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A TANDEM-QUEUE ALGORITHM FOR EVALUATING OVERALL AIRPORT CAPACITY

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16. Abstract Development is given for an analytical model of an airport system that can be used to evaluate overall airport capacity. Capacity is defined as the maximum flow-rate that can be imposed on airports without violating user-specified, level-of-service criteria for airport components. A deterministic queueing algorithm is presented. The approach ties individual component models together and relates input to one component and output from preceding components. Arrival patterns at airport boundaries are carried all the way through the airport; adjustments are made for delays and patterns are shifted according to service times and configuration of individual components. Sucessive components are treated as tandem queues. Special treatment is given to pairs of successive components between which there are ancillary activities which tend to randomize the translation of flow. For this case, input to a component is expressed as a function of output of preceding components and an estimated probability and dwelling time associated with joining intervening activities. To define these probabilities and expected dwell times, data were collected on the use of ancillary activities between major airports components; data collection technique is called the "flash-card method." Model estimates of total dwell time at a set of ancillary activities are compared with measured total dwell times; close agreement was found. The overall algorithm is intended for estimating component level of service measures. These measures are then evaluated by the user of the model.

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EXECUTIVE SUMMARY

INTRODUCTION

The purpose of this study is to develop a method for airport capacity evaluation which can be used either in designing a new airport or in assessing the future need for expanded facilities at an existing airport. Potential applications of the method take two basic forms: (1) identification and specification of research and capital improvement priorities and (2) preliminary testing of alternative designs and sizing of each component to assure that its capacity is adequate to meet demand and is compatible with the capacities of other airport components.

PROBLEM STUDIED

In this report, results obtained in the first year of a two-year project are reported. The following areas are covered herein:

(1) a working definition of an airport system and a discussion of system components,

(2) a review of available capacity models,

(3) a discussion and definition of airport system capacity,

(4) essential concepts regarding overall airport modeling concepts for capacity evaluation, and

(5) an empirical study of the effects of ancillary activities on flow patterns of people within an airport terminal.

The completion of models for various landside components and the implementation of these models in a computer program which characterizes overall landside flow patterns and congestion is being carried out in the second year. The movements of people and baggage within the terminal and of vehicles within the access roadway system will be included.

RESULTS ACHIEVED

Many previous studies of airport capacity might be classified as a "component approach," because each component or subsystem was analyzed independently. Such an approach, however, can lead to an imbalance in component capacities. There is nothing to be gained, for example, by having a highly efficient ticket counter operation if it is followed by an inadequate security check station. The rapid flow of passengers from the ticket counter would simply generate long queues at the security check. It is the purpose of this research to consider the system as a whole, thus assessing the capacity requirements of each component in light of the functioning of the entire system and avoiding capacity imbalances.

This type of systems approach, then, requires a working description of the system to be modeled. Thus, a graphical presentation is given of the system, including

(1) off-airport access/egress,
(2) on-airport access/egress,
(3) terminal building subsystem,
(4) apron subsystem, and
(5) airside subsystem.

Because of the many configurations an airport can assume, the components within each of these categories are presented in an unconfigured format.

A detailed discussion is given on the capacity concept, and several alternate definitions of capacity are presented, including the following: airport system capacity is the maximum level of demand of a given pattern that can be imposed on an airport system, in a given interval of time, without violating any specified level-of-service criterion for the airport system as a whole or any of its subsystems or components.

A discussion and alternate definitions of demand on an airport system are given, and level of service and demand are related graphically.

An airport system can be thought of as a network, with the nodes corresponding to airport facilities such as ticket counters and security check stations. Numerous graphs are presented to illustrate flows among components in series. The complex nature of the flows within an airport and the handling of these flows by network methods are emphasized.

Finally, the effects of intervening activities on the flow patterns from one essential activity to another, i.e., from the ticket counter to the security check, are discussed. An empirical study was employed to quantify the probabilities of (1) proceeding directly to the following essential activity and (2) of proceeding from intervening activities to the next essential activity, both as functions of the available time until flight. These probabilities were described functionally as a cumulative normal distribution function, with certain parameters being included to differentiate among different airports to which the model might be applied. A chi-square goodness-of-fit test showed that this function adequately represented the data.

UTILIZATION OF RESULTS

This report documents the initial work in the development of a computer method for evaluating the capacity requirements of an airport. It is anticipated that a working landside model will be completed by the end of the second year of the project. The model will be usable either for determining the capacity requirements of a new airport or for assessing the possible future need for additional capacity at an existing airport.

CONCLUSIONS

The results of this report, including the airport system definition, capacity discussion and definition, model for time spent in intervening activities in the terminal, and the network approach for system modeling, constitute the first phase of the development of a generalized airport model for capacity evaluation. The completion of a working model, which is now being carried out in the second year of the study, will depend heavily on the results presented herein.

PREFACE

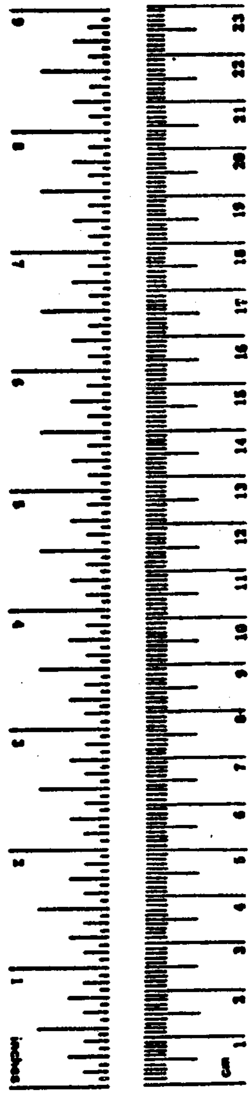
This is the 44th in a series of research reports produced by the Council for Advanced Transportation Studies. It is also the first in a series of research reports describing the findings and activities carried out as a part of the work done under the research project entitled "A Systems Analysis Proecedure for Estimating the Capacity of an Airport."

This project is sponsored by the Office of University Research, U. S. Department of Transportation, under contract number DOT-OS-50232. This scheduled two-year project began on June 1, 1975.

Approximate Conversions to Metric Measures

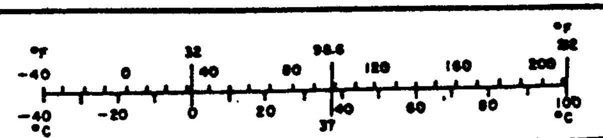
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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CHAPTER 1. INTRODUCTION

Objective and Scope

The objective of this study is to provide an airport capacity evaluation method with which one can plan improvements to airside and landside components through the use of a systems approach rather than analyzing each component as an independent part of the airport system.[1] This capacity evaluation method will be a valuable tool to airport planners, designers, and decision makers. It has application both to the analysis of existing airports and future airports. Applications will take two basic forms: (1) identification and specification of research and capital improvement priorities, and (2) preliminary testing of alternative designs and sizing of each component to assure that its capacity is adequate to meet demand and compatible with the capacities of other airport components.

To achieve the foregoing research objectives, this dissertation presents a definition of an airport system and definitions of capacity, and the development of an analytical model for airport system evaluating overall airport capacity. The study

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[1]The term airport system refers to single airport and its associated activities. This term differs from a "system of airports" which consists of several airports serving a single metropolitan area.

discussed here, however, represents only the first-year output of the multi-year research project entitled "A Systems Analysis Procedure for Estimating the Capacity of an Airport," being conducted by The University of Texas at Austin under contract with the U. S. Department of Transportation, Office of University Research. Due to the nature of the overall research approach, actual implementation of the system model is not within the scope of this thesis; implementation, including the sensitivity analysis and validation of the system model, is in progress by the project team as part of the second-year research.

Background

Historically, studies of airport capacity have emphasized the airside facilities. In fact, most previous research has considered only the runway component of the airside subsystem. Other airport subsystems, especially the terminal building, have received relatively little research attention. The reasons for this imbalance in research have been mainly institutional. According to Robert Horonjeff (Ref 1),

> 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 passenger 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.

There is increasing evidence that the landside is becoming the constraint on the overall capacity of many airports. For example, the Airport Operators Council International (AOCI) and the American Association of Airport Execu Executives (AAAE) recently conducted a joint survey to obtain estimates of airport capital development needs to 1980 (Ref 2). This survey showed that for the 24 large hub airports sampled, 56 percent of the total projected capital developed needs, or almost 2 billion dollars, was for landside improvements. In a recently completed FAA study of airport capacity based on examination of eight major U. S. airports, it was found that the airport landside will become the primary source of congestion and restriction to further growth in the early 1980's at nearly all locations, while, with a program of terminal air traffic control improvements, it was estimated that saturation of the airport airside can be postponed for a decade, into the mid to late 1980's (Ref 3).

In response to the foregoing evidence of potential landside problems, the U. S. Department of Transportation (DOT) asked the Transportation Research Board to convene a workshop conference to discuss problems relating to airport landside capacity including:

(1) level-of-service methodologies to quantify airport landside capacity,

(2) engineering techniques to increase landside capacity, and

(3) analytical tools fc use in improving landside capacity (Ref 4).

The study described in this dissertation incorporates some of the concepts and recommendations of that conference.

Research Approach

Previous studies of airport capacity might be termed "component approaches" because each component or subsystem was analyzed as an independent part of the overall system; such an approach can lead to an imbalance in airport component capacities. Thus, what is required is a systems approach in which the individual components are analyzed simultaneously.

This report is concerned with the analytical development of an airport system model. The approach is to tie individual component models together and to relate the input to a component and the output of previous components in sequence. The arrival patterns at the airport boundaries, which are a major factor affecting component operation, are carried all the way through the airport; adjustments are made for delays and arrival patterns are shifted according to the service times and configurations of individual components. The concepts of the algorithm which estimates these successive arrival patterns are explained and illustrated using deterministic queueing methods but the actual computations may be carried out with a network of stochastic queueing models or empirical regression models, e.g., (Ref 5).

Special treatment is given to pairs of successive components between which there are intervening activities (also called "ancillary activities"), e.g., coffee shops, newstands, and restrooms, which tend to disrupt the assumed deterministic nature of airport flow. The effects of these facilities has not been taken into account in past research. The probabilistic nature of passenger behavior is incorporated into the overall algorithm for this case by expressing the input to the second component as a function of the output of the first component and an estimated probability and dwelling time associated with joining each of the intervening ancillary activities. These probabilities and dwell times are estimated from two sets of collected data, one at Robert Mueller Municipal Airport in Austin, Texas and the other from San Antonio International Airport, using the data collection technique called the "flash-card method."

Overview of the Remaining Chapters

This first chapter has presented an introductory note to the research problem. Chapter 2 provides the airport system definition which specifies the physical boundaries of the airport system and the subsystems and components within the system. Available airport component and system capacity models are discussed in Chapter 3. In Chapter 4, the existing definitions of airport capacity are reviewed and definitions are proposed which apply to the airport system as a whole, as well as the individual components. Chapter 5 documents the conceptual framework for overall airport capacity modeling and Chapter 6 describes the model of intervening activities. The validation of the intervening activities model is presented in Chapter 7. That chapter also includes a brief description of the data collection technique for studying passenger behavior in using ancillary activities. The final chapter, Chapter 8, contains a summary and conclusions of this research and offers suggestions for further study.

CHAPTER 2. AIRPORT SYSTEM DEFINITION

Airport System

For this study, the boundaries of the airport system are the airport entrance gate on the landside and the terminal airspace on the airside.[1] Figure 2.1 is a schematic of the airport system and its input variables from the environment. The airport system transforms the input variables into the outputs and performance measures as depicted in Fig 2.2.

In order to analyze a complex and large-scale system, it is helpful to divide the system into functional subsystems. For this study the airport system has been divided into four subsystems:

(1) On-Airport Access/Egress Subsystem,

(2) Terminal Building Subsystem,

(3) Apron Subsystem, and

(4) Airside Subsystem.

Figure 2.3 shows this breakdown.

The On-Airport Access/Egress Subsystem entails the movement and storage of vehicles entering the airport gates and proceeding either to the terminal curbside or parking. Because an airport generally has both curbside activity and parking, the On-Airport

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[1]The near-terminal airspace under the jurisdiction of the air traffic control (ATC) tower is included in the system while approach/departure airspace is not included.

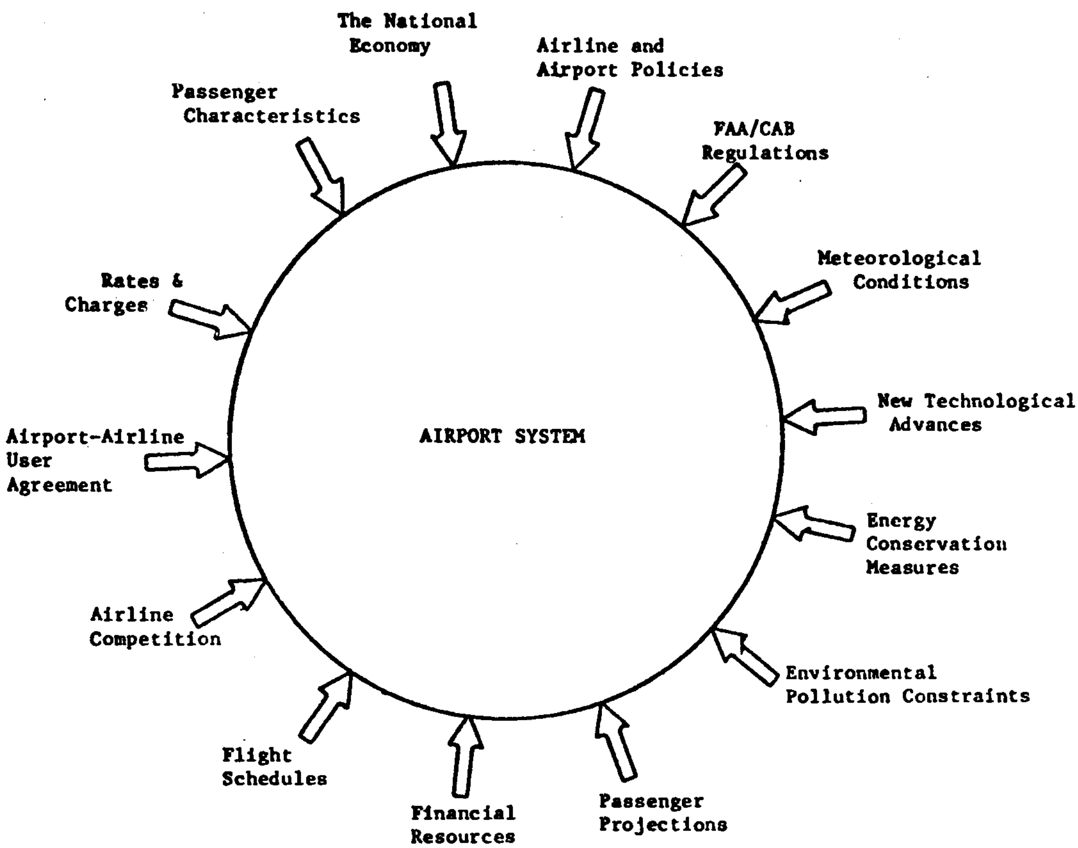


Fig 2.1. Input variables to an airport system from the environment.

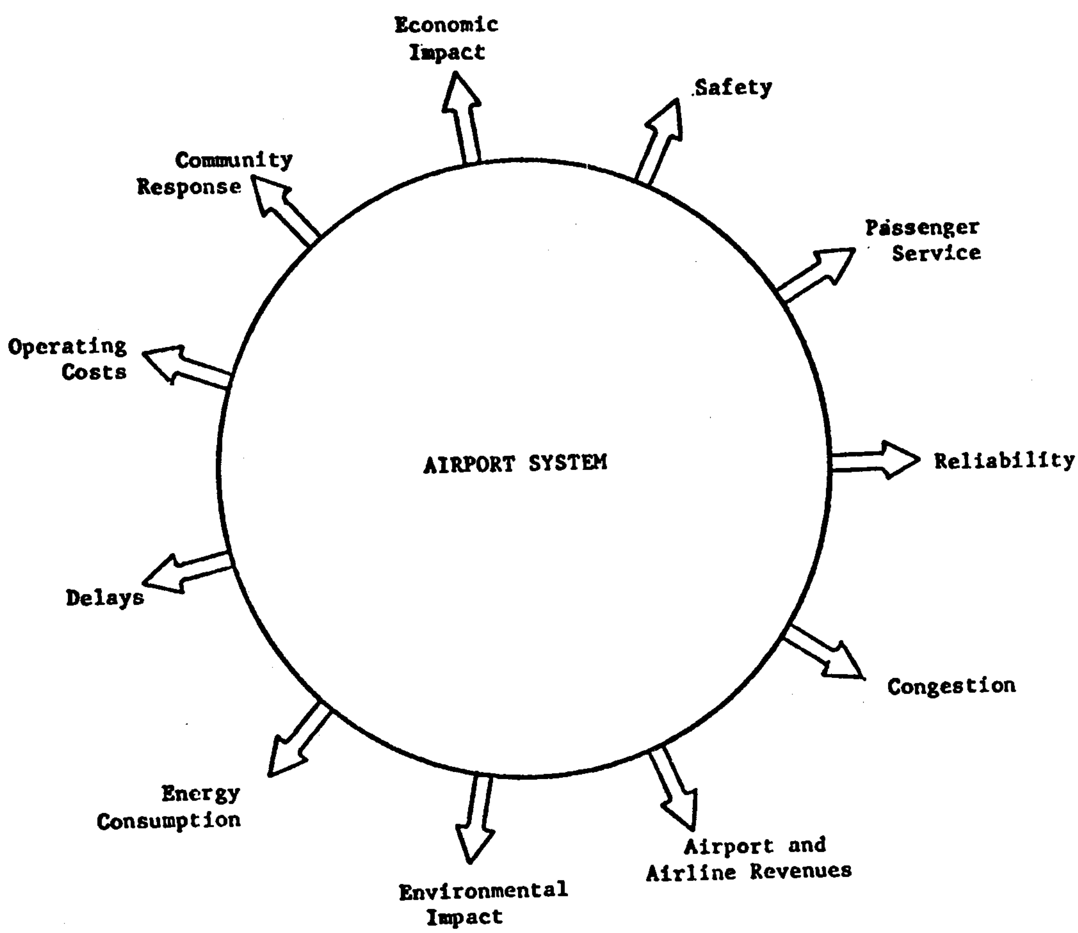


Fig 2.2. Output variables to the environment from an airport system.

