeoff,

(4) total time in departure queue,

(5) total time in taxiway network,

(6) total delay,

(7) number of conflicts, and

(8) departure runway used.

In addition to these outputs, the model determines the delay distributed at each node in the network.

Verification of Maddison's Model

Validation tests performed by Maddison in the development of the model showed good correlation between observed values and values predicted by the model. Tests were performed on individual system components and on the total system. The individual system components tested were aircraft departure rates, departure queue lengths, times in departure queue of individual aircraft, and exit taxiway usage. Tests made on the total system were total time the aircraft spent on the ground and the average delay to the aircraft.

These tests showed that the weakest part of the model was in its ability to predict delays in the apron/gate area. This is probably due to the grouping of the gates into gate sinks. Maddison recommends refining this portion of the model if a detailed analysis of the apron/gate area is required.

SUGGESTIONS FOR THE IMPLEMENTATION OF THE MADDISON MODEL

The detailed discussion of the Maddison model presented in the previous section has little practical value unless the model can be used by airport analysts or designers. Assuming the model is valid, three questions need to be answered before a designer or analyst can use the model. Can the model be used to analyze any airport configuration? Can the user of the model obtain necessary input data? Finally, how is the output from the model useful?

Required Modifications to Maddison's Program

Although the Maddison model was developed for general use, the computer program written to verify the concepts of the model was written specifically for the San Francisco airport. Therefore, more work is needed in developing the computer program in order to make the program general. Conceptual methods for making required modifications are presented in this section.

Modifications of Input Data. Since the program was developed specifically for the San Francisco airport, most of the details required for describing the airport's physical layout are contained within the program. Therefore, the first modification which needs to be made is to remove these physical parameters from the program and devise a method of making them part of the input data. This would substantially increase the amount of input data required. In order to reduce the task of inputing this data each time the program is run for the same airport, a system should be devised to save input data from a previous run.

In order to simplify the task of laying out a node and link system, a method should be devised to allow the user to describe the airport in terms of X and Y coordinates of a right angle grid layout. By using this method to describe the airport, the only input required would be as follows:

(1) the coordinates of the ends of the runway(s),

(2) the coordinates of the exit taxiways,

(3) the coordinates of the tangent sections of the taxiways,

(4) the degree of curvature (or radius) and end points of any curves in the taxiway network,

(5) coordinates describing the apron area, and

(6) the coordinates of the various gate sinks, along with a description of the airlines which are assigned to the various gates.

A subroutine could be written which could take this data and calculate the following:

(1) distance from runway threshold to the exit taxiways,

(2) length of taxiways,

(3) node points separated by approximately 300 feet spacing,

(4) points where taxiways intersect with other taxiways, runways, and aprons,

(5) shortest path routes between the runways and terminal buildings, and

(6) taxiing velocities of aircraft on the various taxiway links.

The output from this subroutine could be saved for future runs on the same airport layout.

Modifications in Operation of the Main Program. Again the changes required are a result of the program having been written for a specific airport rather than any flaw in the logic of the simulation process. The majority of the changes required are simply a matter of changing certain "multi-numbered" to dimensioned variables. For example, the "multi-numbered" variables EXLOC5, EXLOC6, EXLOC7, and EXLOC8 are used to designate the distance from runway 28C's threshold to the four exits. In order to make the program general, these variables would need to be changed to EXLOC (I,J) , where I designates the number of the runway this variable is associated with and J designates the number of the exit. The majority of the remaining changes required are related to implementing the newly-dimensioned variables into the main program.

Updating Maddison's Model. Table 5.3 shows the aircraft used in formulating Maddison's model. It is obvious that several important aircraft such as the Boeing 747, the Douglas DC 10 and the Tristar 1011 were not included. Therefore the model needs to be updated to take these aircraft into consideration.

Methods for Determining Input Values

Since it is not the purpose of this paper to present a method of designing an airport, it will be assumed that the basic physical layout of the system has been determined and the analyst is interested in answering the question, "Is the system adequate?" The corresponding question, "Where does the system need improvement?", will be discussed later in this chapter.

Estimating the Operational Parameters. Assuming that the basic physical layout of the runway, taxiway, apron, and gate networks has been determined fixes the parameters associated with the physical layout. However, the analyst must still determine several parameters associated with the physical layout. These factors are:

(1) the amount of separation between two arrivals, arrival and departure, and two departures;

(2) the distance from the runway threshold to the point where the aircraft touches down;

(3) the deceleration rate of the aircraft on the runway;

(4) the operational speeds on the exit taxiways;

(5) taxiing velocities; and

(6) maneuvering time for aircraft entering and departing the gate positions.

A sensitivity analysis needs to be performed to determine the degree of accuracy required for each of these variables. Basic intuition indicates that the separation between aircraft landing and taking off would probably be the most significant factor. Probably the second most important factor would be runway occupancy time. These two factors combined with the airport schedule have the greatest influence on the departue queue length and the arrival stacks which are usually the points of greatest delay in the aircraft handling subsystem.

Fortunately, a considerable amount of work has been carried out in determining runway occupancy times and FAA regulations specify the minimum separation between aircraft. Therefore, the estimates presented earlier in this chapter are probably adequate. A reasonable estimate of the exit taxiway operating speed can be made based on the design speed of exit taxiways. Airline policy, usually, regulates the maximum taxiing speeds that the aircraft will use for any given section of taxiway.

The remaining variable which needs to be quantified is the maneuvering times of the aircraft arriving at and departing from the terminal gates. Due to the lack of information about this variable and the fact that it depends upon the layout of the apron/gate area and the type of aircraft parking at each airport, the airport analyst needs to determine values for this variable for the specific airport being analyzed. When an existing facility is being analyzed, values of the maneuvering times can be measured using the procedure described on page 81.

When a new facility is being designed, the analyst should measure maneuvering times at airports with similar airline mixtures, aircraft mixtures, and apron/gate layouts in order to get a reasonable value for this parameter. Using these procedures, the analyst should be able to determine reasonable values for all of the operational parameters.

Estimating the Scheduling Parameters. Maddison's Model requires information about the traffic at the airport as input data. The following data are required for each aircraft using the airport:

(1) schedule time of arrival and departure,

(2) origin or destination,

(3) type of aircraft, and

(4) name of airline.

The accuracy to which these variables need be determined depends upon the analytical situation. If the purpose of the analysis is to find the reasons for delay at an existing airport, then obviously there is no problem in obtaining this information. If an airport is being designed for an area which has a minimal amount of passenger service, then it is doubtful that a detailed capacity analysis is worthwhile.