Access/Egress Subsystem has been further subdivided into these two categories as shown in Fig 2.3.

Within the Terminal Building Subsystem, the processing unit changes from ground vehicles to passenger and baggage. Because the passenger and his baggage are handled separately within part of the terminal building, the Terminal Building Subsystem has been further divided into passengers and baggage handling facilities.

After being processed through the Terminal Building Subsystem, the passenger and his baggage are loaded onto the aircraft parked on the apron. It was felt that a good subsystem dividing line would be between the apron proper and the connecting taxiways. The two resulting subsystems are called the Apron Subsystem and the Airside Subsystem, respectively, as shown in Fig 2.3. As mentioned previously, within the apron area the aircraft has many different interactions. Passengers are boarding or deboarding the aircraft, baggage is being loaded or unloaded, and the aircraft is being fueled, cleaned, and serviced. The Airside Subsystem encompasses the movement of the aircraft from the apron to the boundaries of the terminal airspace via the runways and taxiways and vice versa.

Within each of the above subsystems, there are many different activities. Therefore, it is necessary to further divide each subsystem into components. In systems engineering terminology, a component is the smallest functional unit into which the system is divided for analysis purposes. In this study a component is used to describe an individual processing or storage facility.

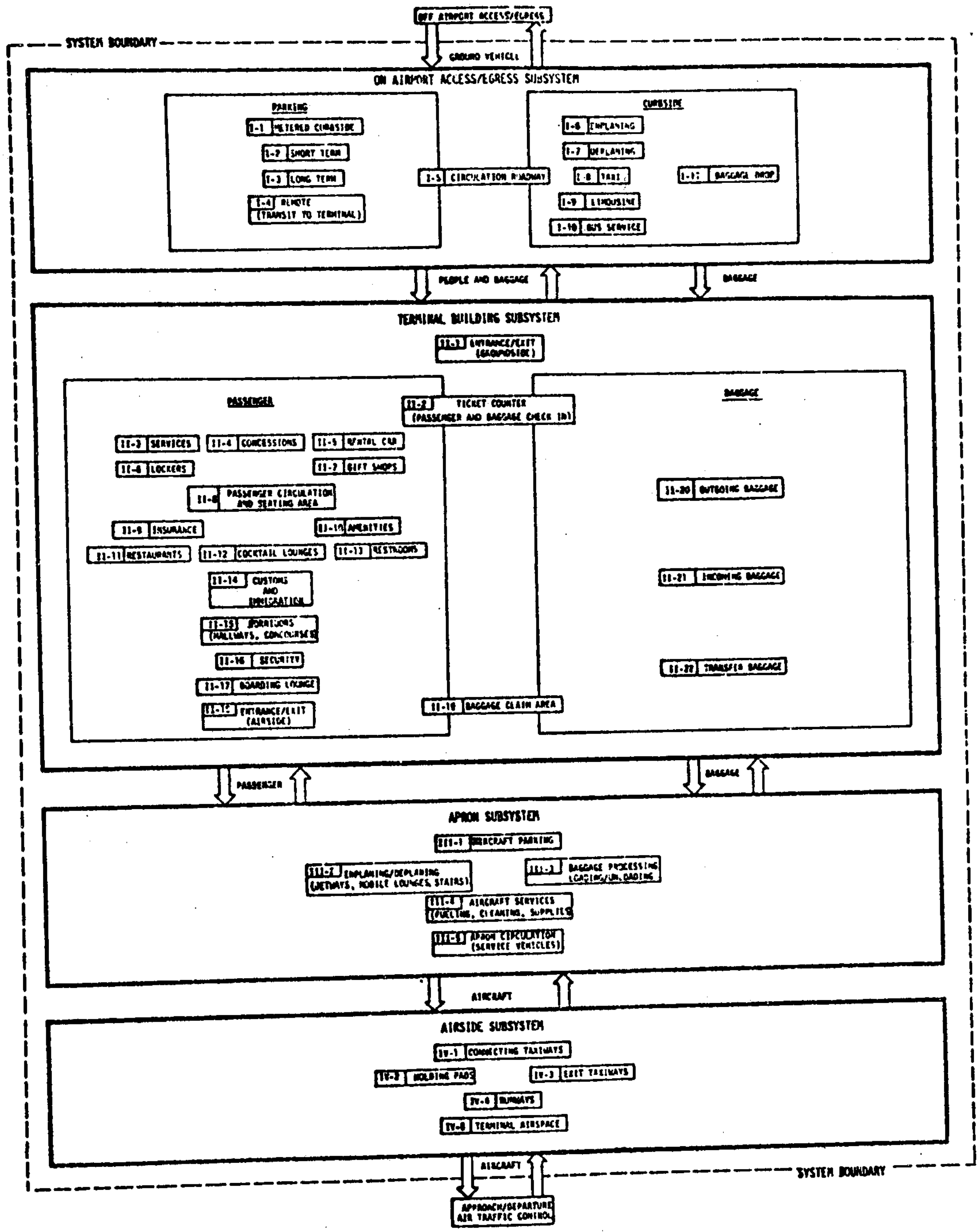


Fig 2.3. The airport system, subsystems, and components.

Figure 2.3 is only a schematic representation of the airport system. Most past schematic diagrams of an airport depicted an exact functional flow through the different component, especially within the termianl building. Note that Fig 2.3 does not depict any exact flow pattern. The subsystems are roughly fixed and arranged in the order through which one would proceed. The components are arranged close to actual flow paths, but their exact linkages are left unspecified to provide flexibility in adapting the precise system definition to a particular airport configuration.

System Components and Their Performance

In order to evaluate performance of a system, it is necessary to start with criteria at the component level. Thus, one must determine which activities occur at each component and what factors might impede its operation, develop methods to measure the level-of-service provided by the activity, and determine which variables influence this level of service. This is attempted in Table 2.1; only major processing components are included. In Table 2.1, the term "activity" is defined as the service or function performed by a specific component while "level-of-service" is the physical appraisal of how a component performs.

Summary

Using systems engineering concept, the airport system along with appropriate subsystem and components has been defined for an overall airport capacity analysis. Figure 2.3 is a schematic representation of the airport system. The figure is arranged so that

TABLE 2.1. AIRPORT SYSTEM COMPONENTS

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
I-1	Metered Curbside	Storage	Holding capacity Space availability Proximity to terminal	1) Arrival rate of vehicles 2) Number of spaces available 3) Turnover rate
I-2 I-3 and I-4	Parking	Entrance Processing	Queue length at entrance Waiting time	1) Time required to process each vehicle 2) Number of entrance lanes
		Storage	Holding capacity Stall availability Proximity to terminal	1) Physical characteristics (aisle widths, number of stalls, stall widths, arrangement of stalls) 2) Duration and turnover rate
		Exit Processing	Queue length at exit Waiting time	1) Number of operators, service rate of each operator 2) Arrival rate of people from terminal
I-5	Circulation Roadway	Vehicle Flow	Delay Circulation time Safety Priority Lane	1) Number and type of intersections involved 2) Roadway geometric characteristics 3) Origin/Destination pattern
I-6 thru I-10	Curbside	Storage	Holding capacity Space availability Waiting time	1) Arrival rate of vehicles and/or passengers 2) Dwell time 3) Spaces available at curb 4) Vehicle type mix

(Continued)

TABLE 2.1. (Continued)

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
II-2	Ticket Counter	Processing	Queue length Waiting Time Congestion	1) Passenger processing rate per agent 2) Number of lanes or agents 3) Available number of bags per passenger
		Storage	Holding Capacity	1) Area Available 2) Peak hour passenger arrival rate 3) Minimum standing area 4) Number of visitors per passenger
II-8	Passenger Circulation and Seating Area	Storage	Holding Capacity Number of seats Density	1) Area available 2) Peak hour passenger flow patterns 3) Space requirements per passenger 4) Number of visitors per passenger
II-14	Customs and Immigration	Processing	Queue length at entrance Waiting time Congestion Complexity of procedure	1) Passenger processing rate per agent 2) Number of agents available 3) Number of passengers going through customs
		Storage	Holding capacity	1) Area available 2) Passenger arrival rate 3) Area required for each passenger and his baggage
II-15	Corridors	Walking	Capacity pedestrian flow Walking distance or time Density	1) Effective dimensions of each corridor 2) Passenger(and visitor)accumulation rate 3) Walking rate of passengers

(Continued)

TABLE 2.1. (Continued)

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
II-16	Security	Processing	Queue length at entrance Waiting time Congestion Complexity of procedure	1) Passenger processing rate 2) Size of security force 3) Number of hand-carrying bags
		Storage	Holding capacity	1) Passenger arrival rate 2) Presence of visitors 3) Space required for each passenger
II-17	Boarding Lounge	Entrance Processing	Queue length Waiting time Congestion	1) Arrival rate of passenger/visitors 2) Service rate of attendants 3) Number of attendants
		Storage	Holding capacity, i.e., Number of seats Size of area	1) Flow into departure lounge 2) Time of arrival before flight 3) Flow into aircraft (pass/min/door) 4) Space required per passenger 5) Time lounge is opened 6) Time boarding begins
II-18	Entrance/Exit (Airside)	Processing	Delay Congestion Walking distance Convenience	1) Width of doorway 2) Walking rate of passengers 3) Space requirements per passenger
II-19	Baggage Claim Area	Storage and processing	Queue length Waiting time Congestion Area size Proximity to curb Seating	1) Walking distance & flow rate of arriving passengers 2) Aircraft load factor (passenger/aircraft) 3) Baggage processing time from aircraft 4) Number of bag/passenger 5) Size of facilities (carousel, conveyer belt, etc.)

(Continued)

TABLE 2.1. (Continued)

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
II-20	Outgoing Baggage	Processing and storage	Delay to aircraft Congestion Number of bags not loaded	1) Number of bags/passenger 2) Check in rate at the ticket counter 3) Flow rate from baggage check-in points to central sorting area 4) Number of workers and capability in sorting baggage 5) Time to move baggage to proper aircraft 6) Time to load baggage into aircraft
II-21	Incoming Baggage	Processing and storage	Delay from aircraft	1) Time required to unload, sort and convey to baggage claim areas
II-22	Transfer Baggage	Processing	Delay to and from aircraft Number of bags not transferred	1) Time required to identify transfer baggage from incoming baggage and to deliver to receiving flight
III-1	Aircraft Parking	Aircraft Maneuvering and Hook-up to Terminal	Delay to aircraft Apron congestion & interference	1) Space per aircraft requirements 2) Number of gates 3) Compatability of aircraft mix with gates 4) Number of push-back tractors (if used)

(Continued)

TABLE 2.1. (Continued)

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
III-2	Enplaning/ Deplaning	Processing	Queue length Waiting time Congestion	1) Width and slope of device 2) Width and number of aircraft doors 3) Walking rate of passengers 4) Space requirements per passenger
III-4	Aircraft Services	Preparing Aircraft	Service time Delay to aircraft	1) Availability of equipment 2) Type of servicing required 3) Size and number of crews
III-5	Apron Circulation	Transferring Baggage, Passengers, and Cargo	Service time Delay to aircraft Congestion	1) Apron layout 2) Available space per aircraft 3) Number of vehicles required 4) Speed of vehicles
IV-1	Connecting Taxi-ways	Aicraft Movement	Occupancy time Taxiing distance Taxiing interference	1) Speed of aircraft 2) Length of taxiways 3) Number of active runways crossed 4) Geometric layout
IV-2	Holding Pads	Aircraft Runup Aircraft waiting for other Activities	Occupancy time Queue length	1) Aircraft arrival and departure rates 2) Arrival/departure ratio 3) Air Traffic Control procedures
IV-3	Exit Taxiways	Aircraft Movement off Runway	Runway occupancy time Fraction of aircraft using proper exit	1) Location and design speed 2) Aircraft speed mix and airline mix 3) Airport configuration

(Continued)

TABLE 2.1. (Continued)

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
IV-4	Runways	Aircraft Arrivals and Departures	Flow rate delay Congestion Wave offs	1) Air traffic control rules 2) Aircraft mix 3) Location of exit taxiways 4) Pilot and controller capability 5) Weather conditions 6) Arrival/Departure ratio 7) Length of common approach paths 8) Navaids available 9) Number of runways and configurations
IV-5	Terminal Air Space	Aircraft Holding Aircraft Approach Aircraft Departure	Controller work load Delay to aircraft Aircraft conflicts and Congestion	1) Aircraft mix 2) Controller capability & procedures 3) Navaids 4) Proximity to other airports 5) Topography, manmade structures 6) Weather 7) Approach/Departure path configuration

an exact flow can be specified for a particular airport configuration.

To facilitate model development, activities at each component have been defined along with a method to measure the activity, its level-of-service, and the variables which influence its operation (Table 2.1).

CHAPTER 3. REVIEW OF AVAILABLE CAPACITY MODELS

Objective and Scope of the Review

In order to be in a position to develop a new capacity model, it is necessary to become familiar with the general concepts and methodologies of the available modeling procedures. One obvious objective of the literature review is to derive some insight from existing modeling techniques as well as to identify possible limitations of each model's applicability to a specific problem under consideration. This review is brief in that discussions are given only to such models that are reasonably compatible with the objectives of this research. Some of the significant simulation models are briefly discussed, but the scope of this review is limited mainly to the analytical models.

For convenience, the available capacity models are classified into models of individual components and of a whole airport system. Models developed for individual airport components are presented in Appendix A according to the list of components defined in the previous chapter. Therefore, their descriptions are not reiterated here except as they relate to the system modeling procedure.

The Capacity Models

Early capacity models involved an analysis of airside components, especially runways, by the use of stochastic queueing theory. The models were usually based on the assumption of Poisson arrivals and exponential service times. It has been a common practice to apply the same concepts to other components. There exist a large number of stochastic queueing models of airside components and some landside components and these are discussed in Appendix A.

As the assumption of Poisson arrivals and service times is not easily justified for certain components, e.g., baggage handling facilities, there have been several attempts to analyze such components by use of deterministic queueing approaches. The baggage claim area models developed by Barbo (Ref 6) and Browne, et. al. (Ref 7), and Paullin's boarding lounge model (Ref 8), are examples. These models apply empirically determined demand patterns to service rates of components in question, which may or may not be time-dependent, in order to obtain estimates of level-of-service measures.

It has been only a few years since the interaction of two or more components became a focal point to some researchers although the subject of tandem or serial queues of this sort has long been discussed in the queueing theory literature. In dealing with a problem which has stochastic flows, the analysis of tandem queues, in which the output of one component becomes the input to the next, is quite difficult. The major analytical problem is to determine the output distribution of each component. Under certain assumptions this is theoretically possible to solve, but the solution generally lacks practicality. Difficulties in solving this problem have tended to restrict the analytical work on such systems to Poisson arrivals and exponential service times.

From the work of Burke (Ref 9), it has been known that, under certain capacity assumptions, the steady-state output of a queueing system with a Poisson input rate and negative exponential service times is also Poisson of the same rate. The implication is that the initial Poisson process is propagated providing that the effect of spatial separation of components on queueing times in tandem queues is negligible. The application of this model is limited to systems in which components are assumed independently of each other.

In analyzing an airport system, however, the application of Burke's model or its slight variations is not likely to hold because flows are filtered through many components having different queueing mechanisms. The treatment of tandem queues not fitting into Burke's categories has been, therefore, mainly by simulation. From a practical point of view, Rosenshine and Chandra (Ref 10) proposed an approximate solution technique for solving tandem queue problems under the Erlang service time assumption, but its use is questionable for a system having more than two queues in series.

There have been numerous simulation models of airports developed in the past several years, as briefly discussed in Appendix A. One of them is the airside system model developed by Douglas

Aircraft Company, Peat, Marwick, Mitchell and Co., et. al. (DAC/PMM) (Ref 11) which includes an analytical capacity model that treats runways, taxiways, and gates independently, and a critical event simulation model that treats the airside components as integrated parts. The simulation model computes the aircraft delay while component models separately compute the ultimate capacities of individual airside components. One important feature of this model is that each aircraft is traced through space and time on the airfield, which is represented by a series of links and nodes depicting all possible paths an aircraft can follow. The input or output rate at any point on the airfield is, therefore, successfully treated which results in a modular composition of component models.

Aside from several simulation models, there are few analytical models available treating serial queues or network of queues. The model recently developed by Battelle Columbus Laboratories (BCL) (Ref 12) seems to be the only analytical model available studying an entire airport system. This model, which consists of three separate parts, analyzes airport system components including: runways, runway turnoffs and gates, and components of terminal building and access/egress subsystems.

The BCL's runway model, given aircraft mix, first calculates the maximum service rate under saturated demand conditions, and then uses this rate to determine the aircraft delays expected for an actual demand pattern. The maximum service rate is computed similarly to Harris' and DAC/PMM's methods (Refs 13 and 11), while delays are obtained through transient solutions of a queueing model having Poisson arrivals and exponential service times. Input from the runway model is used in the second model concerning runway turnoffs and gates to estimate optimal turnoff locations and compute delays at gate areas. In computing delays, the model allows flexibility of using either mean arrival rates or Poisson arrivals with parameter estimated from the output of runways. Given these arrival rates, the third model determines the spatial distribution of airport users among various landside components to estimate their space requirements. The overall model thus, operates with respect to a given airside demand pattern.

In the BCL model, the three segments of an airport are treated as tandem queues. The landside components, however, are characterized by network of queues in which some arbitrary branching mechanism is imposed in tracing the flow. This landside model involves a couple of important assumptions. One is that the flow is input to the next component immediately after being dispatched from the first. The other is that each component has an infinite capacity resulting in zero delay to every unit of flow. For example, passengers arriving at a ticket counter in one time interval will be processed and available for the waiting area in the next time interval; similarly, vehicles travel along the roadway during two time invervals and will be available for the curbside in the next time interval, and so on. These *a priori* assumptions may cause some significant drawbacks in actually applying the model as the landside often is a serious bottleneck to passenger and baggage flows.

It is noted that the BCL model was developed specifically for a single airport, La Guardia, as a part of its space planning programs, and has not been used elsewhere. The model is, therefore, a design model; it was not designed for capacity evaluation purposes. In the BCL design model, for example space requirements are computed according to prespecified level-of-service criteria. In summary, the model is limited in application to certain airports which have similar geometric configuration of components to that of La Guardia Airport, and therefore, it still needs several changes to be actually applied generally.

Some Observations from the Review

In viewing an airport as a system composed of a large number of interrelated components, the preceding discussion makes several points quite clear.

(1) There is considerable difficulty in using stochastic queueing approaches for system modeling unless every component assumes Poisson arrivals and exponential service times. If a system consists of, in part, independent queues and in part dependent queues, then one way is to combine Burke's model and simulation.

(2) To construct a system model in general, a desirable approach is to use a set of available component models, each having deterministic structure; this facilitates the estimation of output distributions. There exists no such set of models in the literature. Some models, e.g., Paullin's boarding lounge model, Barbo's baggage

model, DAC/PMM's component models, do provide the basis for the estimation of output patterns.

(3) The discussion of the BCL model reveals its shortcomings as a system capacity model. Due to the nature of the problem considered, its application is limited to a certain airport configuration, and it does not offer flexibility of user inputting desired level-of-service criteria. The infinite capacity assumption imposed on the landside model is the major drawback.

(4) No model has reported passenger behavior related to intervening ancillary activities and its associated input and output estimation. Although the effect of intervening activities on flows may be considered marginal, the fluctuation of flow caused by these activities may result in large variations in estimating capacity of a component located beyond these activities.

Constructing an analytical system model by the use of existing component models is a formidable task. The contribution of the literature is, therefore, limited to information on maximum service rates of individual components and input demand patterns.

CHAPTER 4. AIRPORT SYSTEM CAPACITY DEFINITION

Capacity Concepts in General

In traffic flow theory, capacity is usually defined as the upper bound of the flow rate. In an airport, where holding or storage capacities must also be considered, a more general definition is required to account for the physical and functional provisions required for holding and processing the flow at the maximum service rate. Capacity will be defined generally as a maximum flow rate or storage that can occur under specific operating conditions.

In defining capacity, the ambiguous notion of "upper bound" or "maximum" generally relates itself to the ultimate capacity and the concept is viewed strictly from the supply side. With the introduction of level-of-service concept, the realization of the demand side incorporated with the concept of practical capacity. This capacity thus establishes a relationship between flow rate and a prescribed level-of-service standard. The concepts of practical capacity and ultimate capacity are not mutually exclusive but rather, are closely tied together; both are needed to make intelligent decisions about airport expansion.

These capacity concepts can be easily understood from Fig 4.1, where two different hypothetical demand patterns are imposed on a system in which the maximum service rate is μ . As shown in the figure, the system is operated at its ultimate capacity (μ) during the time intervals (t_0, t_1) and (t_2, t_3),

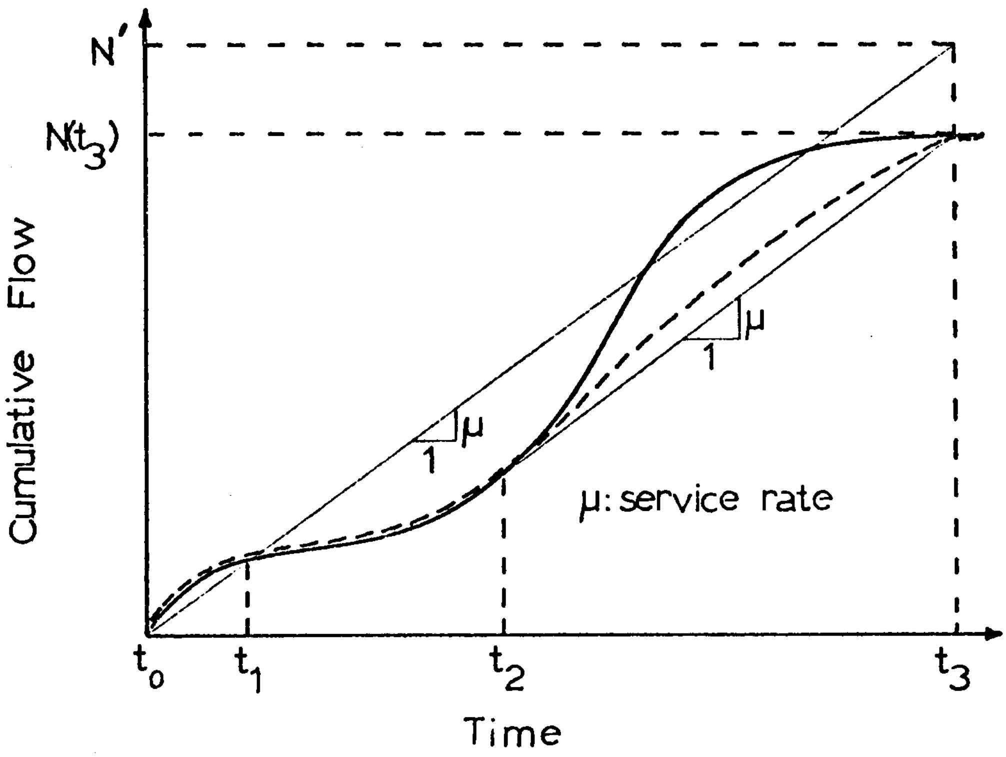


Fig 4.1. Demand patterns and capacity relationship.

during which there is a continual demand. Whereas the system can handle μ or $N'/(t_3 - t_0)$ at its ultimate capacity, the maximum achievable capacity of the system, which is limited by the pattern of demand, is $N(t_3)/(t_3 - t_0)$. If the system had not been under-utilized during time interval (t_1, t_2), the two capacity figures would be the same. In Highway Capacity Manual (Highway Research Board Special Report 87), these two concepts are defined as "capacity under ideal conditions" and "capacity," respectively.

It is important to notice that for two demand patterns A and B in Fig 4.1 the system yields the same maximum achievable capacity of $N(t_3)/(t_3 - t_0)$. Realizing the demand side, however, the practical capacities for A and B differ in their corresponding levels-of-service. If the total delay is an adequate measure for level-of-service, it is apparent from the figure that the system can provide higher level-of-service for demand pattern A than for B . Therefore, once the demand profile is imposed on the system for which the ultimate capacity is known, one has a measure of level-of-service. In general, higher level-of-service would be associated with the lower practical capacity. In an idealzed case, however, the highest level-of-service volume (with zero delays) may coincide with the ultimate capacity if the demand input rate happened to be exactly the same as the service rate. Highway Capacity Manual defines this practical capacity as "service volume."

From the above discussion, it becomes evident that the "reasonable" capacity is dependent upon the ultimate capacity, pattern of demand, and level-of-service chosen for the system. An adequate capacity provision is achieved with constant monitoring and experimentation with respect to these three factors. When evaluating a given system capacity, however, the pattern of demand becomes the overriding factor.

Previous Concepts of Airport Capacity

Until recently, the capacity of an airport was assumed to be limited by its airside operation. Airside capacity has been defined in two ways. The first definition, referred to as "practical capacity, is "the maximum number of aircraft operations during a specified time interval corresponding to a specified tolerable level-of-service delay" (Ref 14). Another previously used definition of airside capacity is "the maximum number of aircraft operations that an airport can accommodate during a specified interval of time when there is a continuous demand for service" (Ref 11). For application to airports, this ultimate capacity concept (also called saturation capacity or maximum throughput rate) was first introduced by Blumstein (Ref 15) and extended by Harris (Ref 13); but their applications were limited to runways. Recently, Douglas Aircraft Company and Peat, Marwick, Mitchell, and Company, et al., refined the ultimate-capacity concept to analyze capacity of the airside as a whole (Ref 11).

Whereas a great deal of attention has been directed toward airside capacity development, the landside portion has received relatively little attention. As airports begin to reach their physical limits, a balance is needed between the airside and the landside to maintain the effectiveness of the whole system.

It is noted that airside capacity definitions and level-of-service criteria are not always compatible with those for the landside. A review of papers presented at the Airport Landside Capacity Workshop Conference and others shows that it is becoming increasingly common to consider capacity to be associated with or defined by a level-of-service criterion (Refs 4 and 16). In very general terms, the workshop participants defined capacity as the physical provision required for a given demand at a given time at a specified level-of-service. This is similar to the concept of highway capacity.

Heathington and Jones point out that, "Different levels-of-service can occur at different times or even at the same time within large systems. However, the lowest level-of-service that occurs at the peak design period determines the overall operating level-of-service for a given facility" (Ref 4).

Beinhaker highlights definitions and concepts of capacity as follows (Ref 4):

Norminal (or Rated) Capacity: the amount of demand (traffic) the facility can handle if there is a continual demand,

Practical Flow Rate: a function of the demand pattern and the service level,

Achievable Flow Rates for individual components depend on:
the nominal (or rated) capacity
the pattern of demand
the service level which is to be provided, taking into account the benefits and costs.

He goes on to conclude that "The key factors in assessing capacity include the achievable flow rate, defined as the practical flow rate of a system associated with a level-of-service that is acceptable to the user and is economically justifiable, and dwell times that reflect the holding capacities required at each processor." On the other hand, since operating conditions that affect capacity vary with time, any single capacity value may imply a fixed set of operating conditions. Brink and Maddison propose to define capacity as an expected or average maximum flow or storage (Ref 4).

In considering the above mentioned relationship between capacity and level-of-service, two major issues arise. One is the problem of specifying an acceptable level-of-service. The other issue deals with the relationship between the measurement of the capacity of each airport component and measurement of the capacity of the airport system as a whole.

According to Beinhaker, "The service level must be expressed in terms of percentage of demand subject to more than a specific amount of delay or in some other similar manner" (Ref 4).

On the other hand, Heathington and Jones say that, "In general, the dimensions best suitable for levels-of-service appear to be time, distance, area, cost, comfort, and convenience" (Ref 4). Hockaday and Horonjeff agree that this categorization gives the best dimensions for levels-of-service (Ref 16).

A paper based on work done by Klingen for Eastern Airlines presents level-of-service standards and ratings for various functional areas in a terminal (Ref 4). The ratings are based on average pedestrian area occupancy of specific facilities, with the ratings going from level A to level F, similar to the highway level-of-service ratings.

Level-of-service relates to quality of service which airport users are experiencing. Since quality is made up of innumerable factors, many of which are subjective, level-of-service does not lend itself readily to measurement. Although many recognize that level-of-service involves a number of qualitative factors, the best measure of level-of-service developed to date, from the standpoint of the traffic engineer, is time - probably because time is relatively easy to measure, and comfort and convenience are not. Hockaday and Horonjeff point out that, "... with the current lack of information of methodology to obtain valid measures of passengers terminal level-of-service, there are hazards associated with the use of such a measure." However, they also comment, that "The level-of-service concept can serve a useful purpose even if it cannot be measured in strictly numerical terms.

If we can develop a better understanding of level-of-service and if there can be developed a consensus as to the relative importance of each element of level-of-service, these judgements can then be used to produce guidelines or criteria to form a basis for improving level-of-service" (Ref 4).

Nearly every author of recent papers on airport capacity defends the usefulness of the level-of-service concept, although most also point out the difficulty in establishing level-of-service criteria for airport components as well as for the airport system as a whole. In terms of measuring capacity of an airport system, Heathington and Jones report that all participants at the Tampa Conference indicated taht each segment on the landside of the airport could have a capacity and level-of-service rating (Ref 4). Also, "... the majority of the workshop participants felt that a given airport should have a single capacity and level-of-service rating; a minority of participants felt strongly that this could not be accomplished" (Ref 4).

Hom and Orman treat airport airside and landside interaction (Ref 4). They recognize that in order to realize the optimal capacity of an airport, airside and landside capacity must be in balance. However, they also point out that there is no clear definition of balance. For them, "In a limited analysis, balance between the airside and the landside might be achieved when the two elements have equal capacity or when delays on the elements are at the same level." They also state that, "... application of the concept are natural units for expressing the various subsystems' capacities (and hence for all the components of each subsystem), e.g., ground vehicles for access/egress subsystem, aircraft for the apron and airside subsystems, and passengers and/or visitors for the terminal building subsystems. It is possible to convert from one set of the above units to another using vehicle occupancy and passenger group size information, i.e., interface characteristics. This is important because it enables one to express the capacity of the airport system as a whole in a single set of units. For this purpose, it is proposed to use the "total passenger (enplaning and deplaning) demand rate." Expressing the capacity of an airport system as a whole in terms of total passenger demand is consistent with the usual practice of characterizing an airport's level of activity by its total number of enplanements and deplanements.

Notice that in the case of the terminal building subsystem, special care must be taken in using passenger rate as the common subsystem capacity unit. The complication stems from the fact that at some points in the terminal building only passengers are being processed, e.g., the boarding lounge, while at other points both passengers and visitors (and perhaps even employees in corridors and lobbies) must be processed. Whether a particular component handles only transfers or passengers plus their visitors depends on the particular terminal building layout and airline/airport policy.

An additional complication is that it is necessary to distinguish originating and terminating (O/D) passengers from transfer passengers. Clearly some airport components handle transfer passengers along with O/D passengers, e.g., departure lounges, jetways, and some corridors. Other components do not handle transfer passengers at all (the entire access/egress subsystem, baggage check-in, baggage claim, security, etc.)

In order to solve the above mentioned issues, it is proposed that total passenger demand rate including transfers, i.e., enplanements and deplanements be used as the common unit of capacity. The actual passenger demand rate on any particular component is then obtained by taking the total airport demand and factoring in (or out, depending on the component) transfer passengers, visitors and employees where appropriate.

Overall Airport Capacity

In order to estimate total airport system capacity, it is necessary to transform the total airport passenger demand rate into the actual demands on the individual components and subsystems. Hence there is a hierarchy of demand that can be described as follows:

(1) Demand on Airport System (say, at system boundary): a function of the service rate or output of either off-airport access/egress system on the landside or the approach/departure airspace on the airside.

(2) Demand on an Airport Subsystem (at subsystem boundary): a function of the service rates and intra-airport transfer times of preceding subsystems and the fraction of airport passenger demand using the subsystem.

(3) Demand on an Airport Component (at component boundary): a function of the service rates of preceding components and the fraction of airport passenger demand using the component.

It is also necessary to know the level-of-service criteria and to estimate the maximum service rate of each component. The relationships among the above three levels of capacity are illustrated conceptually by the schematic representation in Figs 4.2, 4.3, and 4.4.

Figure 4.2 illustrates the relationship between component capacity and overall airport capacity, given the relationship between total airport demand and the component demand and a level-of-service measure and criterion. Thus, it is theoretically possible to obtain, for a particular component, the kind of relationship illustrated in Fig 4.3, where from a given component level-of-service criterion, it is possible to derive the corresponding component-limited overall airport capacity. Figure 4.4 illustrates the way to obtain subsystem and overall airport system capacity from a comparison of the various component-limited capacities. The limiting airport demand rate is imposed by the component which, receiving this demand as an input, first reaches its specified level-of-service criterion--see line D-D in Fig 4.4. Any demand rate above this limiting one violates the level-of-service criterion of that particular component.

Note that all of the level-of-service criteria in Figs 4.2 through 4.4 apply to individual components. It is also possible to specify a level-of-service criterion for an entire subsystem, or even for the airport system as a whole. It may turn out that the level-of service criterion is an overall system criterion. To estimate overall airport system capacity, one necessary condition is to identify

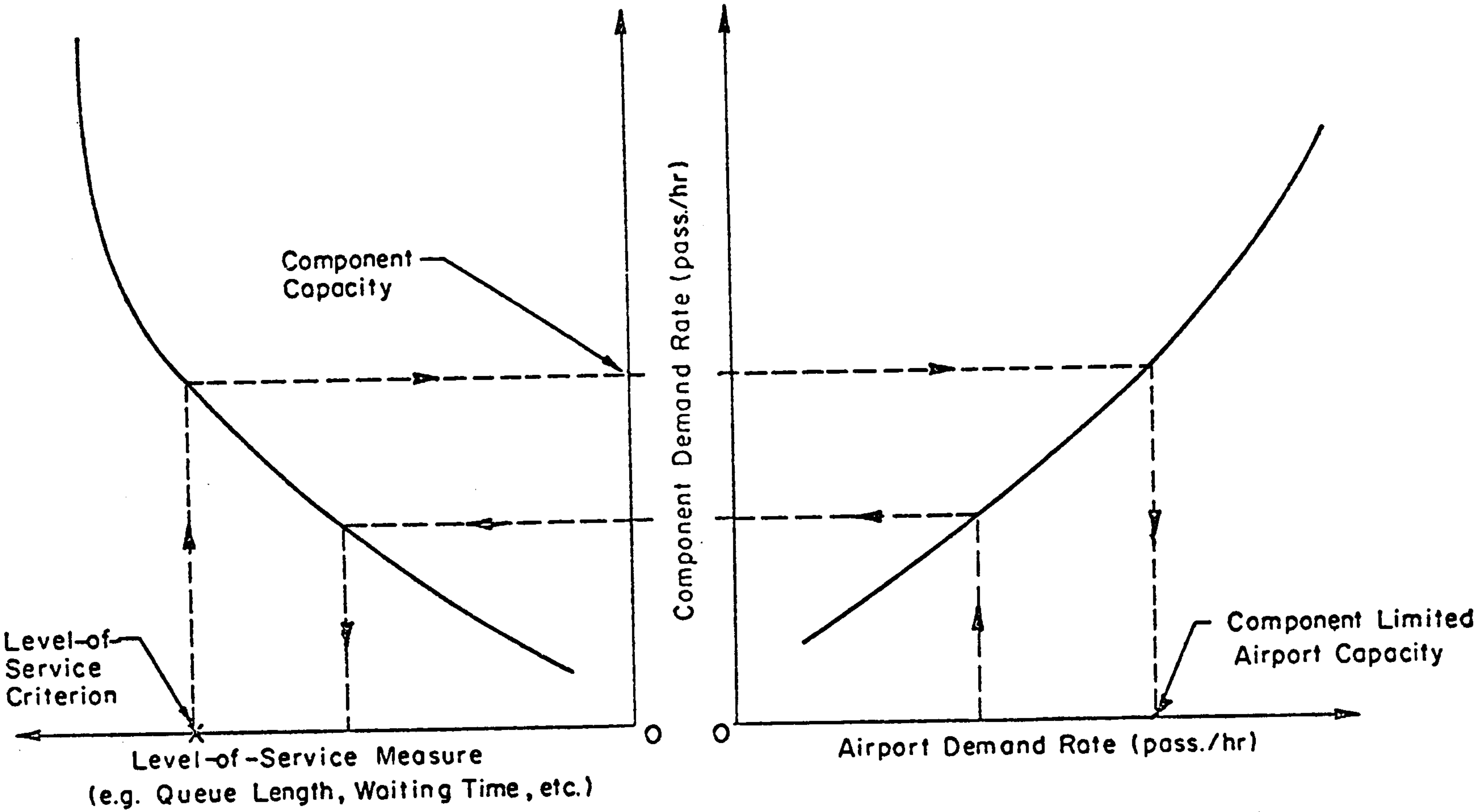


Fig 4.2. Relationships between airport demand and a particular component's demand and level-of-service.