The situation which requires the greatest effort in obtaining accurate estimates of the scheduling parameters is the case where an existing airport has reached capacity and the facility must either be expanded or replaced by a new facility. In this situation, it should be possible to make estimates to the desired degree of accuracy required. An analyst should keep in mind how the parameters are used in the model.

The schedule times of arrivals and departures are used to "load" the system. In a detailed analysis, the analyst should input several different schedules to find the delays caused by different flow rates.

The origin and destination information is used in assigning lateness to each flight. This is done on the basis of the length of flight; therefore, all the analyst really needs to be concerned with is estimating the ratio of short flights versus medium and long range flights.

The type of aircraft is important in determining runway occupancy time and separation between two successive arrivals; see page 75. Therefore, this is an important factor and should be determined carefully. In estimating this parameter, data on airline aircraft purchasing trends should be correlated with historical data about airlines and aircraft serving the area at the time of the analysis.

Due to the policy at U.S. airports of assigning each airline a set of gates, it is necessary to know the airline associated with each flight in order to assign a route and gate-sink to the flight. An estimate of the percentage of flights associated with each airline should be sufficient.

The airline information is also used in determining the aircraft maneuvering time in the apron/gate area (Table 5.4). In the case where the airline associated with each flight cannot be estimated a constant value will

have to be assigned to these flights for the maneuvering time variable. This will probably give acceptable results since this parameter has little effect on the delay experienced by the aircraft.

Using these concepts, the analyst should be able to estimate the scheduling parameters to a degree of accuracy consistent with the accuracy of the model.

Using the Maddison Model

Maddison's Model has great potential as a tool for analyzing the runway, taxiway, and apron/gate components of the aircraft handling subsystem. The delay information the model prints out can be used to find the weakest points in the subsystem. Capacity can be determined through proper interpretation of the delay and flow rate data.

Using the Maddison Model for System Analysis. The Maddison Model can be used for analyzing points of conflict in the runway, taxiway, and apron/gate networks. One method of performing an analysis of the network is to input aircraft flow rates which cause excessive delay in the system. By analyzing the delay data at the nodes, one can determine the location of the weakest point in the network. Table 5.5 summarizes where bottlenecks occur and corrective measures for reducing delays. Once the weakest point in the system has been located, several types of corrective measures should be tested in the model to find the most beneficial measure. This process can be repeated until the required flow rate can be handled with an acceptable amount of delay.

Using the Maddison Model for Capacity Analysis. The Maddison Model can be used for capacity analysis by using the Airborne Instruments Laboratory definition of capacity as the flow rate which corresponds to some maximum amount of delay. In order to do this, several different flow rates would be tested in the model to find the corresponding delays. This information would then be graphed (Fig 5.3) with the flow rate as the abscissa and average delay as the ordinate. As can be seen from this graph, there is a point where the flow rate is not greatly increased with an increase in delay. At this point, it becomes impractical to allow the delay to increase any further. Therefore, the capacity would be the flow rate corresponding to this amount of average delay.

TABLE 5.5. METHODS OF REDUCING DELAY IN THE AIRCRAFT HANDLING SUBSYSTEM

Source of Bottleneck	Corrective Measures
Delay in apron area	Change departure schedule
	Alter aircraft mix in the congested area
	Alter aircraft maneuvering procedures
	Expand apron area
	Change gate assignment procedures
Delay at intersections	Build parallel taxiways
	Build waiting pads so that aircraft waiting to use one route can get clear of aircraft wanting to use another route
	Examine routing procedures for possible changes to reduce delays
Delay in departure	Build another runway
	Upgrade existing runway exits through the use of high-speed exits
	At multi-runway airports, use separate departure and arrival runways

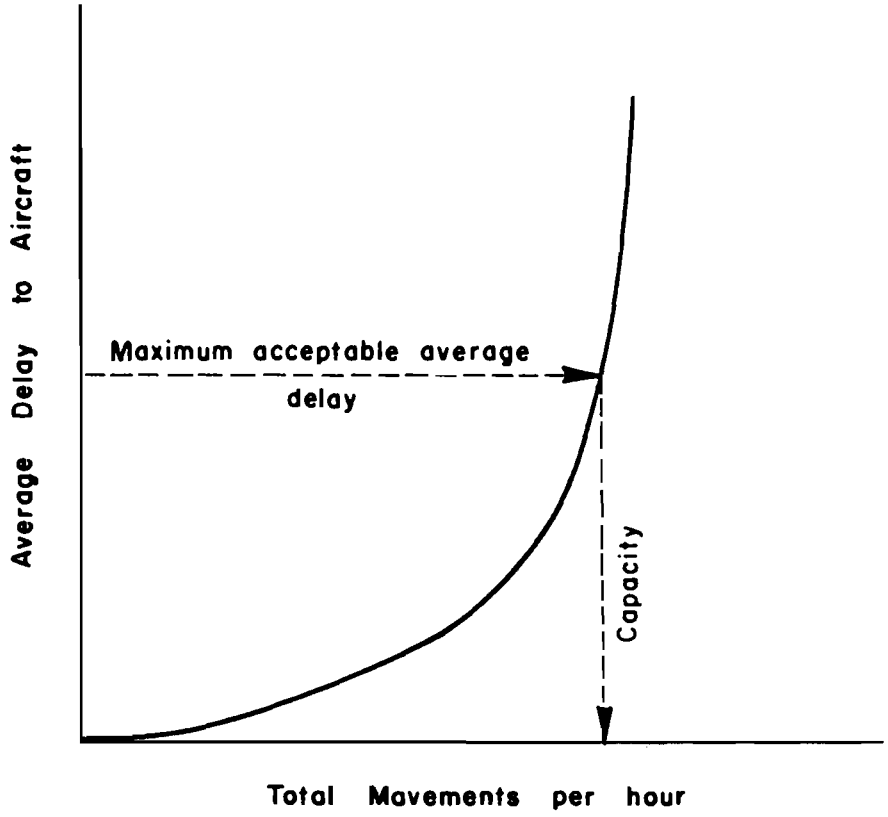


Fig 5.3. Typical average delay curve.

SUMMARY

The first section of this chapter presents the various techniques for analyzing components of the aircraft handling subsystem. Since there are no models available for analyzing the complete subsystem, it was necessary to review models which analyze the various components of the subsystem.

Two types of models are presented for analyzing the air component of the subsystem. In both of these models controller workload is used as the capacity limiting criteria.