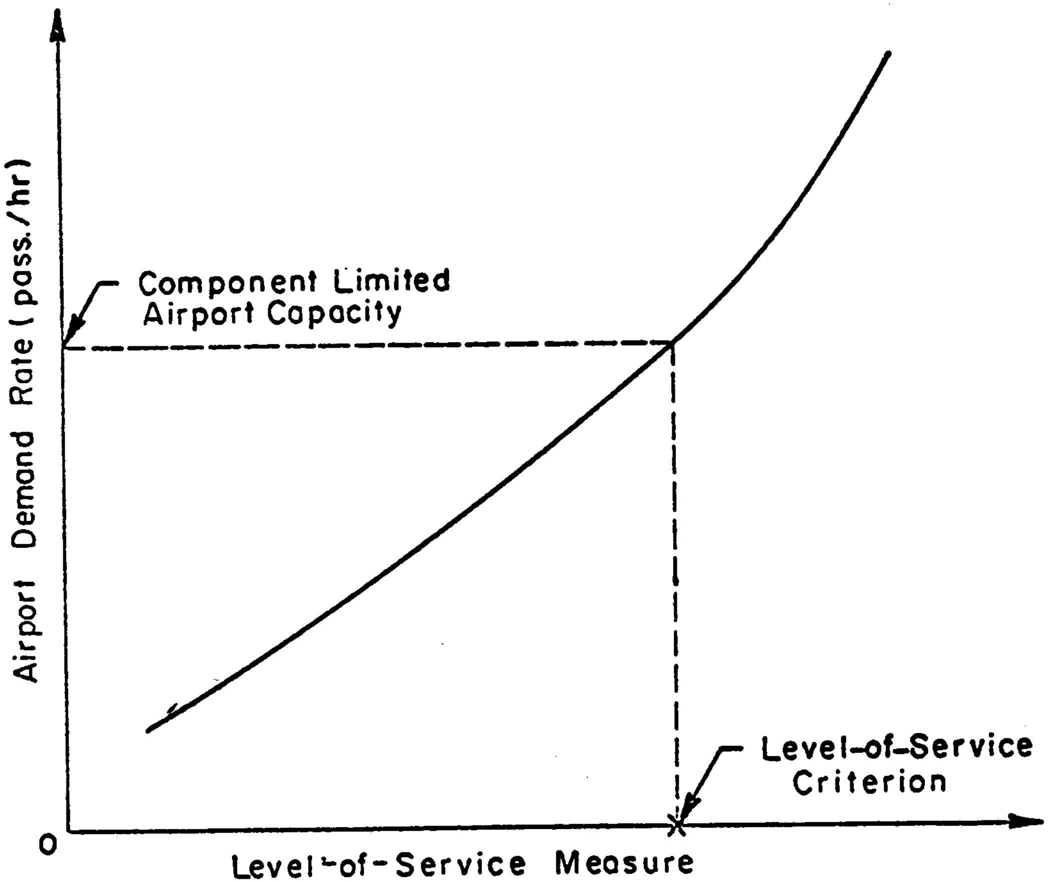


Fig 4.3. Derived relationship between airport demand and a particular component's level-of-service.

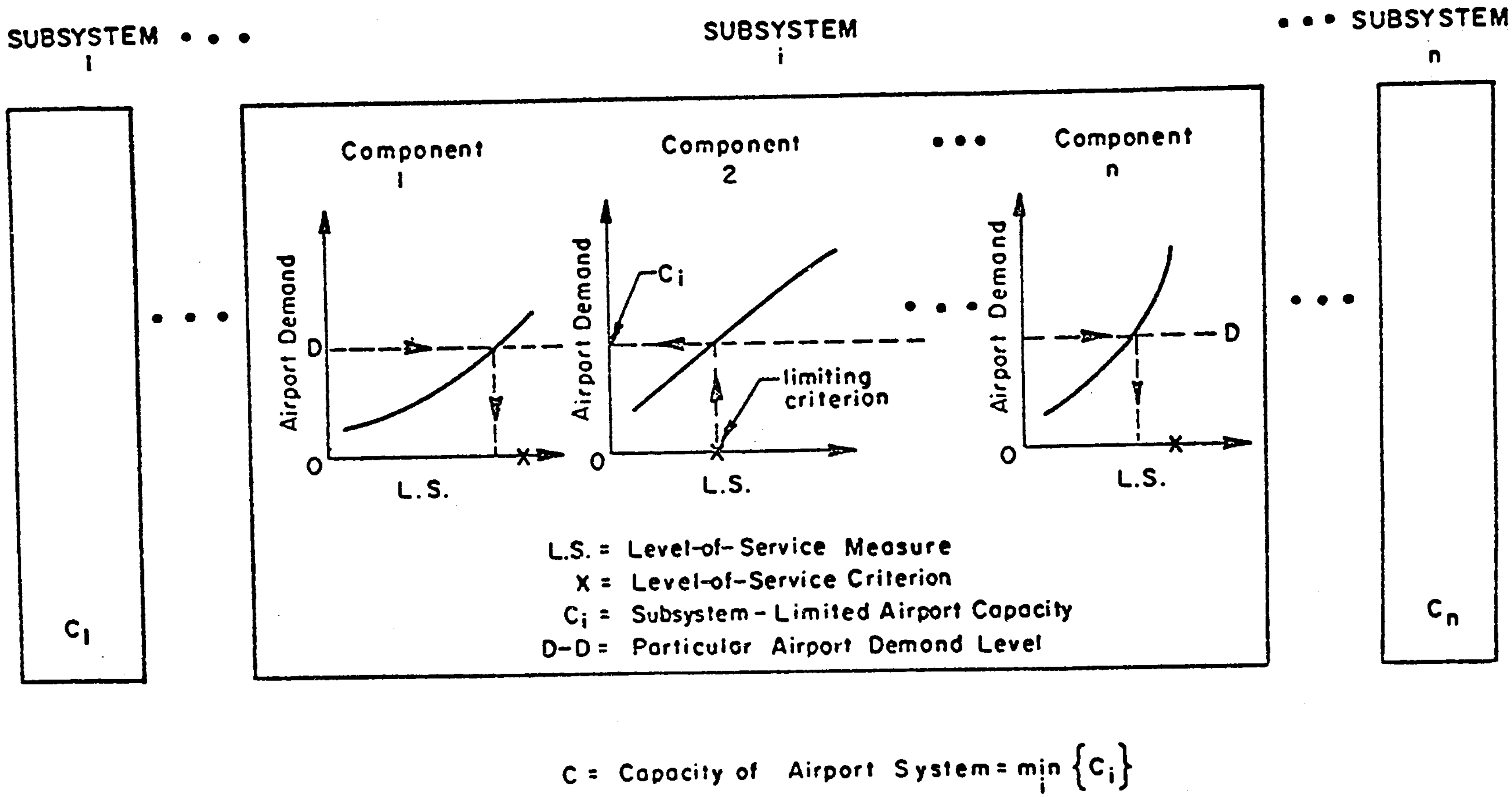


Fig 4.4. Concept of airport system capacity as minimum of various-component-limited airport capacities.

bottlenecks. Bottlenecks, however, do not necessarily increase or balance the overall capacity since some bottlenecks may cause other bottlenecks or alleviate potential bottlenecks at other components or subsystems. One bottleneck may have as critical an impact on overall level-of-service as many bottlenecks. The total delay incurred by a system may be more crucial than the number of components that fail to meet specified level-of-service criteria. There need to be some behavioral studies for many alternative systems as to which systems are better or more balanced. The flexibility to estimate capacity restrictions imposed by subsystem and system level-of-service criteria is a subject to be developed further.

Summary

The existing definitions of airport capacity are reviewed, and definitions are developed for airport capacity, which apply to the airport system as a whole as well as the individual components. Level-of-service concepts are used in the definition of airport capacity in order to include qualitative as well as quantitative measures of the service provided by the airport.

There appears to be no accepted definition of level-of-service regarding airport capacity. To determine the most appropriate dimensions in which to express levels-of-serivce, attitudinal surveys should be conducted to explore the attributes of airport service that passengers value the most.

CHAPTER 5. OVERALL AIRPORT CAPACITY MODEL

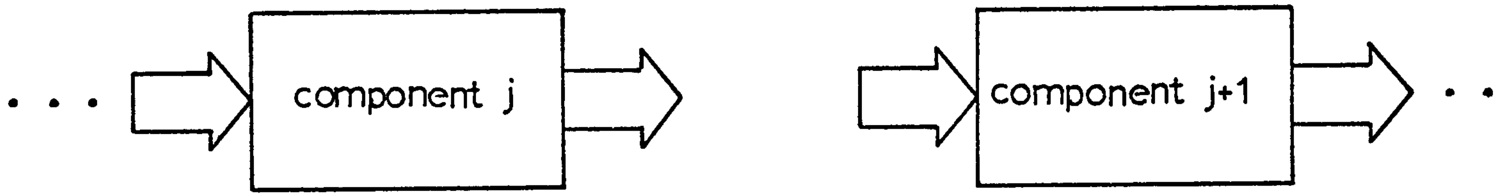
Introduction

Many of the processes occurring in airport passenger flow can be explained as a sequence of queueing processes. In the passenger terminal, for example, a passenger checks his baggage at a ticket counter, then joins a queue at a security inspection station, and so on, until finally he joins a queue to board the aircraft. The characteristic feature of this series system is that the output from one set of services contributes to the input to the next.

The purpose of this chapter is to present an analytical procedure of tying together airport component models into a modular airport system model. The main thrust of the approach lies in the hypothesis that the arrival rate at a component can be expressed as a function of the output rates of preceding components. Figure 5.1 illustrates the general concept of this procedure.

Deterministic queueing models are used for illustration in this chapter. This overall model is designed to estimate the input demand to each component in succession and to estimate component level-of-service measures. This estimation using a tandem queue concept is depicted in a simplified form in Fig 5.2.

The initial input demand to an airport system is assumed to be generated at the airport gates on the landside and the terminal airspace on the airside. These initial patterns are



Input to Component j+1 = f(Output from Component j)

Fig 5.1. Concept of synthesizing component models together.

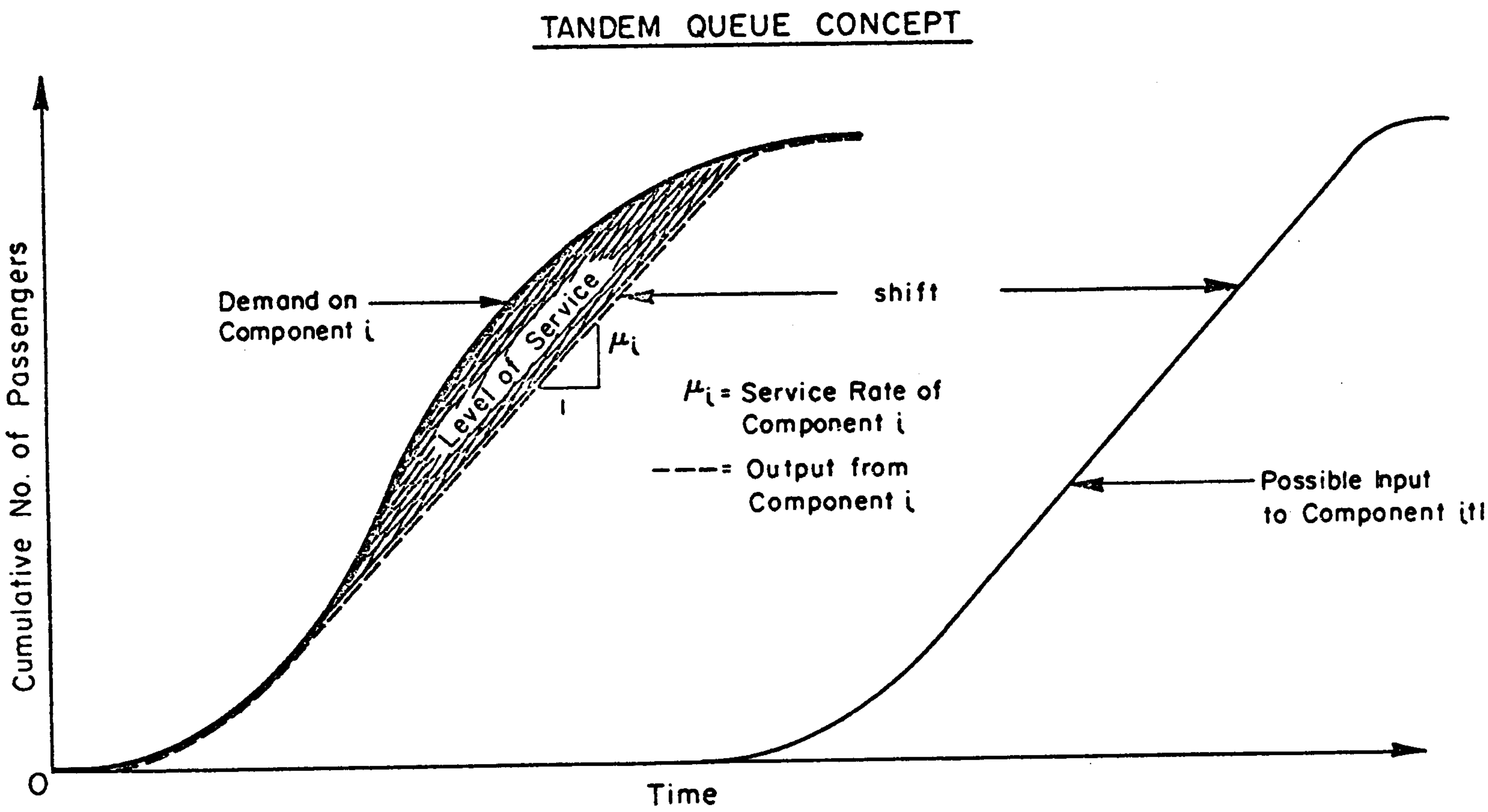


Fig 5.2. Tandem queues concept of translating input/output distributions.

subject to change according to service restrictions imposed by the successive airport components. Because of the changing patterns of demand within an airport, it is necessary to analyze components in sequence in order to evaluate overall airport capacity. The main underlying reason for this procedure is the non-uniformity of the levels-of-service at various airport components which leads to the development of one or more bottleneck situations. Since a bottleneck may govern overall airport capacity, the ability to identify such situations is essential in any capacity model of an airport system.

Demand Generation

Given ultimate capacities or maximum service rates of individual components, one of the basic factors in defining level-of-service related capacity is the demand pattern, which defines the expected variation in demand for airport component by time of day as well as day of year.

A key factor in identifying the demand pattern is the schedule of aircraft movements, since the pattern of aircraft movement is directly related to the role of the airport and the type of traffic that is served.

Definition of Airport Configuration

A flow on an airport system is quite complex. Multiple orgins are connected to one or more destinations and vice versa. A flow for an individual flight merges, diverges, and sometimes backtracks at various points within the airport. A network is used to represent the configuration of an airport system. In the adopted network representation, airport components are represented by nodes; that is, node j refers to either a processing component or a transport component, e.g., a ticket counter or a roadway, respectively. The links describe the connectivity of the components and directions of flow. No meaning is given to the link except that of a precedence relationship between the components at its two ends.

As shown in Fig 2.3 in Chapter 2, any airport can be represented by an unordered set of nodes. Depending upon the actual configuration of an airport in question, ordered sets of nodes can be defined by applying relevant link connections.

Conceptual Framework of Modeling

As an illustration of the approach, consider any one-way flow, either boarding or deboarding, in an airport. It is assumed that all the trips are generated at the airport system boundary from the airline schedule. To explain the modeling procedure in general terms, however, assume that arrivals can be generated at any arbitrary airport component. Based on the hypothesis that the output of one component contributes the input to the next, estimates of delay at each component are obtained by superimposing component service-rates on derived aggregate demand patterns. This delay and a deterministic time shift are used as the basis for estimating each component's contribution to the arrival patterns at subsequent components in sequence.

Consider first a simple conceptualization of a flow on a directed network in Fig 5.3 in which all the flight demand is fed from one component to one or more succeeding components. For simplicity, suppose that one flight demand uses one and only one path. A demand for one flight will not be split along the path on this network and each path evidently serves flows for disjoint sets of flights.

Assume now that one observes the arrival pattern of passengers for flight i at component j . The cumulative number of arrivals can be plotted versus time as in Fig 5.4, where;

$a_i^{(j)}(t)$ = instantaneous arrival rate for flight i at component j at time t , and

$A_i^{(j)}(t)$ = $\int_{-\infty}^{t} a_i^{(j)}(t)dt$ = cumulative number of arriving units by time t ,

t_o^i = departure time of flight i (say, from a schedule), and

M_i = total number of arriving units for flight i .

The arrival pattern in Fig 5.4 is the input to component j . This component may be either a processor or a transport component. If one assumes that the service times for component j are approximately the same for all units of flow and that no delays occur at j ,

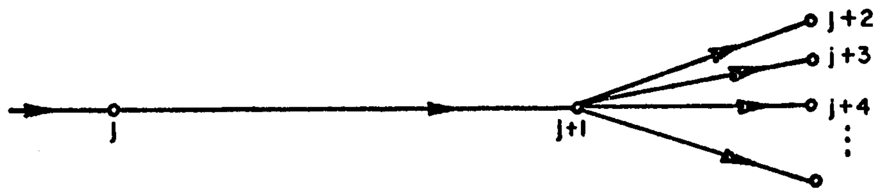


Fig 5.3. Flight dependent network with one-feeder.

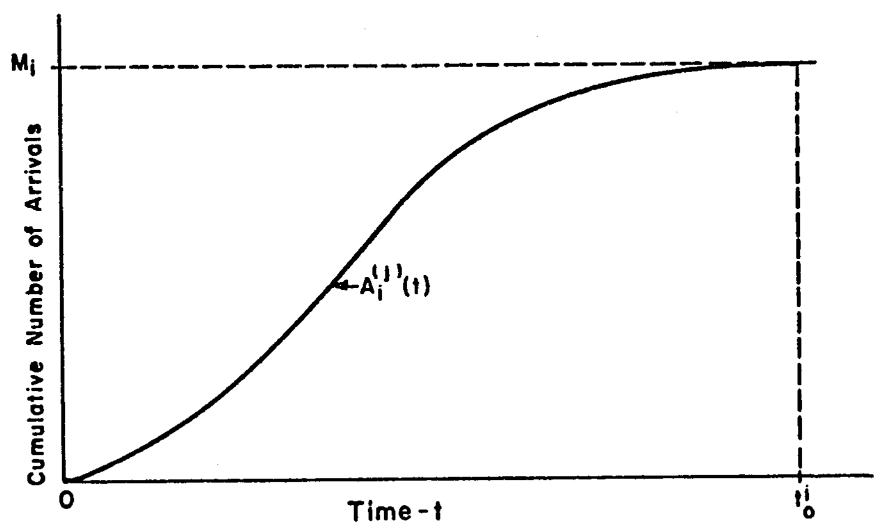


Fig 5.4. Cumulative number of arrivals for flight i at component j .

the progression of flows through component j is a mere translation of its arrival pattern, $A_i^{(j)}(t)$, along the time axis by an amount equal to component j's service time. This no-delay case is shown in Fig 5.5. That is to say, the arrival pattern at component $j + 1$, say $A_i^{(j+1)}(t)$ would be simply a translation in time of the arrival pattern at component j, if there is no delay due to limited capacity at component j. Thus, one could relate the two input distributions as

$$A_i^{(j+1)}(t + \tau_j) = A_i^{(j)}(t) \tag{5.1}$$

where

$$\tau_j = \text{service time of component } j .$$

During peak periods, it is likely that the demand rate will exceed the maximum component service rate resulting in delay being imposed on the travel units. In this case, the arrival pattern at $j+1$ is obtained by shifting the arrival pattern at j by an amount equal to the service time of j plus instantaneous (time dependent) delay. There is a need to estimate how arrival patterns for individual flights would change at subsequent components because of the delay incurred at previous components. This application of the delay at the disaggregate level, i.e., to individual flight arrival patterns is necessitated by the fact that airport flow tends to merge and diverge along airport components

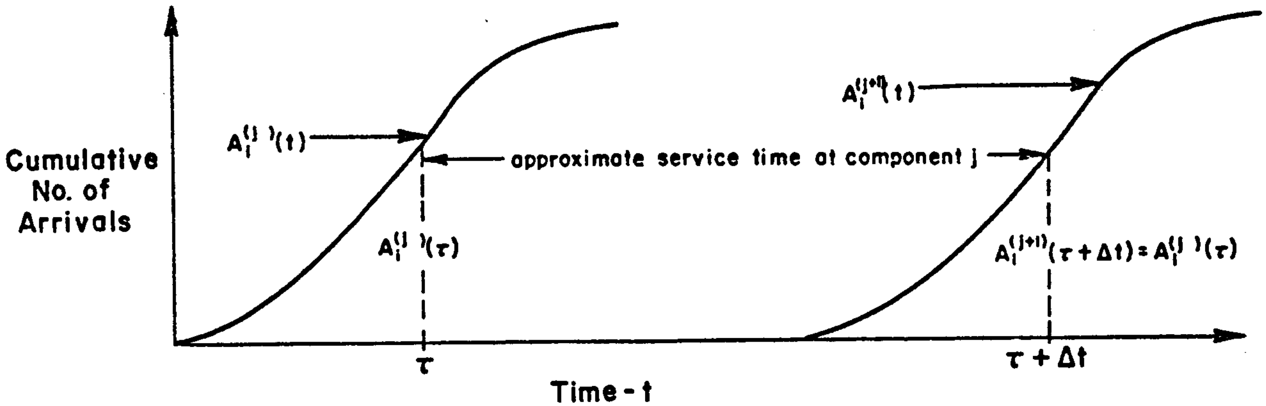


Fig 5.5. Translation of flow without delay.

and that any one component handles demand aggregated over a particular set of flights. The arrival pattern at component j is in fact a superposition of the individual arrival patterns at j of individual flights. By superimposing individual arrival rates as in Fig 5.6 and overlaying the maximum service rate of component j, one can obtain the time dependent delay, if any, caused by a restrictive service rate of a component during peak periods as shown in Fig 5.7, where

$$a^{(j)}(t)dt = \sum_i a_i^{(j)}(t)dt$$

$$= \sum_i [A_i^{(j)}(t + dt) - A_i^{(j)}(t)] \text{ and}$$

$$A^{(j)}(t) = \sum_i A_i^{(j)}(t) \tag{5.2}$$

Any travel unit arriving at some time t' in the interval (t_a, t_b), regardless of flights, suffers a delay, $W^{(j)}(t')$, and each individual flight arrival pattern would be shifted accordingly at that instant. With delay information obtained in Fig 5.7, one can go back to Fig 5.5 and adjust each individual flight arrival pattern at component $j+1$ as shown in Fig 5.8, where $A_i^{(j+1)}(t)$ is the delay-adjusted arrival pattern at component $j+1$. When delay occurs, two adjacent arrivals patterns are equated as

$$A_i^{(j)}(t) = A_i^{(j+1)}(t + W^{(j)}(t) + \tau_j) \tag{5.3}$$

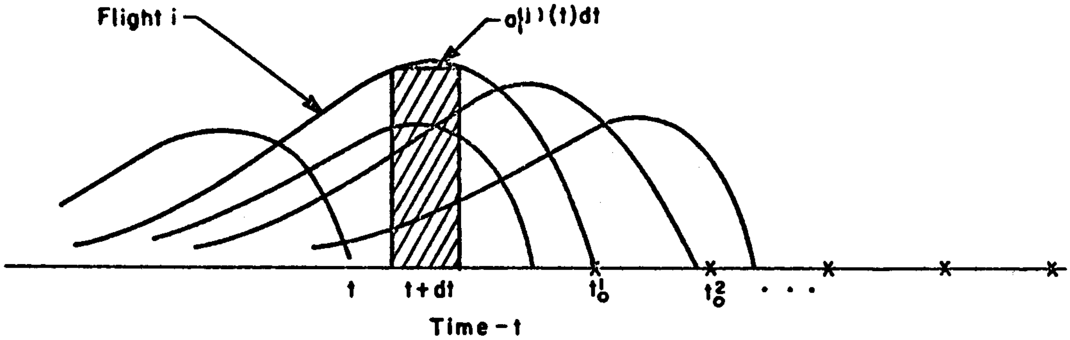


Fig 5.6. Supposition of arrival rates.

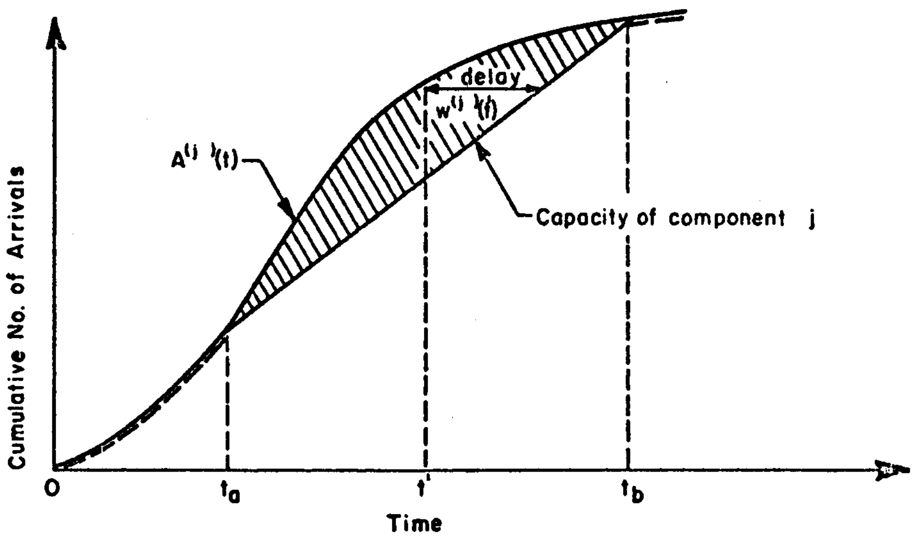


Fig 5.7. Delay caused by component j's capacity constraint on aggregate level.

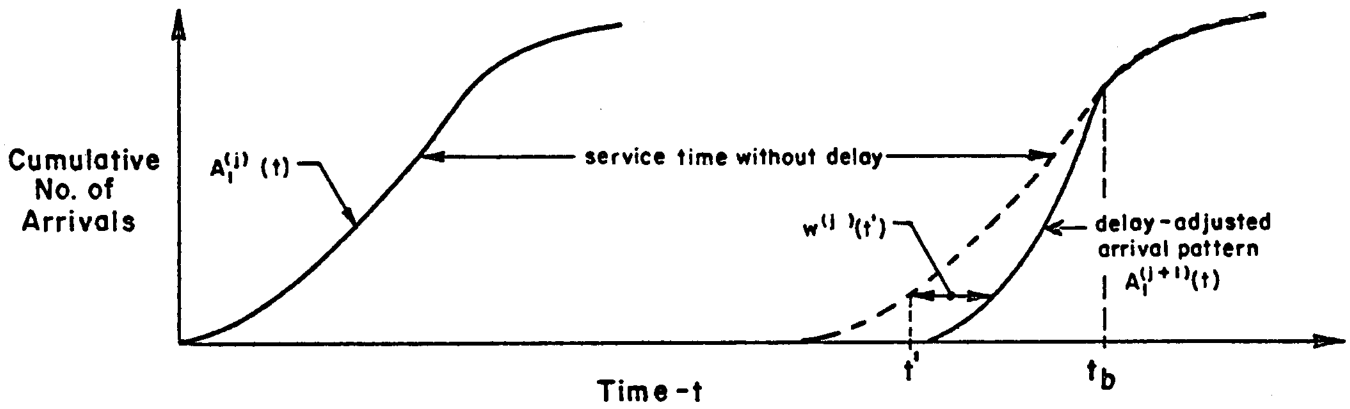


Fig 5.8. Translation of flow with delay.

Note that if the disaggregate arrival patterns in Fig 5.8 were superimposed for all flights one would get exactly the inside envelope of curves in Fig 5.7 provided that no flow is lost from component j and $j+1$.

Individual flight arrival patterns can be aggregated for any appropriate set $\{I\}$ of flights. In Fig 5.3, for example, all of the flights are aggregated at components j and $j+1$. However, beyond component $j+1$, the aggregation will be over disjoint sets of flights going to each of components $j+2$, $j+3$, etc. One can follow the same procedure and can equate the input and output distributions by using delay measures and transfer times. The tandem-queue algorithm discussed above is illustrated and explained in Figs 5.9 and 5.10 for two adjacent components for the simplified case where component j is the one and only contributor to the arrivals at component $j+1$ and all flow from j goes to $j+1$ (see Fig 5.3).

Generalization of the Concept

The conceptual framework has been demonstrated for the simplest case of a pair of successive components j and $j+1$. In some cases, however, many of the airport components are flight-independent and demands are fed from multiple sources. A flow for a single flight, for example, may split apart at some components and flows from several flights may join together at others. To generalize the above conceptual framework, consider the following cases:

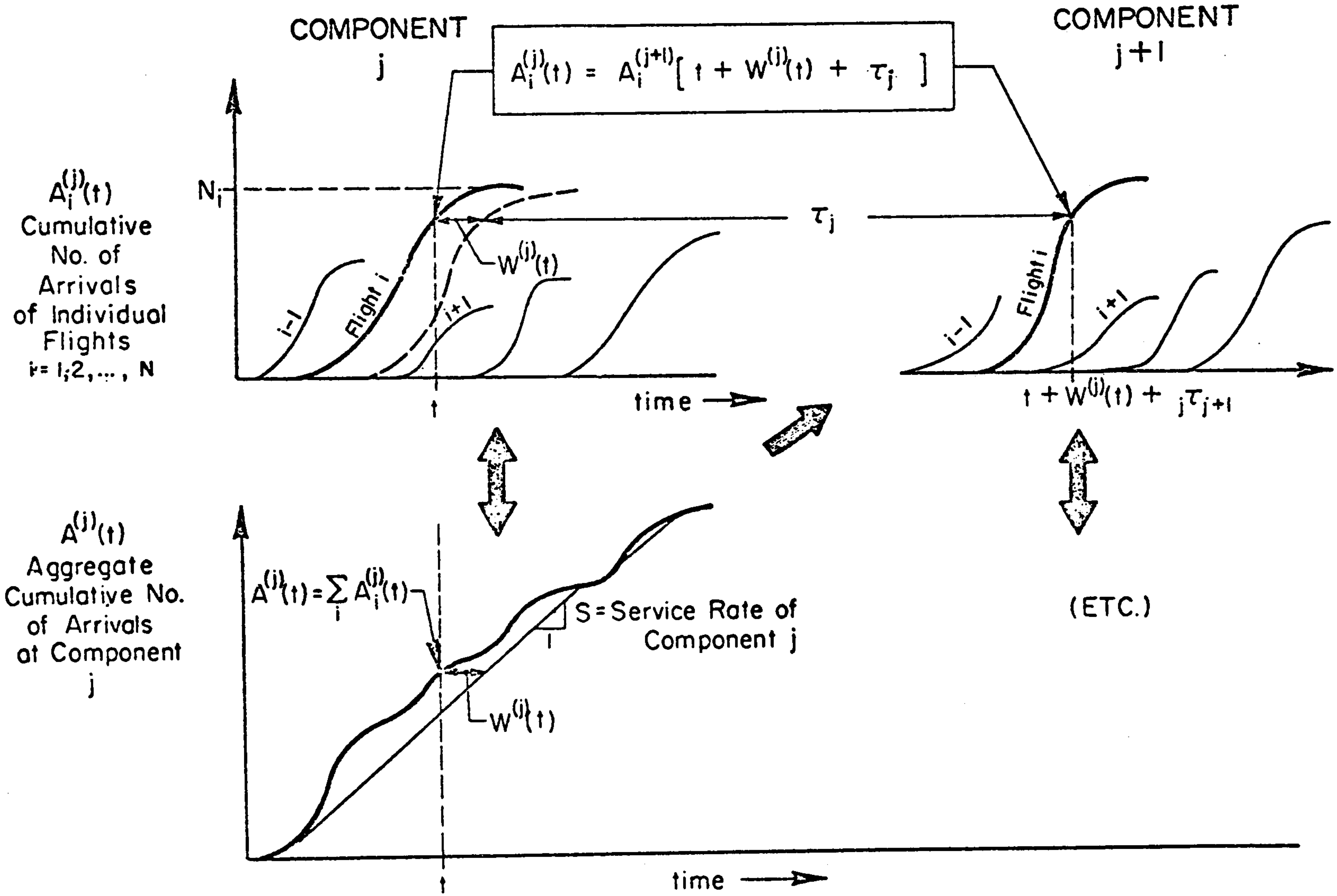


Fig 5.9. Capacity evaluation algorithm.

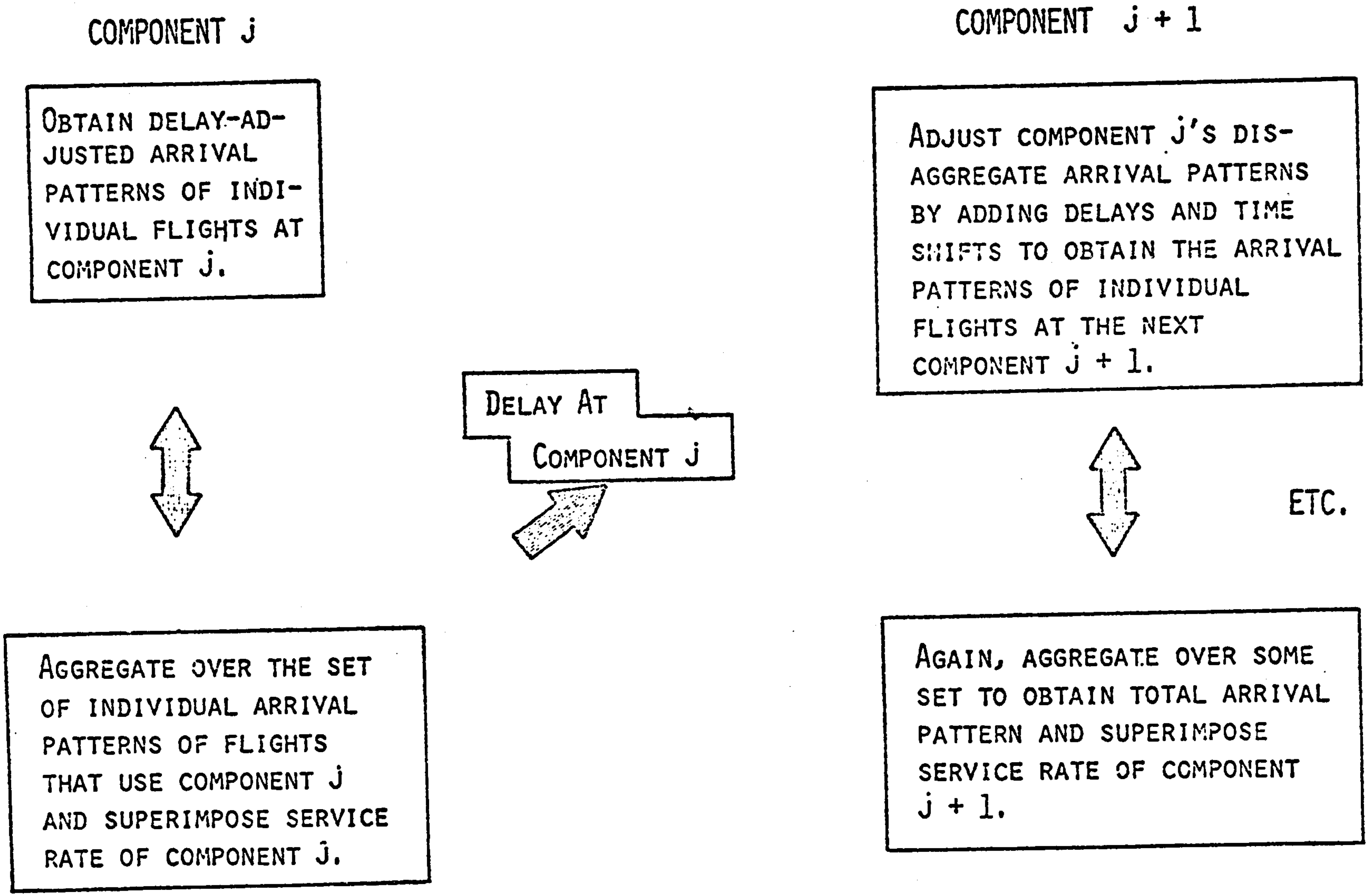


Fig 5.10. Capacity evaluation algorithm.