Three types of models are presented for determining the capacity of the ground component of the subsystem. The Airborne Instruments Laboratory model is based on analytical procedures to determine the runway capacity. This model is available in handbook form and is the most widely used model for analyzing runway capacity. The Mitre model is based on a combination of analytical and simulation methods. The Maddison Model is a simulation model which can be used to analyze the runway, taxiway, and apron/gate components.

CHAPTER 6. MODAL INTERFACES WITHIN THE AIRPORT SYSTEM

As stated in the introduction, this report is concerned with a systematic approach to designing or analyzing airports. The chapters up to this point have been concerned with methods of analyzing the individual subsystems of the airport system. In these chapters, flow has been defined in terms of the mode of transportation used in the subsystem. In Chapter 3 on access/egress, flow was defined in terms of private automobiles, buses, and limousines. The chapter on the terminal building subsystems, defined flow in terms of passengers. The chapter on the aircraft handling subsystem defined flow in terms of aircraft. In order to perform a systems analysis of airport capacity, a method must be devised for comparing the flow rates of the various subsystems. The degree of accuracy of the conversion factors could be used in estimating the number of passengers per car or the number of passengers per plane.

A reasonable estimate of the passenger-load factor would be in the range of 45 to 50 percent. A reasonable estimate of the cargo-load factor would be in the range of 35 to 45 percent. These load factors could be combined with a "weighted" average aircraft capacity to determine the number of aircraft necessary for handling the passenger and cargo flow rates at the airport (Ref 8).

Load factors for the ground/terminal interface are more difficult to analyze because, as shown in Chapter 3, there is a great deal of variation in the ratio of passengers to cars. This factor needs to be estimated for the particular situation existing at the airport.

After the passenger-car ratio has been determined, it is necessary to analyze the duration of parking. This involves studying the distributions of passenger parking duration in each type of parking lot, the distribution of parking duration for visitors who drop-off or pick-up passengers, and the distribution of passengers who use public transit. Because these distributions almost certainly vary at each airport, no "average" values are presented in this report.

The ground/terminal interface for cargo is a simpler problem than the passenger ground/terminal interface. This interface consists of providing an adequate number of truck bays to handle peak-hour flows and a minimum amount of parking to handle trucks waiting for unloading. Procedures for estimating the number of truck bays required were discussed in Chapter 4.

In a detailed systems analysis of an airport, one must obtain an accurate analysis of the modal interfaces. One method of performing a detailed analysis of the interfaces is through the use of computer simulation. This method of analysis was performed on the proposed design of the Dallas-Fort Worth Regional Airport by the architectural firm, Hellmath, O'Bata, and Kassabaum - Brodsky, Hopf and Adler. The remainder of this chapter will discuss the procedure used in this analysis as an example of applying computer simulation. For the remainder of this report, the simulation program of the Dallas-Fort Worth Airport terminal buildings will be referred to as DFWSP.

Simulation of modal interfaces requires a great amount of input data. Table 6.1 summarizes the data which are used in the DFWSP. Each of these data is described by a probability function. The program assigns values to variables according to these probability functions. For example, the number of passengers on an aircraft is assigned according to the load-factor probability distribution function. This function breaks down the total number of passengers according to passengers remaining on board, transfer passengers, and terminating passengers. This step gives the number of passengers who will be transferring from one flight to another, and the number of passengers who will be using the terminal/ground interface. A visitor-expansion factor is assigned to each of the terminating passengers. This step assigns from zero to five visitors to each of the terminating passengers. To simulate the arrival of the visitors, the visitor-lead-time distribution is used.

At this point the passenger is ready to use the ground/terminal interface. The mode of egress assigned is dependent upon the distribution of egress modes, the visitor-expansion factor, the passenger-expansion factor (the number of passengers using the same egress vehicle), the "land-use factor," (land user assignments are places of employment, residence, hotel, and other), and the length of flight. If the mode of access assigned is private automobile, parking-distribution functions are used to assign a parking lot to the passenger and visitors. The parking lot assignment is dependent upon the length of flight, the number of bags the passenger has, and the visitor-expansion factor.

TABLE 6.1. INPUT DATA REQUIRED FOR INTERFACE SIMULATION

<u>Airline Data</u>
Route structure and market share
Distribution of arrivals and departures by hour of day
Distribution of scheduled arrivals and departures within hourly scheduled ground time
Aircraft type
Load factors (type of passenger and total passengers)
Distribution of actual arrivals and departures
<u>Passenger Data</u>
Land use of trip origin and destination
Mode of access/egress
Passenger lead time by mode
Passenger expansion factors (by mode)
Visitor expansion factor
Number of check-in bags per passenger
Primary parking decision
Secondary parking decision
Visitor lead time
Passenger behavior pattern
Curb usage
Transit passengers

This simple example of an arriving flight has been used to show the basic decision process used for simulating interfaces. Similar processes are used in the simulation of departing passengers and transfer passengers. By using this type of simulation procedure, accurate estimates of the methods of access used, the number of visitors, and the number of passengers on each plane can be made. Similar analysis could be made for determining the cargo interfaces. This information allows the airport analyst to determine if the access/egress, terminal building, and aircraft handling subsystems of the airport are in the proper proportions, which is the goal of the systems analysis proposed in this report.

CHAPTER 7. NOISE CAPACITY OF AIRPORTS

One of the newest constraints to an airport's capacity is the noise problem. This problem started when the first commercial jets were introduced, and has increased in magnitude along with the increase in jet traffic. The noise created at airports is unlike most other generators of noise, in that an airport's noise is not confied to the airport site. The noise is widely distributed to the surrounding community, especially those areas which are under the approach and climb-out corridors.

Airport noise becomes a constraint to capacity when the population of the community surrounding the airport becomes sufficiently irritated that they take action to reduce the amount of noise coming from the airport. There are three basic methods for reducing the amount of airport noise in the surrounding community. First is to reduce the quantity of noise that each aircraft produces. Second is through the use of zoning and land use planning. The third method is to change the aircraft operating procedures.

Reduction of the noise produced by modern jets will be realized as the new breed to quieter jets enters the inventory of the airlines. This trend has already started as the new wide-bodied jets are approximately 10 EPNDB* quieter than the earlier 707's and DC-8's. Presently, the feasibility to retrofit current aircraft with sound reduction devices is being debated. Therefore, the current problem of noisy jets will probably continue until these aircraft are retired from service. This means that the other ways of reducing the airport noise problem must be implemented where noise problems currently exist.