Flow on Flight-Independent Network with One Feeder. Consider a network segment in Fig 5.11, where flight demand is fed from one source and splits into flows to n subsequent components, e.g., flow from a main access roadway to ramps. To equate the arrival patterns of two successive components j and $(j+1)_k$, $k = 1, 2, \ldots, n$, let $A_i^{(j+1)_k}(t)$ be the input to component $(j+1)_k$. Using the same argument as before, arrivals are related as follows:

$$A_i^{(j+1)_k}(t + w^{(j)}(t) + \tau_j) = \alpha_k A_i^{(j)}(t) \qquad (5.4)$$

where

α_k is a factor describing the proportion of flow which splits to component (j+1), $k = 1, 2, \ldots,$ n , so that $\Sigma\, \alpha_k = 1$.

Note that the α_k factor is, itself, probably time dependent; thus one could write $\alpha_k(t)$ for α_k in Eq 5.4.

Flow on Network with Multiple Feeders. The arrivals for even a single flight can be fed to a particular component from multiple sources as shown in Fig 5.12. For example, curbside arrivals for flight i may be from different access routes. Arrivals at a ticket counter may consist of outputs from parking lits, curbsides, etc. In this case, the disaggregate arrivals at two successive components j_k , $k = 1, 2, \ldots, n$, and j+1 are equated as follows:

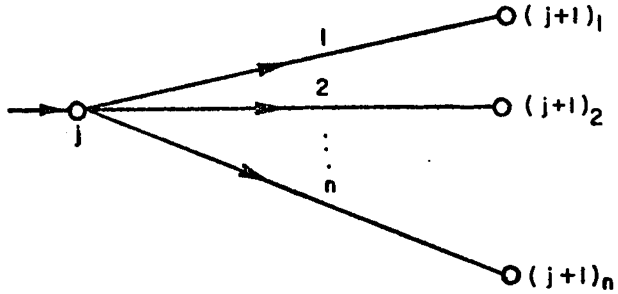


Fig 5.11. Flight independent network with one feeder.

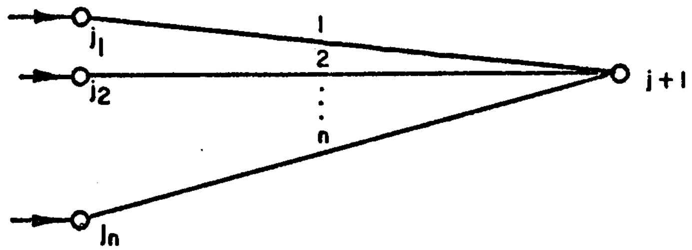


Fig 5.12. Network with multiple feeders.

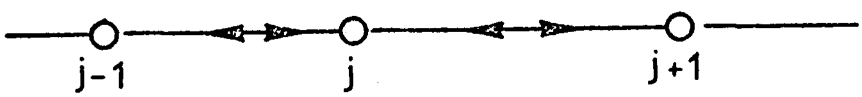


Fig 5.13. Network with two-directional feeders.

$$A_i^{(j+1)_k}(t) = \sum_{k=1}^{n} A_i^{(j)_k}(t - w^{(j)_k}(t) - \tau_{j_k}) \qquad (5.5)$$

where

$$A_i^{(j)_k}(t) = \text{flight } i \text{ demand for component } j_k .$$

Multiple Feeders and Multiple Sources. In general, when there are m possible previous components and n possible subsequent components, the input relationship on this network of queues can be constructed as

$$A_k^{(j+1)_k}(t) = \sum_{\ell=1}^{m} \alpha_k A_k^{(j)_\ell}(t - w^{(j)_\ell}(t) + \tau_{j_\ell}) \quad (5.6)$$

where

α_k^{ℓ} = flow split proportion from component j_ℓ to $(j+1)_{k'}$,

ℓ = 1, 2, . . . , m and k = 1, 2, . . . , n ,

$A_i^{(j)_\ell}(t)$ = flight i demand to component j_ℓ by time t ,

$w^{(j)_\ell}$ = delay at component j_ℓ , and

τ_{j_ℓ} = service time at component j_ℓ .

Considerations have been given to the flow on a directed network. However, there are some components in an airport, which serve bi-directional flows at the same time, e.g., corridors.

This is illustrated in Fig 5.13, where component j must serve two directioal flows. If the interaction of two opposite flows is assumed negligible, it is reasonable to assume that applicable service rates for each direction would be determined by the demand ratio of two opposite flows. To get the delay measure, the same procedure still applies, but demand aggregation now includes opposite flows. To illustrate, for example, consider bi-directional arrival patterns at component j, $A^{(j)}(t)$ and $D^{(j)}(t)$, and let μ_j be the component j's service rate. The service rate applicable to each directional flow can be determined by ratios of demand rates, i.e.,

$$\mu_j^{1}(t) = \mu_j \cdot a^{(j)}(t) \{a^{(j)}(t) + d^{(j)}(t)\}$$

and

$$\mu_j^{2}(t) = 1 - \mu_j^{1}(t) \tag{5.7}$$

for demand patterns $A^{(j)}(t)$ and $D^{(j)}(t)$, respectively,

where

$$a^{(j)}(t) = d\,A^{(j)}(t)/_{dt}$$

and (5.8)

$$d^{(j)}(t) = d\,D^{(j)}(t)/_{dt}$$

By the same procedure described earlier in the chapter, delay adjusted arrival patterns for individual flights can be obtained by applying the delay due to $\mu_j^{1}(t)$ and $\mu_j^{2}(t)$.

Notes on Overall Capacity Evaluation

The evaluation of overall airport capacity is concerned with funneling the flow through an airport system and finding a maximum allowable amount of flow as limited by level-of-service criteria chosen within the system. As an initial input flow rate to a system is processed through system components, its pattern is subject to change with time and space, and expected to carry a sum of delays incurred by limited service rates of individual components. The overall algorithm presented in this chapter shows a continuing process of estimating input flow rates to successive components from previous component's input flow rate given the maximum service rates of individual components.

The discussion of Chapter 4 reveals that a set of specified level-of-service criteria then finally determines the maximum demand rate imposed by a component, subsystem, or system as a whole, whichever is considered most critical. The demand rate is said to be limiting when any demand rate above this violates the critical level-of-service criterion selected. The selection of this critical level is largely dependent upon economic or institutional constraints imposed on the user. The derived limiting demand gives the estimate of overall airport capacity. Overall capacity, then, must be characterized by identifying when, where, and how much this violation occurs.

From the algorithm description, it is clear that one necessary input is a set of component models which provides maximum service rates of individual components and estimates some level-of-service measures with respect to given input demands. In this research, component models are left to be developed in the future. In addition, no models have been developed for flow conversions which involve a flow assignment on network, estimation of actual travel units, and spatial distribution of visitors and transfer passengers. Thus, the algorithm as presented is only conceptual; its implementation can be accomplished in many ways.

Notice that the concept of algorithm has been explained and illustrated using deterministic queueing methods. However, this does not necessarily limit component models to be deterministic. When actual computations are involved, non-deterministic queueing models could also be used as long as they are able to predict output distributions. Once component models are given, the problem of manipulating the algorithm on the computer rests on how to handle the flows among nodes (components) within the system. This would in general require large computer storage and execution time due to a large number of nodes in a system and associated number of node combinations on which flows can be assigned. For a reduction of effort, it may be suggested to prespecify a sequence of nodes which is most likely to handle particular flows in question.

It is finally noted that in the continuing effort of this research, Williamson and McCullough are currently proposing a method of implementing the algorithm based on empirically determined component models (Ref 5). Flows entering and leaving a component are monitored within user-specified discrete time steps, and an output rate in one time step is expressed as a regression function of variables describing the situation of a component in the previous time step; a level-of-service measure is subsequently obtained. These component models are then applied as a network of queues for capacity evaluation.

Summary

A conceptual procedure for system modeling has been discussed in this chapter. When treating a tandem queueing problem, neither Poisson nor some other probabilistic models provide useful results except in very simple and special cases. This is due to the difficulty of estimating output distributions from queues. The tandem queue approach presented here realizes this fact and tries to relate the output distribution as a function of the input distribution and service characteristics by a deterministic approach.

Certain pairs of components between which this deterministic approach is not applicable are treated in the next chapter.

CHAPTER 6. EFFECTS OF ANCILLIARY ACTIVITIES

Introduction

In the previous chapter, it was assumed that arrival distributions are translatable by the use of delay time and deterministic time shifts. Furthermore, every unit of flow was assumed to experience a uniform, deterministic transfer time and to go directly from component j to $j+1$. Inside the terminal building, however, there are sets of component pairs between which there are intervening ancillary activities such as restrooms, coffee shops, cocktail lounges, etc., which tend to randomize the order of flow. Such sets of component pairs inside a terminal building are: ticket counter to boarding lounge, ticket counter to security check, and security check and boarding lounge.

Between such component pairs, it is believed that passenger behavior renders a non-deterministic time shift to the flow of passengers. Using a probability and dwell time associated with joining each of the intervening activities, it is attempted in this chapter to estimate this time shift to relate successive input distributions of such component pairs.

Postulated Model

Consider a pair of terminal building components, j and $j+1$, which are connected by an area where intervening ancillary activities exist. This area is itself a component. Within this component, define a network in such a way that nodes represent intervening activities and links denote corridors connecting these activities.[1]

Assume that each component serves all the flows for flight i . One now expects a pause of flow between components j and $j+1$ at least equal to the total expected amount of dwelling time at the intervening activities. Equation 5.3 can conceptually be rewritten to take this into account as follows:

$$A_i^{(j+1)}(t + w^{(j)}(t) + \tau_j + {}_j\Delta_{j+1} + {}_jD_{j+1}) = A_i^{(j)}(t) \quad (6.1)$$

or

$$A_i^{(j+1)}(t + {}_j\Delta_{j+1} + {}_jD_{j+1}) = G_i^{(j)}(t) \quad (6.2)$$

where

$${}_j\Delta_{j+1}$$ = transfer time from component j to $j+1$,

$${}_jD_{j+1}$$ = total expected dwelling time at intervening activities between component j and $j+1$, and

$$G_i^{(j)}(t)$$ = cumulative number of departures of flight i passengers from component j by time t .

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[1]Since in most cases this component is a wide area and transfer times are determined by the length of trajectories of passenger movements, this network is defined separately from the overall network. The length of a link can be determined by the expected value of the lengths of trajectories of passenger movements.

When a passenger whose flight departs at time t_o is dispatched from component j at time t , his available time for passing through the remaining components is $(t_o - t)$. It is assumed that he allocates this available time to various intervening activities (if any) using his own judgement. He may go directly to the next component or he may spend time at one or more intervening attractions before joining the next queue. Thus, the time at which a passenger joins the next component depends upon his available time and on the available intervening attractions.

To estimate the total dwelling time, consider a split of passenger flows; a person dispatched from component j faces two choices: (1) going directly to component j+1 , and (2) joining one or more of the N possible intervening activities and then going to component j+1 . If he chooses to join an intervening activity, he will subsequently again be faced with the choice of going to component j+1 or joining another intervening activity. This set of serial choices is depicted in Fig 6.1.

Let T be a random variable representing the total time between leaving component j and joining component j+1 , and let D_k be the expected dwell time at each individual intervening activity k , $k = 1, 2, \ldots, N$. The total time shift between components consists of a transfer time plus expected dwell times at intervening activites. To estimate this total time shift, one can compute an expected value conditioned on the activity he chooses. Let X_1 denote the first choice the person makes after

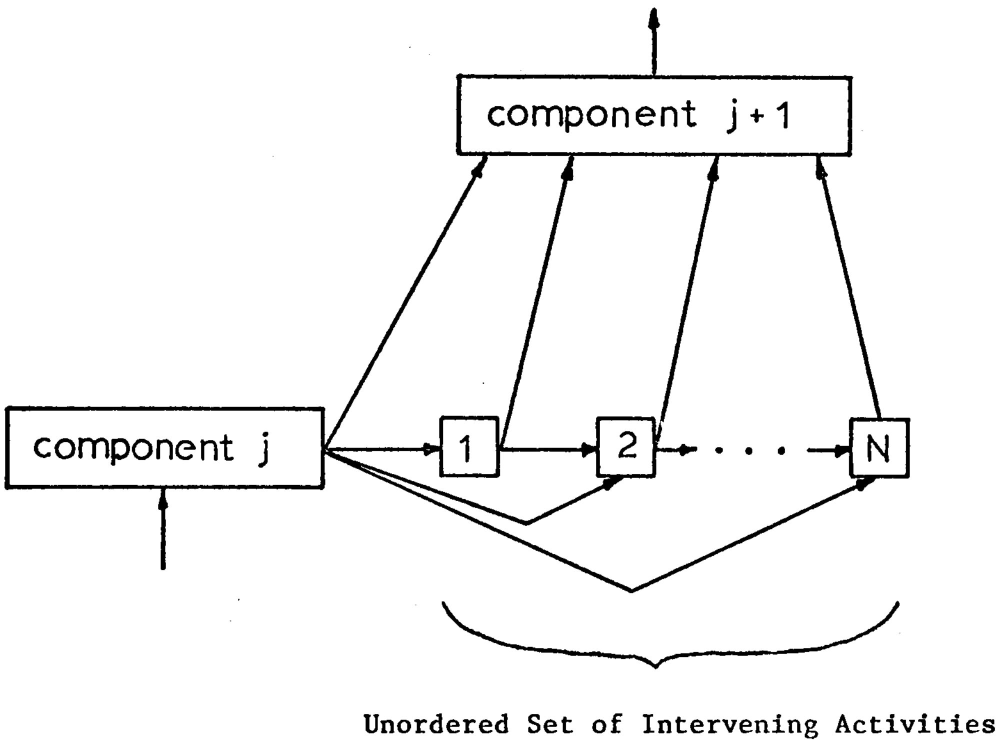

Fig 6.1. Conceptual split of passenger flows.

leaving component j , $X_1 = \{j+1 , k ; k = 1, 2, . . . , N\}$, i.e., X_1 may be component $j+1$ or any of the N intervening activities with probabilities $P \{X_1 = j+1\}$ and $P \{X_1 = k\}$; $k = 1, 2, . . ., N$, respectively. Then

$$E\{T\} = {}_j\Delta_{j+1} P\{X_1 = j+1\} + \sum_{k=1} E\{T|X_1 = k\}P\{X_1 = k\} \qquad (6.3)$$

If a person elects to go to component $j+1$ directly, then he spends only a transfer time, ${}_j\Delta_{j+1}$, but once he decides to join intervening activities, his time shift depends upon his second choice. By conditioning on the activity he chooses on the second time, X_2 , the second term on the right-hand side of Eq 6.3 can be expanded to read:

$$\sum_{k=1}^{n} E\{T|X_1 = k\}P\{X_1 = k\}$$
$$= \sum_{k=1}^{n} \sum_{X_2} E\{T|X_1 = k,X_2\}P\{X_1 = k, X_2\} \qquad (6.4)$$

Equation 6.4 can be further broken down into two portions: the first going directly to component $j+1$, and the second joining still other intervening activities. If Eq 6.4 is expanded for all possible combinations of intervening activities and included in Eq 6.3, the resulting expression for the total expected time shift can be expressed:

$$
\begin{aligned}
E\{T\} = \; & {}_j\Delta_{j+1} P\{X_1 = j+1\} \\
& + \sum_{k=1}^{n} ({}_j\Delta_k + D_k + {}_k\Delta_{j+1}) P\{X_1 = k,\ X_2 = j+1\} \\
& + \sum_{k} \sum_{k+1} ({}_j\Delta_k + D_k + {}_k\Delta_{k+1} + D_{k+1} + {}_{k+1}\Delta_{j+1}) P \\
& \{X_1 = k,\ X_2 = k+1,\ X_3 = j+1\} \\
& + \sum_{k} \sum_{k+1} \sum_{k+2} \ldots
\end{aligned} \tag{6.5}
$$

The first term corresponds to going directly to component $j+1$. Each succeeding term, say the m^{th} term, corresponds to visiting $m-1$ intervening activities. Thus, a passenger who leaves component j at time t is expected to reach component $j+1$ at time $(t + E\{T\}) \leq t_o$.

As stated earlier, the time shift of a person is most likely to be dependent upon his available time. In Eq 6.5, the transfer times are considered constant. Split probabilities and dwell times, however, may be functions of time. Concerning split behavior and dwell times, assume: (1) split probabilities are time-dependent, e.g., Fig 6.2, and (2) dwell times are independent of the order in which a passenger uses the intervening activities and also independent of available time.

Dwell times may be to some extent governed by the available time. For simplicity, however, assume that dwell times are stationary random variables; only their expected values are used in the analysis of this study.