The second method of noise control is to actually control the land uses surrounding the airport. This method achieves its greatest advantage when it is implemented in the early planning stages of an airport. With proper planning, land use control prior to construction of the airport is a very

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*Effective Perceived Noise Decibels = Perceived Noise Decibels corrected for tone and duration of the noise.

effective way of controlling the noise situation before it becomes a problem. This has been done for the new Dallas/Fort Worth airport. This method has drawbacks in that it usually must be executed on an interregional level and it is costly. If this method has to be used after the airport becomes operational, then it becomes extremely costly. This is because the community surrounding the airport usually develops very rapidly. Zoning becomes unacceptable because the nature of the community is established. Land values escalate, making land purchases extremely expensive. For example, recently the Los Angeles Airport had to purchase 200 acres in order to alleviate its noise problem. The cost of these 200 acres was approximately equal to the cost of the entire 17,500 acres for the Dallas/Fort Worth site. Due to the high cost of the land control method of noise control, it is desirable to investigate the third method of noise control, changing the aircraft operational procedures of the airport.

There are three changes to operational procedures which can be made in order to alleviate a noise problem. First, the flight path can be changed in the plan view, i.e., making curved landing approaches and take-off climbouts as opposed to straight patterns. This has a drawback in that it merely shifts the noise corridor, it does not eliminate any noise. If the noise corridor is moved from one community to another community with similar characteristics, then no benefit will result.

The second change which can be made to operational characteristics to reduce a noise problem is to alter the flight profile. Making steeper approaches and climbouts and leveling off the profile while over a community where noise is a problem are some of the techniques which may be used to reduce noise problems. Care must be taken, when recommending these changes, that safety is not jeopardized. For example, the FAA is currently recommending a two-segment* approach at some airports to reduce noise problems. Pilots are against this because the operational characteristics of some jet engines do not give an immediate response when the throttles are applied.

The third operational procedure which can be changed is to reduce the number of operations, especially night operations. For obvious reasons, this is a highly undesirable and expensive method to use. However, some airports

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*A two-segment approach entails a steep initial slope, then a reduction in slope when close to the ground.

have found it necessary to resort to this technique. For example, National Airport in Washington, D.C. has found it necessary to completely eliminate night operation in order to alleviate the noise problem.

METHODS FOR ESTIMATING AIRPORT NOISE WHEN PLANNING

There are currently two techniques for estimating the effect of airport noise on the surrounding community. The first is the Composite Noise Rating (CNR). This method was originally developed in 1952 and has been subsequently refined to include changes in noise response data. The Noise Exposure Forecast (NEF) is a more refined version of the CNR method. Neither of these methods has been officially adopted by the FAA or DOT; however, they are widely used in the planning process and have been adopted by HUD for assessing financing in high noise areas. It needs to be emphasized that these methods are approximations and can only be used as guidelines. They cannot be used for law enforcement and they do not define what is tolerable or intolerable.

These methods are designed to enable the planner to plot noise contours and provide guidelines for interpreting the meanings of these contours. The CNR method has been put in a handbook which the planner may use directly (Ref 31). The NEF method can only be solved by a computer program. The FAA through its Regional Airport Division will make available, on a selected basis, computer processing of input data submitted by the organization requesting the contours (Ref 3).

METHOD FOR ESTIMATING EFFECTS OF VARYING OPERATING PROCEDURES

A computer program has been written based on the CNR method which enables an airport operator to estimate the effects of varying the various operational procedures which were discussed earlier. This program will provide the airport operators with a useful tool for evaluating community complaints and determining what changes can be made to alleviate them. For the remainder of this report, this new method will be referred to as the CNR-1.

The inputs for the CNR-1 method are:

(1) the desired CNR for the location studied, based on the CNR's given in Table 7.1;

(2) the coordinate in feet, of the area under study, where x equals the distance along the extended runway centerline and y equals the perpendicular distance from the extended runway centerline, to the area;

(3) the percentage of aircraft (of the type being studied) using the runway being studied;

(4) the take-off roll*;

(5) climbout rate or approach slope;

(6) flight deviation from a straight-in or straight-out flight path; this is input as the distance, in feet, perpendicular to the centerline when the flight is at the x distance (along the centerline) from the runway threshold;

(7) length of flight, less than or greater than 2000 miles;

(8) type of aircraft, either turbofan or turbojet;

(9) maneuver being executed, either takeoff or landing; and

(10) time of operation, either night (2200-0700) or day (0700-2200).

It is not necessary to determine the input values to great accuracy, since the CNR-1 method can only be used as a guideline for estimating community response.

The coordinates may be scaled from a map of the area. The percentage of aircraft utilizing the runway need only be within the values given in Table 7.2. The average values assumed by the program for the take-off roll, will usually be accurate enough. Flight deviation from centerline can be scaled from a map after the revised flight plan is traced onto it. The most critical input is the slope of the approach or climbout. For the approach slope, the computer will assume a value of 0.05 ; this value has a normal range of 0.044 to 0.078 . This corresponds to approach angles of 2 1/2 degrees to 4 1/2 degrees respectively. For the climbout slope, the computer will assume an average value 0.085 for flights longer than 2,000 miles, and 0.150 for flights less than 2,000 miles.

The output of CNR-1 is "excess number of PNdB." This value is equal to the number of CNR input minus the number of PNdB calculated by the program. This value was chosen because it is equivalent to the amount of correction which would be necessary to certain numbers of aircraft movements when using the CNR method. By taking the excess number of PNdB's given in the output and entering Table 7.3, the "noise capacity" of the airport can be found. For example, if the excess number of PNdB was found to be +5 for a given set of

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*These values may be left out and "average" values will be assumed.

TABLE 7.1. TOLERABLE LIMITS OF NOISE OUTSIDE VARIOUS ROOMS FOR NOISE CONTINUOUSLY PRESENT FROM 0700 HOURS TO 2200 HOURS

Type of Space	CNR
Broadcast studios	85
Concert halls	85
Legitimate theaters (500 seats, no amplification)	90
Music rooms	90
School rooms (no amplification)	90
Apartments and hotels	95
Assembly halls	95
Homes	100
Movie theaters	100
Hospitals	100
Churches	100
Courtrooms	100
Libraries	100
Offices:	
Executive	95
Secretarial (mostly typing)	110
Drafting	100
Meeting rooms (with amplification)	100
Retail stores	105
Restaurants	115

Note: 10 CNR could be added for masonry or well sound insulated buildings

Source: Approximately the values given by Kryter, Karl D., in The Effects of Noise on Man (New York: Academic Press, 1970), p 338

TABLE 7.2. RANGES FOR PERCENT RUNWAY UTILIZATION (REF 31)

PERCENT RUNWAY UTILIZATION RANGES
31 - 100
10 - 30
3 - 9
Less than 3

TABLE 7.3. CAPACITY BASED ON EXCESSIVE NUMBER OF PNdB (REF 31)

Excess Number of PNdB	Number of Takeoffs or Landings Per Period	
	Day (0700 - 2200)	Night (2200 - 0700)
-10	Less than 3	Less than 2
- 5	3 - 9	2 - 5
0	10 - 30	6 - 15
+ 5	31 - 100	16 - 50
+10	More than 100	More than 50

data, the "noise capacity" of the airport would be approximately 30 aircraft during the day period. Again, it is emphasized that these are approximate values and an excess of +5 PNdB cannot be interpreted to mean that if you have 29 movements, you are safe, and if you have 31, you will exceed the noise capacity.

Figure 7.1 is a graph of the range of movements versus the excess number of PNdB. This graph shows that the excess number of PNdB is rather insensitive to the number of aircraft operations, especially at a busy airport. For example, it is conceivable that an airport would need to go from 100 movements per day down to 10 in order to achieve a reduction of 10 PNdB.

PROCEDURE OF THE CNR-1 METHOD

The computer program used in the CNR-1 method goes through four basic steps in calculating the PNdB produced by a given aircraft for a particular situation. First, the distance from the area being studied to the aircraft is calculated. Second, one of the three equations is used to calculate the PNdB based upon the distance between the aircraft and the area being studied. Then this PNdB is corrected for time of day and percent runway utilization. Finally, the excess number of PNdB's are calculated by subtracting the number of calculated PNdB's from the Composite Noise Rating which was input.

The first step, calculating the distance D from the aircraft to the area, is done by Pythagorean Theory. First, the assumption is made that the area being studied is at the same elevation as the airport, $Z_g = 0$. This is valid since airports require a flat terrain and the aircraft will be out of the noise range before the elevation changes a great amount. The greatest noise will occur when D is minimum, which occurs when $X_a = X_g$, i.e., the aircraft is directly over the point where the perpendicular line, from the object to the extended centerline of the runway, intersect - Fig 4.2.

From Fig 7.2, the following equation may be derived.

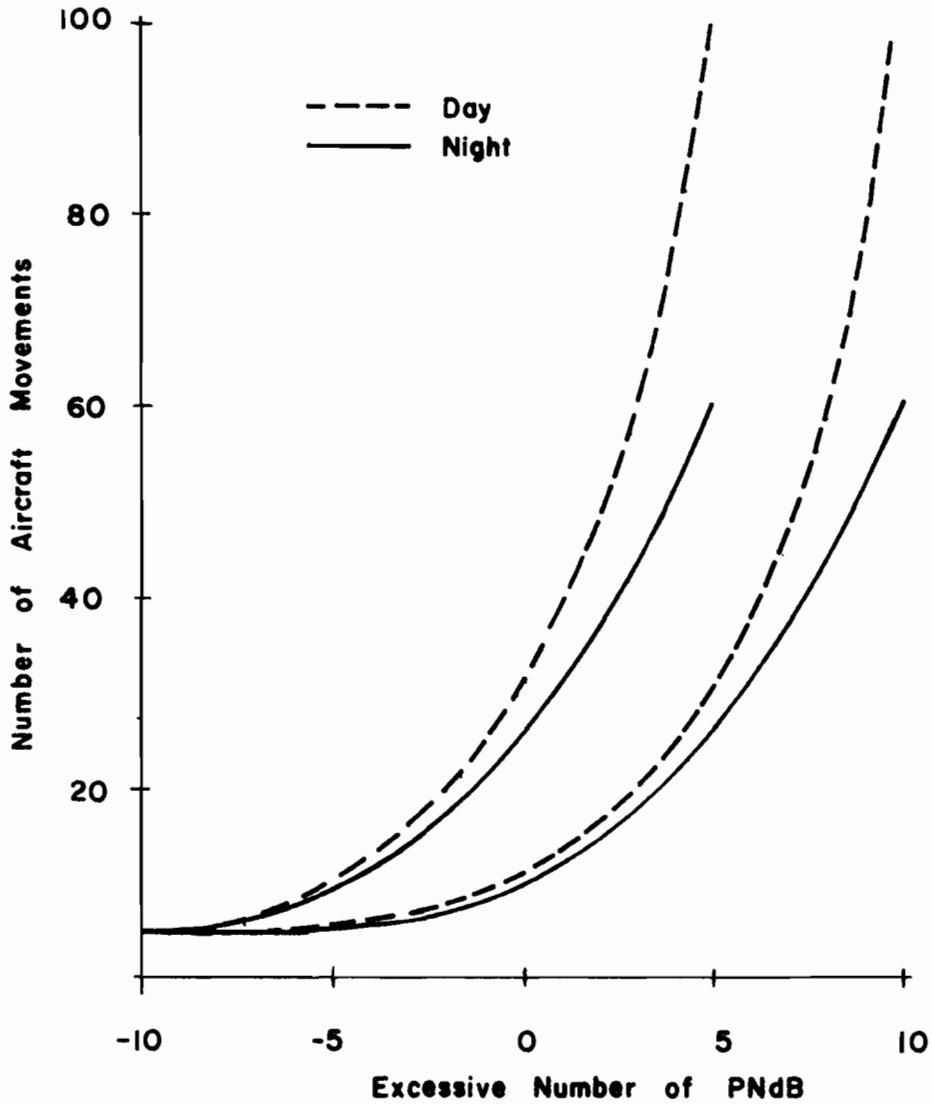

Fig 7.1. Excess number of PNdB versus aircraft movements.