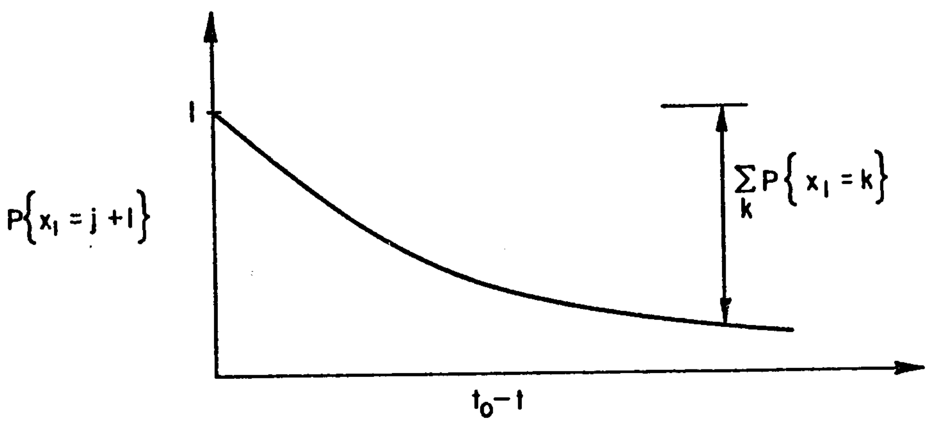

Fig 6.2. Probability of going directly to component j+1 .

Since one can always write

$$P\{X_1, X_2, \ldots, X_n\} = P\{X_1\}P\{X_2|X_1\}. \; . \; .P\{X_n \; X_1, \ldots, X_{n-1}\} \qquad (6.6)$$

the split probabilities can be expressed as functions of the available time. Denoting $P_{j+1} = P\{X_1 = j+1\}$, $P_k P_{k,j+1} = P\{X_1 = k\}$ $P\{X_2 = j+1|X_1 = k\}$, etc., one can write the probability terms in Eq 6.5 as follows:

$$\begin{aligned} P\{X_1 = j+1\} &\doteq P_{j+1}(t_o - t) \\ P\{X_1 = k, X_2 = j+1\} &= P_k(t_o - t) \; P_{k,j+1}(t_o - t - {}_j\Delta_k - D_k) \\ \cdot \qquad\qquad & \qquad \cdot \qquad\qquad \cdot \\ \cdot \qquad\qquad & \qquad \cdot \qquad\qquad \cdot \\ \cdot \qquad\qquad & \qquad \cdot \qquad\qquad \cdot \\ & \text{(etc.)} \end{aligned} \qquad (6.7)$$

Note that Eq 6.5 involves the estimation of a large number of probability functions if the number of activities N becomes large (this is not the case in actual problems). One can simplify the estimation of split probabilities by assuming that a person's probability of joining a particular activity is governed only by his available time, independent of which activities have preceded or will follow that activity, i.e.,

$$\begin{aligned} P_{j+1}(t_o - t) &= P_{k,j+1}(t_o - t) \\ &= P_{(k,k+1),j+1}(t_o - t) = \ldots \end{aligned}$$

$$P_k(t_o - t) = P_{k-1,k}(t_o - t) = P_{(k-2,k-1),k}(t_o - t) = \ldots \tag{6.8}$$

As defined earlier successive right-hand side terms in Eq 6.8 represent one-step probabilities. Equation 6.5 can be rewritten to include the simplifications of Eq 6.8 as follows:

$$E\{T\} = {}_j\Delta_{j+1}P_{j+1}(t_o - t) + \sum_k ({}_j\Delta_k + D_k + {}_k\Delta_{j+1})P_k(t_o - t)P_{j+1}(t_o - t - {}_j\Delta_k - D_k) + \sum_k \sum_{k+1} \ldots \tag{6.9}$$

Given a transfer time matrix and dwell times for intervening activities, along with estimates of the initial split probabilities from component j, then Eq 6.9 gives the total expected time shift between components j and $j+1$. Notice that by Eq 6.9, a passenger is allowed to visit the same intervening activities more than once as long as his available time permits.

Suppose that there are $g_i^{(j)}(t)dt$ [2] passengers released from component j during the time interval $(t, t+dt)$. If one assumes all the passengers are homogeneous, i.e., that their split behavior is alike, then one can compute the number of passengers joining different activities by multiplying the corresponding

---

2

$$\int_{-\infty}^{t} g_i^{(j)}(t)dt = G_i^{(j)}(t)$$

probabilities by the number $g_i^{(j)}(t)dt$. By applying the time shift obtained in Eq 6.9, one finally constructs the input distribution of component $j+1$ as

$$A_i^{(j+1)}(t + E\{T\}) = G_i^{(j)}(t) \tag{6.10}$$

Eq 6.10 transforms an output from component j into an input to component $j+1$ with the order of flow being undisrupted. An application of the intervening activities model is treated in the next chapter.

Summary

The time shift of a flow due to intervening activity usages has been studied by isolating a pair of successive components. The proposed models of Eqs 6.9 and 6.10 can still be applied to other sets of intervening activities between successive sets of components in an airport system, for the time shift can be computed from the airport users available times until scheduled aircraft departure times.

Although the model development has been shown for originating passenger flow, the same principles can be applied for transfer flows by identifying a component pair in which the second component's input is affected by intervening activity usages. Note, however, that the model is not adaptable to arriving/deplaning flows. This is because the available times of arriving units are usually unbounded. In many cases, it is reasonable to assume that intervening activity usage does not affect the arriving/deplaning flows.

In the model, expected values of dwell times are defined for individual intervening activities. No attempt has been made to analyze the variance in total dwell time, which would be composed of variation due to the activities visited and variation in the dwell times themselves. Future research should be aimed at estimating these variances.

CHAPTER 7. VALIDATION OF THE INTERVENING ACTIVITIES MODEL

Objective and Scope

The purpose of this chapter is to validate the intervening activities model, derived in Chapter 6, for estimating the total expected dwelling time of airport users at intervening activities nodes between certain pairs of terminal building components. The major assumptions of the model are tested using data collected at Robert Mueller Municipal Airport in Austin, Texas, and San Antonio International Airport. Model estimates of input patterns to components located beyond the intervening activites are compared with actual observations of these patterns.

Also described in this chapter is a data collection technique adapted from Braaksma's time-stamping technique (Refs 17 and 18). The new method is called the "flash-card technique," and its advantages and disadvantages vis-a-vis Braaksma's method are discussed.

Data Collection -- The Flash-Card Technique

The "flash-card" method was devised to study the usage of intervening ancillary activites inside a terminal building. The survey objective was to examine the number of trip makers who utilize intervening activities, and the duration of usage, as a function of the time remaining before their airline departure; this will enable more accurate estimation of the times at which passengers arrive at components located beyond the intervening activities.

The survey technique involves tracing passenger and visitor movements through the terminal building. Briefly, the technique works as follows: each enplaning passenger and related visitor is handed a numbered card (Fig 7.1) as he enters the terminal building, his flight number is recorded, and he is asked to show or flash the card at designated survey stations within the terminal building. At each survey station, card numbers and times at which persons pass the station are recorded by 1 minute or 30 second time intervals. Finally, the card is collected as the passenger or visitor leaves the survey area, either at boarding lounges, security checks, or at the exit doors. Note that, except at the entrance doors, there is no verbal contact with, nor interruption of, passenger and visitor flows. Thus, there are three basic elements of the flash-card survey: card distribution, recording of card numbers by 1-minute or 30-second time intervals, and card collection.

Survey stations are identified by posted signs. Figures 7.2(a),(b) and (c) show the signs for each of the above three basic functions. The three functions are described below:

Card Distribution -- Cards are handed out and corresponding flight numbers are recorded. Distribution stations are located at terminal building entrance doors. Flight numbers are recorded on the the survey form shown in Fig 7.3(a); groups of passengers and related visitors are identified by circled check marks as shown in the figure.

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AIRPORT USER
SURVEY

PLEASE SHOW THIS CARD EACH
TIME YOU PASS A SURVEY
STATION IN THE AIRPORT.
THIS CARD WILL BE COLLECTED
FROM YOU BEFORE YOU LEAVE
THE AIRPORT.
THANK YOU.

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STUDIES

Fig 7.1. A flash-card.

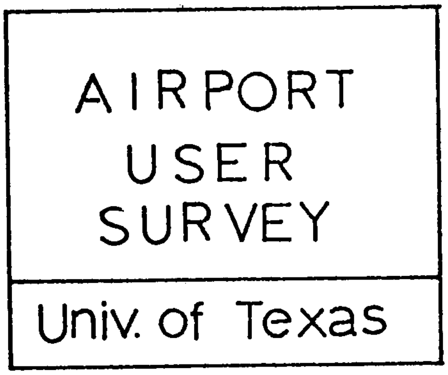


Fig 7.2(a). Posted sign at card distribution stations.

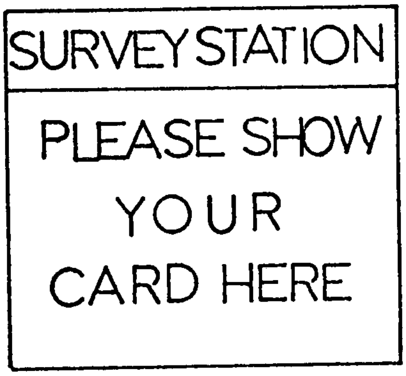


Fig 7.2(b). Posted sign at stations recording card numbers.

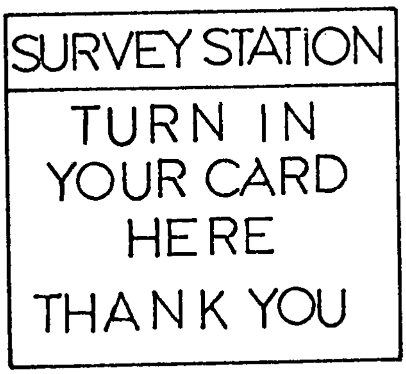


Fig 7.2(c). Posted sign at card collection stations.

Flights / Card Number	pax	vis	pax	vis	pax	vis	pax	vis	pax	vis	pax	vis	pax	vis	pax	vis	Comments
1	✓																
2	✓																
3	✓																
4		✓															

Fig 7.3(a). Survey form at card distribution stations.

Time	Interval Number	Card Numbers Observed	
		In-Flows	Out-Flows
10:30 a.m. to 10:31 a.m	31	548, 321, 389, 951	321, 951

Fig 7.3(b). Survey form for two-way flows.

Time	Interval Number	Card Numbers Observed
10:45 a.m to 10:46 a.m	46	121, 122, 321, 548, 437

Fig 7.3(c). Survey form at card collection stations.

<u>Recording Card Numbers</u> -- Posted signs are located at intervening ancillary facilities such as coffee shops, gift shops, restrooms, newsstands, and the components which immediately precede and follow the intervening activities. Card holders are asked to flash their cards as they pass each survey station. Data are observed and recorded using the survey for in Fig 7.3(b).

<u>Card Collection</u> -- Cards are collected from passengers/visitors as they leave the survey area and the exit times are recorded. Collection stations are located either at boarding lounges or security checks for passengers, and at exit doors for visitors. Figure 7.3(c) shows a data form to be used.

This flash-card method was adapted from the time-stamping technique proposed by Braaksma (Refs 17 and 18). Its principal advantages over Braaksma's method are less expensive equipment (stop watches versus time-stamping machines) and less interference between passengers and surveyors. Braaksma's method, on the other hand, produces data which are more amenable to subsequent analysis, discrete event times rather than events by time slices, and data which are less subject to recording errors. For purposes of this research, the advantages of the flash-card method were considered to outweigh its disadvantages.

An initial survey using the above technique was conducted at Robert Mueller Municipal Airport in Austin, Texas from 12:15 pm to 4:15 pm on June 4, 1976. This airport is well suited for this initial study, because nearly all its intervening activities lie between the ticket counter and security check. The Austin survey was preliminary in that its objective was in part to test public acceptance of the flash-card technique and its impact on terminal operation. The survey results indicated that people were willing to cooperate and the impact of the survey on normal traffic flows was negligible. During this survey a 94 percent card-return rate (344 cards from a total of 368 cards distributed) was obtained for eight scheduled flights of three airlines.

A second survey was performed from 10:00 am to 1:00 pm on November 19, 1976 at San Antonio International Airport. This survey was confined to intervening activities located between the common ticket counter area and a security check which handles most of the major flights. During the San Antonio survey, a total of 712 cards were distributed and 456 were collected, a 64 percent card-return rate, for 12 scheduled flights of 4 domestic airlines. Again, the impact of this survey on normal terminal operation was negligible, but tripmakers at San Antonio were not as cooperative as at Austin as evidenced by the lower card-return rate.

Listed in Table 7.1 are the intervening activities surveyed at two airport terminal buildings as shown in Figs 7.4(a) and (b). It is noted that a dining room and bar at San Antonio airport were closed during most of the survey period. Since so few passengers used these facilities and they are internally connected to a coffee shop as shown in Fig 7.4(a), a dining room, bar, and coffee shop are labeled collectively as a restaurant.

TABLE 7.1. INTERVENING ACTIVITIES AT TWO AIRPORTS

Austin Airport	San Antonio Airport
restaurant	restaurant
gift shop	gift shop
restroom	restroom
telephone	telephone
vending machine	lounge

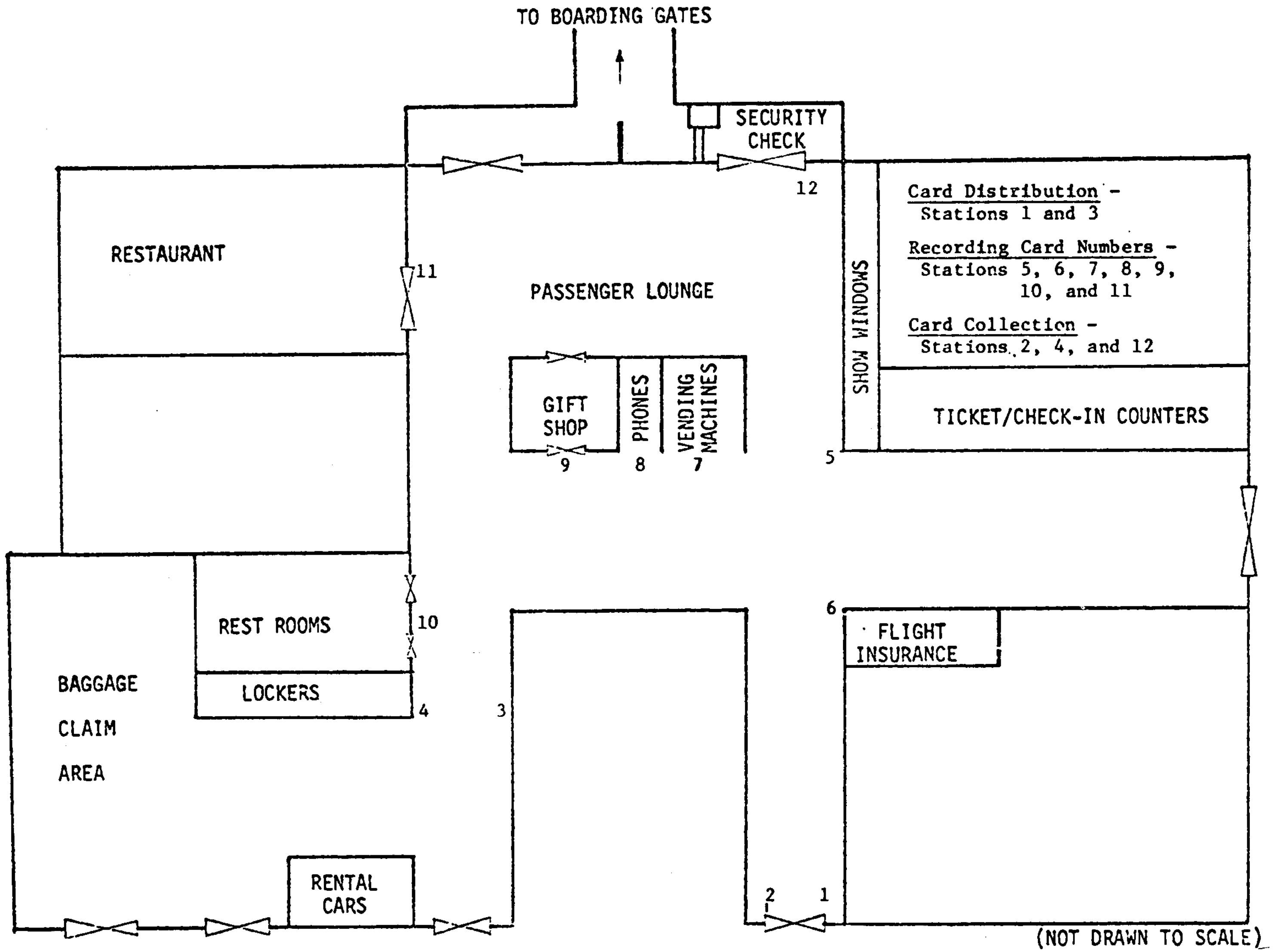


Fig 7.4(a). Austin airport terminal building layout and location of survey stations.