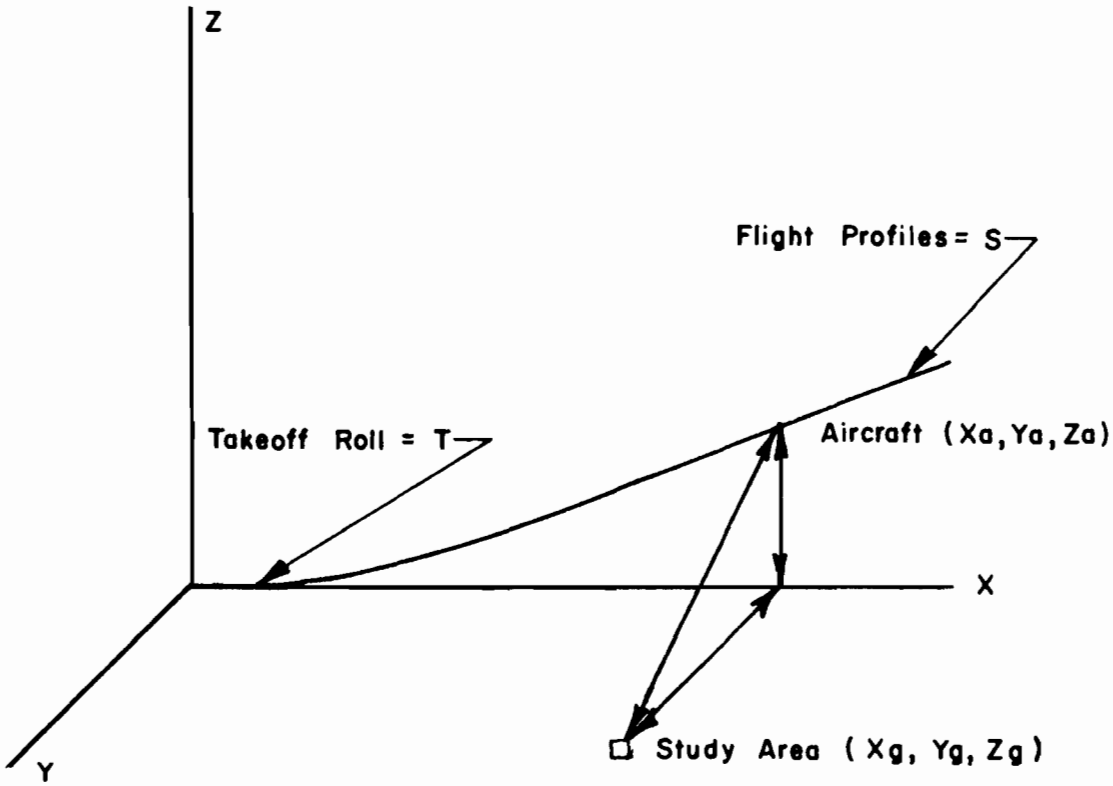

Fig 7.2. Distance from aircraft to study area.

$$Z_a = (X_z - T) \times S$$

and

$$D = Z_a^2 + (Y_g \pm Y_a)^2$$

Substituting in for Z_a results in:

$$D = [(X_a - T) \times S]^2 + (Y_g \pm Y_a)^2$$

where

D = shortest distance from aircraft to area,

T = take-off roll = 0 for landing,

S = slope,

X_a = distance of the aircraft along the extended runway centerline,

Y_a = aircraft deviation from centerline positive when the aircraft is on the opposite side of the centerline from the area, and

Y_g = perpendicular distance from the area to the extended runway centerline.

Step two is the calculation of the PNdB produced by the aircraft. Three equations are used based on the aircraft type and the maneuver being executed. These equations are based on graphs given in the Appendix of the CNR handbook. Straight lines were used to approximate these curves, but they fit very closely, especially with the range of concern. The first equation is for the landing maneuver. No distinction is made based on aircraft type.

Landing:

$$PNdB = 209 - 36 \log D$$

The second equation is for a turbofan using take-off power.

Turbofan - Take-off:

$$PNdB = 212.3 - 32.9 \log D$$

The third equation is for a turbojet using take-off power.

Turbojet - Take-off:

$$PNdB = 220.4 - 33.7 \log D$$

The third step in the program is to make corrections to the calculated PNdB based on Tables 7.4 and 7.5. The source of these tables is the CNR handbook.

The final step in the computer program is to calculate the number of excessive PNdB. This is accomplished by Eq 5.7.

$$\text{Excessive noise PNdB} = \text{CNR} - \text{PNdB}$$

The last step in the CNR-1 method is to take the excessive number of PNdB and get the airport "noise capacity" from Table 7.3, as described earlier.

EXAMPLE OF USING CNR-1

A hypothetical case is given below to illustrate the use of the CNR-1 method.

A hospital is located 30,000 feet from the end of runway K along the centerline. From Table 7.1 the desirable CNR is 100. Turbofan aircraft are the principal users of this runway. There are complaints of noise during the day. Runway K is utilized by 50 percent of the time by these aircraft. Assuming "average" take-off roll and climbout slope and approach slope, "straight-out" approach and climbout patterns, flight lengths are over 2,000 miles. Find the "noise capacity" of this runway.

From the output of the CNR-1 program, it was found that the excess number of PNdB for the take-off case was -5 and the excess number of PNdB for the landing case was +5 . Using Table 7.3, the noise capacity of this runway for take-off is approximately 9 and for landings the noise capacity is approximately 31. This indicates that if the airport operator had a runway which did not have noise problems he could achieve the best "noise capacity" by assigning the take-off to the other runway and reserving runway K for landings.

TABLE 7.4. CORRECTIONS FOR PERCENT RUNWAY UTILIZATION (REF 31)

Percent Runway Utilization	Correction
31 - 100	0
10 - 30	- 5
3 - 9	-10
Less than 3	-15

TABLE 7.5. CORRECTION FOR TIME OF DAY (REF 31)

Time of Day	Correction
0700 - 2200	0
2200 - 0700	+10

TESTING THE EFFECTS OF VARYING OPERATING PROCEDURES

In order to test the effect that varying the operational techniques has upon the noise capacity of an airport, each of the inputs was varied over its feasible range while the other variables remained at the values given in the preceding example problem. Table 7.6 shows the results of this analysis. It quickly became apparent that the most significant variable is the glide slope for the approaching aircraft. So, this variable was examined more closely. Table 7.7 shows the output for the various levels of glide slope entered: all the other inputs remained at the standard level.

Table 7.7 indicates that glide slopes greater than 0.070 (4°) all produce the same noise capacity; this results from the fact that once the glide slope reaches this level, then the noise has been reduced to a level where it is no longer irritating to the community. Therefore, a further reduction in the noise does not increase the capacity of the airport. This indicates there is no need for pilots to use a glide slope greater than 4° in order to achieve the greatest "noise capacity" at the airport, for this set of data.

The benefit of a steeper glide slope will continue as the aircraft gets closer to the threshold as shown in Fig 7.3. However, a steep glide slope will have to be reduced to the landing slope in the final stages of the approach.

CONCLUSIONS

The example problem shows that the CNR-1 method does provide a tool to the airport operator which may be easily used to evaluate noise problems at a given location. This tool can also be used to estimate the airport's noise capacity or the effects of varying some of the operating procedures. It should be remembered that when altering operating procedures, the safety of the new operations must also be considered.

TABLE 7.6. SENSITIVITY OF INPUT DATA

Variable	Input	Excess Number PNdB	Noise Capacity
CNR*	100 PNdB	- 5	9
Coordinates*	x = 30,000, y = o △	- 5	9
Aircraft Type	Turbofan △	- 5	9
	Turbojet	-10	< 3
Time of Day	Day 0700 - 2200 hrs.	- 5	9
	2200 - 0700 hrs.	-15	< 2
Landing Glide Slope	0.044 (2.5°)	+ 3	25
	0.050 (2.9°)	+ 5	30
Takeoff Profile	0.085 (4.9°)	- 5	9
	0.120 (6.8°)	+ 0	20
	0.150 (8.5°)	+ 2	25
Deviation From Straight Pattern	0 feet △	- 5	9
	2,000 feet	+ 0	20
	3,000 feet	+ 4	28
Percent Runway Utilization	2	+ 9	90
	6	+ 4	28
	15	+ 0	20
	50 △	- 5	9
Length of Flight	>2,000 miles △	- 5	9
	<2,000 miles	+ 4	28

△ Denotes standard values

* Not varied

TABLE 7.7. EFFECTS OF VARYING GLIDE SLOPE

Slope	Angles	Excess Number of PNdB	Noise Capacity
0.044	2.5°	+ 3	25
0.050	2.8°	+ 5	31
0.070	4.0°	+10	>100
0.085	4.9°	+13	>100
0.100	5.7°	+16	>100

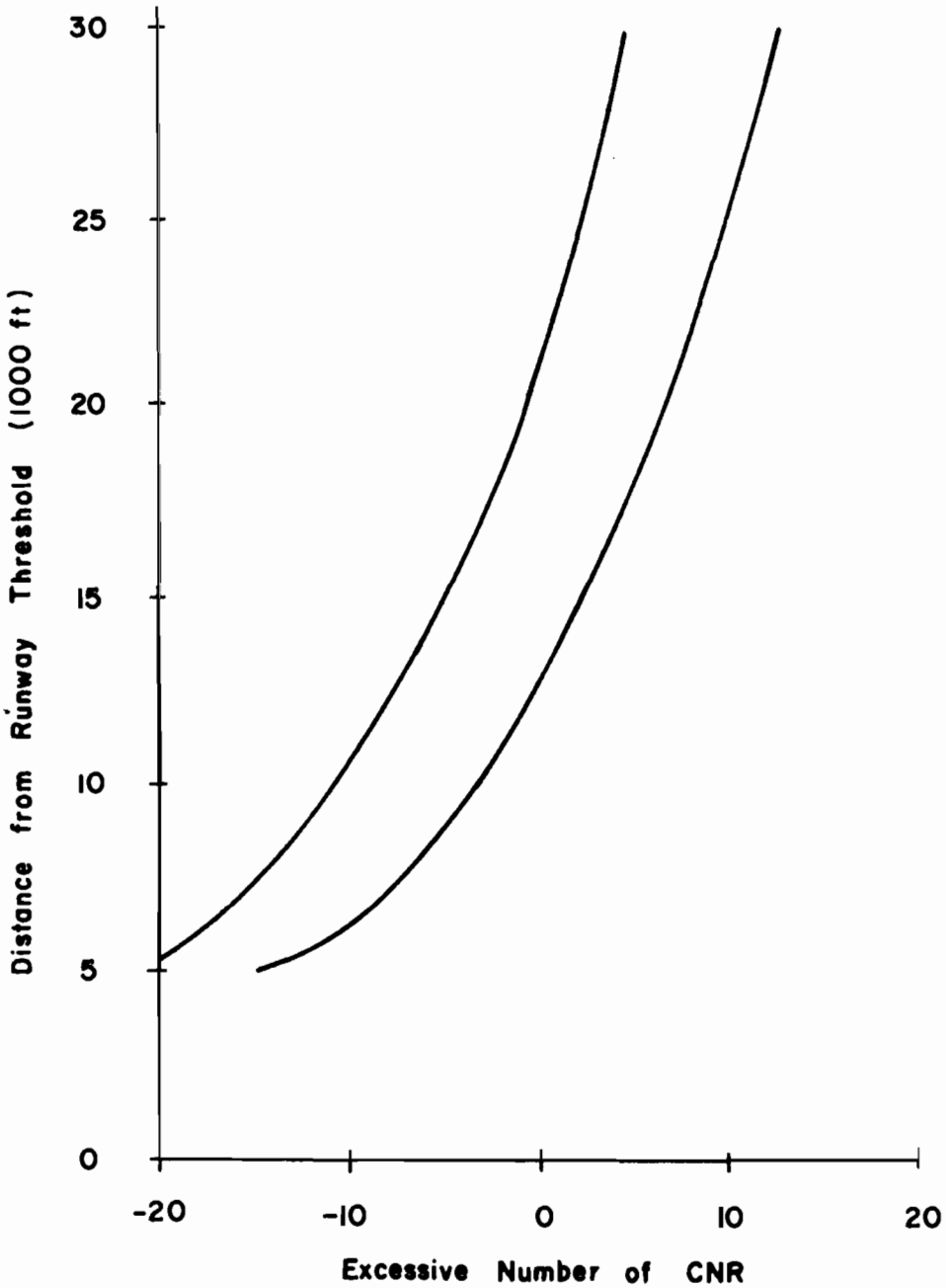

Fig 7.3. Effect of distance on CNR.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

The objective of this report was to investigate the problem of a systems analysis of airport capacity. The method used was to review existing models, select the "best" and discuss in detail, then tie the models together to develop a systems analysis program. This objective has been accomplished in this report.

The components affecting airport capacity were identified in Chapter 2. A method based on the Highway Capacity Manual for analyzing interairport access was presented in Chapter 3, along with methods for analyzing parking lots and curb lengths. Two methods of analysis of terminal buildings were presented in Chapter 4. Several methods of analyzing the aircraft handling subsystem were presented in Chapter 5. The method presented in detail is a simulation model developed by Donald Maddison. The problem of subsystem interfaces was discussed in Chapter 6. Finally, a method for determining the "noise capacity" of an airport was presented in Chapter 7.

CONCLUSIONS

The most highly developed analysis models exist for the aircraft handling component of the airport system. The least developed models are those for the analysis of the terminal building subsystem. The two models presented for analyzing this subsystem, the FAA method and Horonjeff's method, are incomplete. Therefore, there is a need to develop an analytical model for analyzing the terminal building subsystem.

RECOMMENDATIONS

As stated above, there is no really adequate method for analyzing the terminal building subsystem at airports. Therefore, first priority for future research must be given to developing a method for analyzing the capacity of terminal buildings. In order to do this, data needs to be collected to

quantify passenger flow rates within terminal buildings. Once the data has been collected, models can be developed for analyzing passenger flows in terminal buildings. In the interim period, while the new models were being developed, this data on passenger flow rates could be used to update the FAA model.

One approach for a systems analysis of airports which should be investigated, is a fast-time simulation model of the airport system. In this approach one would start with the airline schedule and the physical layout of the airport and then simulate flows through the airport system in the following manner. First, the aircraft handling subsystem would be analyzed, and the airline schedule would be modified according to simulated delays in the aircraft handling subsystem. This modified schedule would then be used along with passenger characteristics data to simulate the flow of passengers and visitors through the terminal building subsystem. Then based on the simulated passenger flows and the characteristics of the access/egress subsystem, the flow through the access/egress subsystem could be simulated, resulting in a systems analysis of the airport system.

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APPENDIX 1

PARKING ENTRANCE AND EXIT SERVICE TIMES

APPENDIX 1. PARKING ENTRANCE AND EXIT SERVICE TIMES

In Chapter 3 average service times for cars entering and exiting the parking lots at the Austin Municipal Airport were reported as 5.8 seconds for cars entering the parking lot and 16.0 seconds for cars exiting the parking lot. The data on which figures are based were collected on July 27 and 30, 1973. The weather conditions were clear and sunny; the temperature was approximately 90 to 95 degrees Fahrenheit. The equipment used at the entrances of Austin Municipal Airport parking lots are Auto-Gate, Model G89, and Ticket Spitter, Model ID-240, Automatic Parking Devices, Incorporated, 16422W McNicholos Road, Detroit, Michigan. Manual collection of the fees is used at the exits of the parking lots.

Figure A-1 shows a cumulative distribution of the service times, the ordinate of the graph showing percentage of passengers and the abscissa showing service times. For example, 40 percent of the exiting cars take longer than 15 seconds to be processed through the exit.

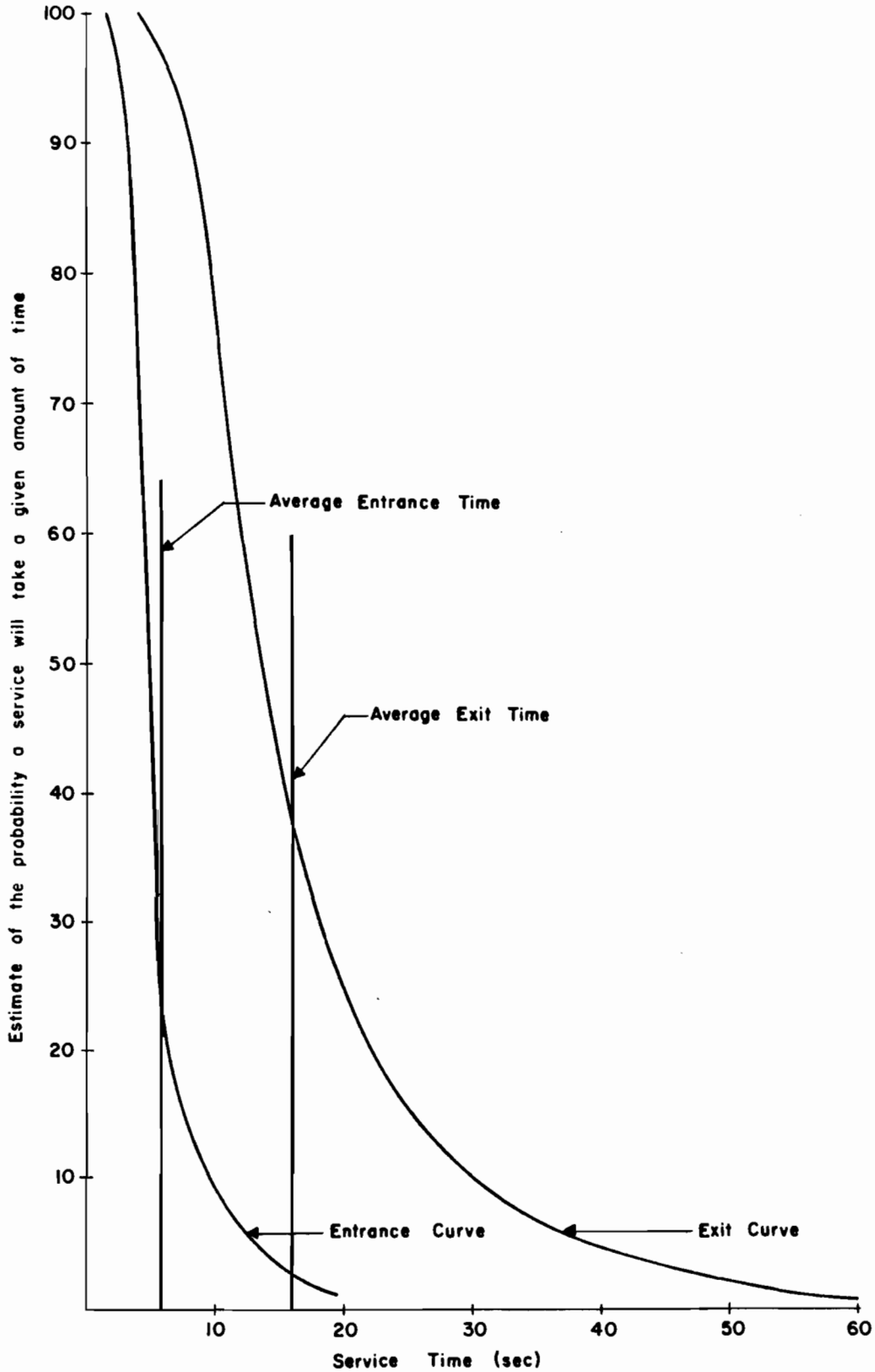

Fig A.1. Parking lot entrance and exit times.

VITA

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