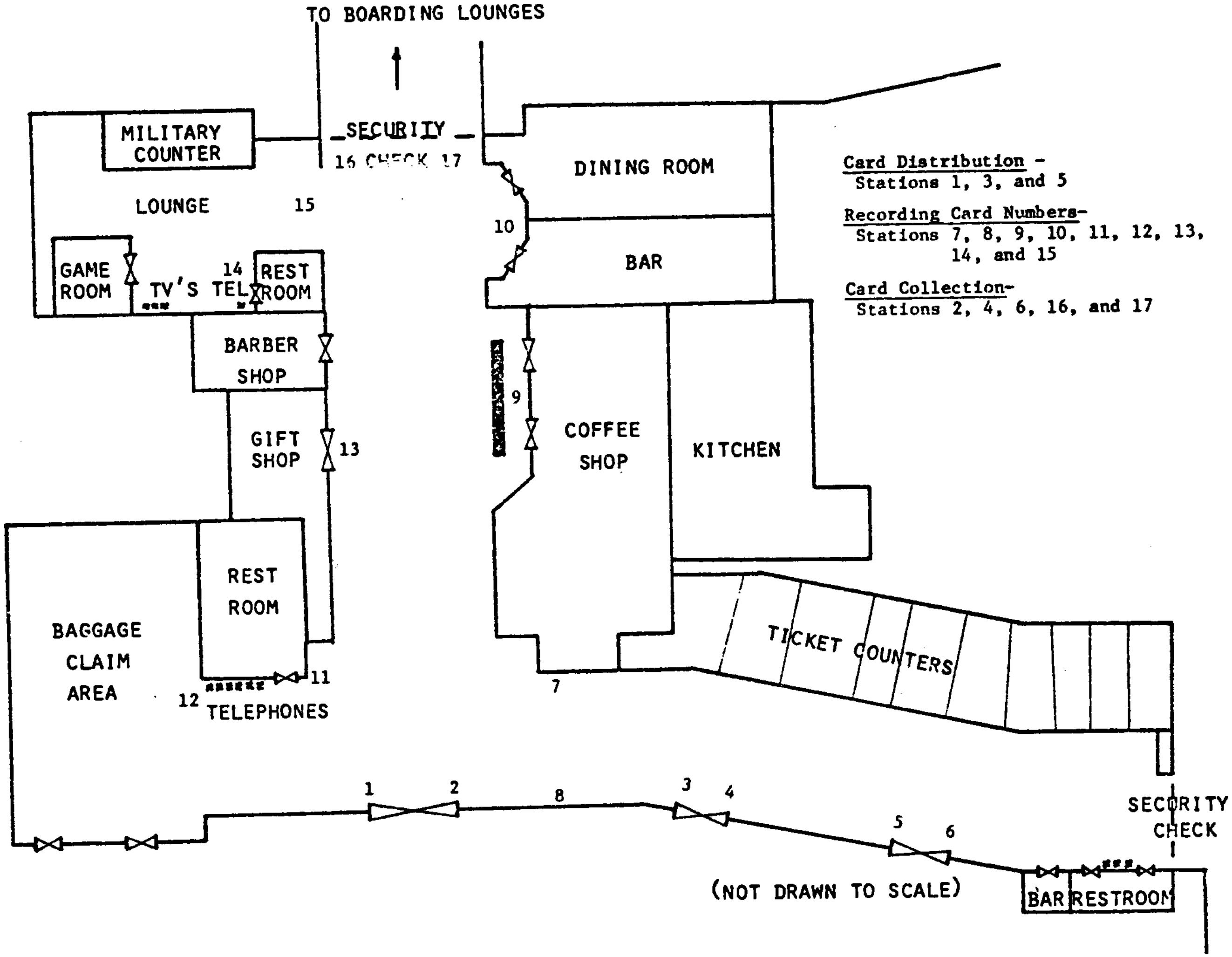


Fig 7.4(b). Layout of San Antonio airport terminal building and location of survey stations.

An attempt was made to distribute as many cards as possible during the two surveys. Although the data provide a fairly complete account of travel patterns of card-holders inside a study area, it has been found that the number of data points is not large enough for the analysis on an individual flight basis. Thus, the data are treated on an aggregate basis except for one or two large flights. The underlying assumption for this data management is that tripmaker behavioral characteristics are independent of individual flights. Only passengers for domestic flights are surveyed. Behavior of international flight passengers probably differs from that of domestic passengers.

Test of Model Assumptions

An important question involving intervening activities is how to characterize their effects on the flow of passengers and visitors. As discussed in Chapter 6, these effects result from a portion of passengers visiting various intervening activities before going on to the next major component. Accordingly, the survey results were analyzed to extract information concerning time-related passenger splits to intervening activities and their dwell times at each one.

Shown in Figs 7.5(a) and (b) are individual trajectories of different persons travelling between the ticket counter and security check for two selected flights, one at Austin and one at San Antonio. The lower scales in Fig 7.5 indicate departure times from the ticket counter while the upper axes stand for input times

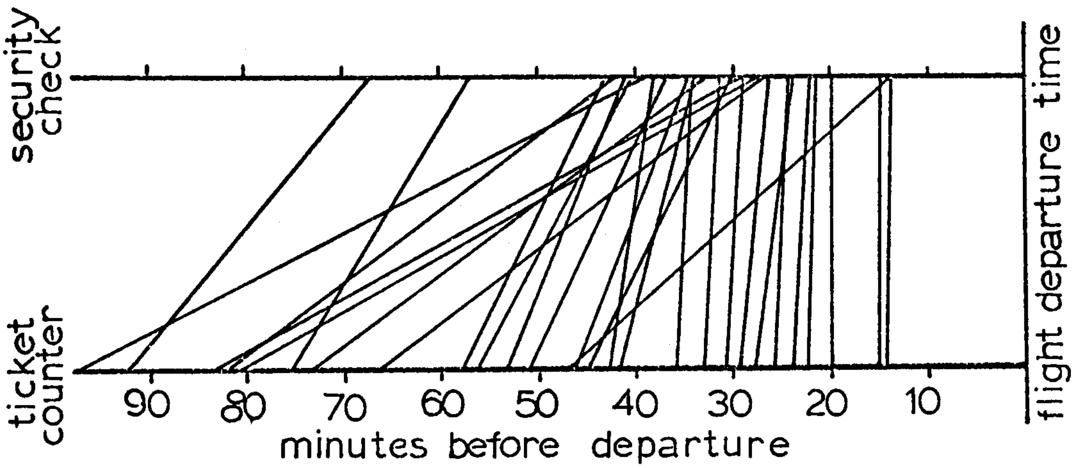


Fig 7.5(a). Randomized order of flow for Flight A at Austin.

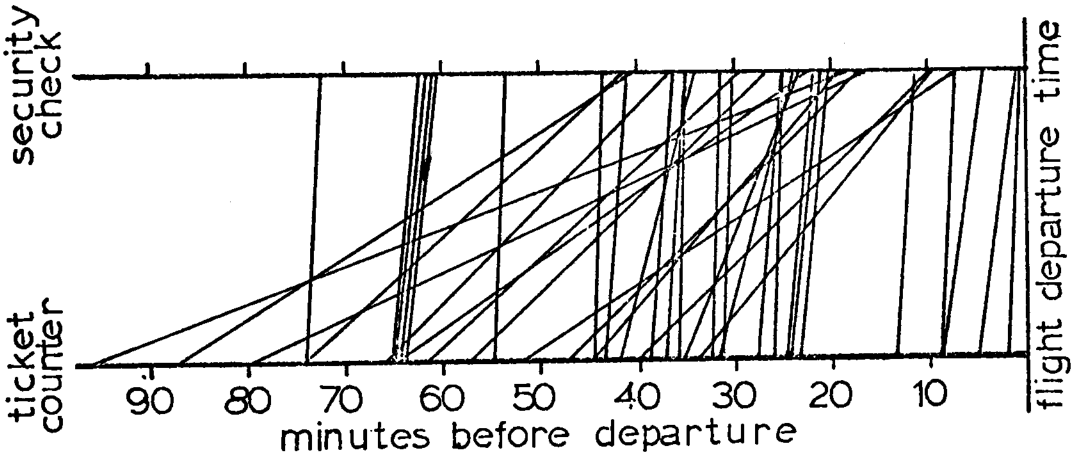


Fig 7.5(b). Randomized order of flow for Flight B at San Antonio.

to the security check. In the figures the lines with flat slopes are associated with passengers using intervening activities; the steep slopes represent persons going directly from the ticket counter to the security check. The many different slopes correspond to different numbers of intervening activites visited and are responsible for the disturbed order of flow and creation of congestions at security checks around 30 to 40 mintues before the flight departure times. Note that this congestion is greater than that which would have occurred if all persons had gone directly to the security check.

Shown in Figs 7.6(a) and (b) are observed time shifts between a pattern of output from the ticket counter and the pattern of input to the security check for same flights as in Fig 7.5. Note that the total dwelling time is represented by the horizontal difference between the two curves. From the figures it is apparent that the longer the available time before a flight, the greater the time shifts, i.e., passengers are inclined not to join the security check immediately when they have excess time before their departure.

The proposed ancillary activities model, Eq 6.9 of Chapter 6, quantifies this total time shift as a function of the given available time by estimating split probabilities of joining intervening activites and corresponding dwell times. Components j and $j+1$ of Chapter 6 are the ticket counter and security check of the present examples. Recall that there were two basic assumptions concerning the model:

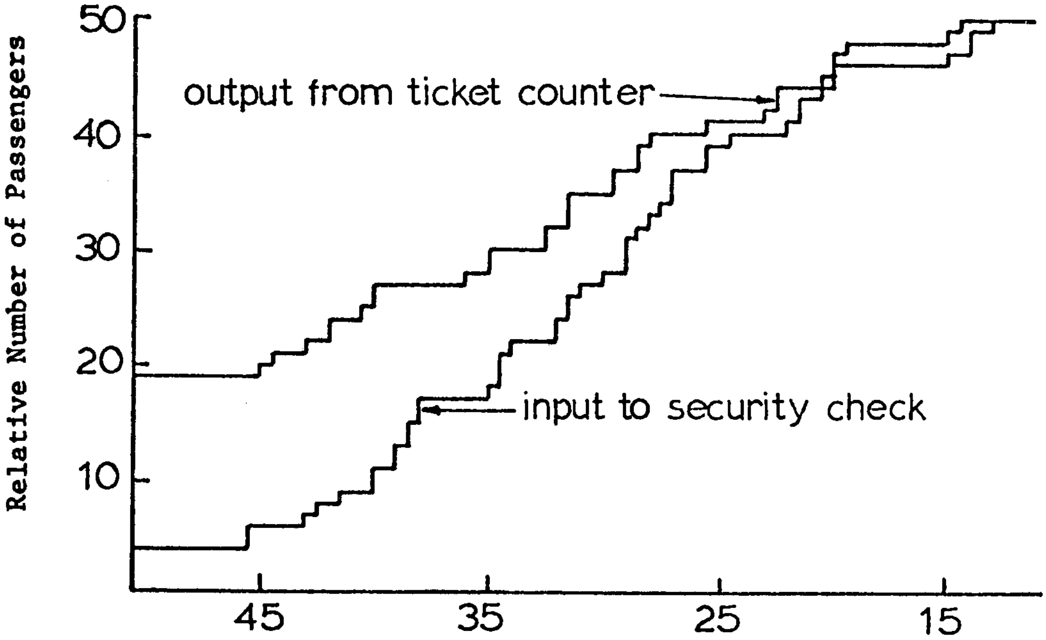


Fig 7.6(a). Time shift of flow for Flight A at Austin.

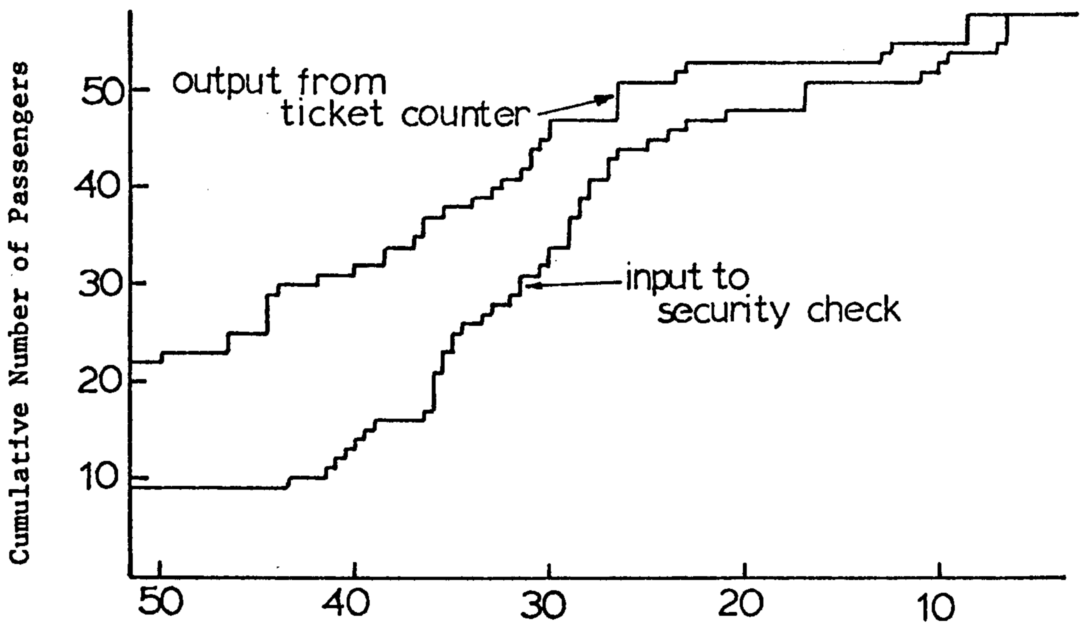


Fig 7.6(b). Time shift of flow for Flight B at San Antonio.

(1) dwell times are independent of available times, and

(2) given the same amount of available time, the probability that a person joins the security check or any particular intervening activity is the same regardless of which activites he has already visited.

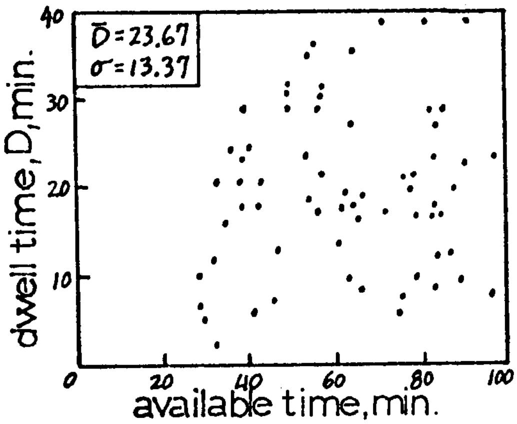
The validity of these assumptions is tested under the following headings:

(1) Dwell Time Versus Available Time

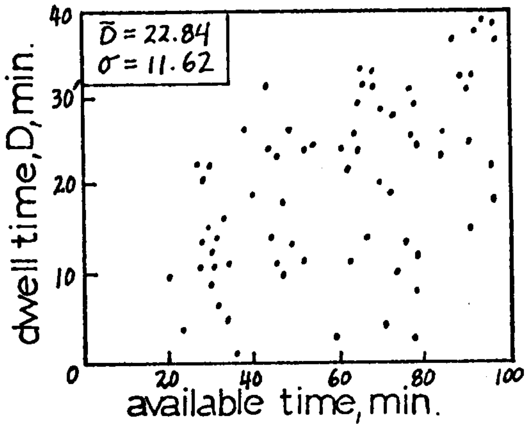
(2) Probability of Joining the Security Check

(3) Probability of Joining Intervening Activities

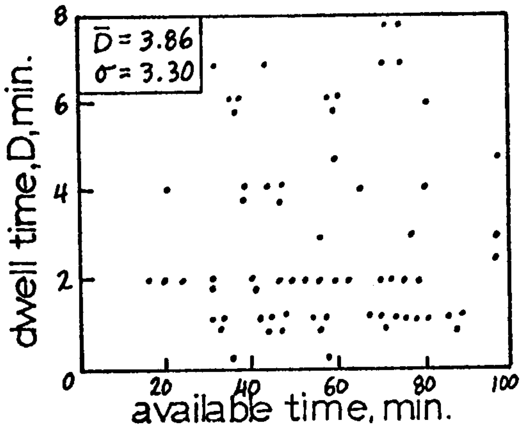
Dwell Time Versus Available Time. Dwell time is the time spent by a passenger at an intervening activity. In the scatter diagrams shown in Fig 7.7, observed dwell times are plotted against available times. It can be seen from the figures that dwell times appear to be independent of available times. There are some intervening activites such as restrooms, telephones, etc. which have somewhat constant dwell times. On the other hand, the dwell time independence is not quite clear for such activities as restaurants and gift shops. In these cases, some statistical evidence of independence is not quite clear for such activites as restaurants and gift shops. For these cases, some statistical evidence of independence is desirable.



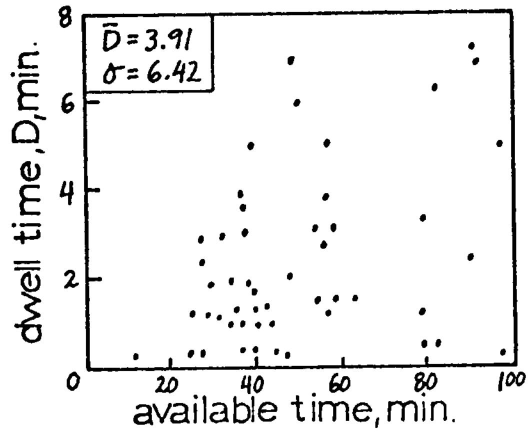
(a). Restaurant at Austin



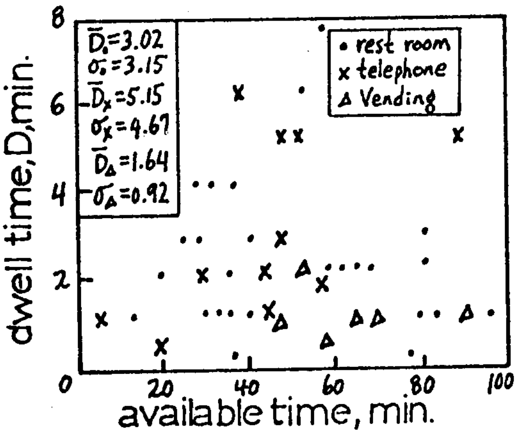
(b). Restaurant at San Antonio



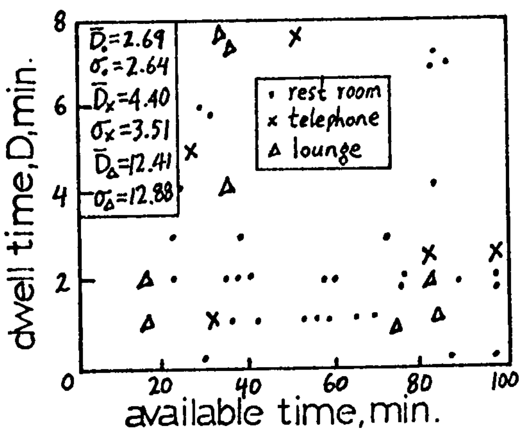
(c). Gift Shop at Austin



(d). Gift Shop at San Antonio



(e). Restroom, Telephone, and Vending Machine at Austin



(f). Restroom, Telephone, and Lounge at San Antonio

Fig 7.7. Scatter diagrams for dwell time versus available time.

Dwell time data on restaurants and gift shops at two airports are arranged in two-way contingency tables in Table 7.2 by subdividing the scatter diagrams into 3 by 3 cells.[1]

Results of Pearson Chi-Square tests[2] of independence are shown in Table 7.3, where P_I indicates the significance probability in the test of the hypothesis that dwell times and available times are stochastically independent.

From the data, there is no reason to believe that dwell times and available times are not independent.

Probability of Joining the Security Check. It is desired to test whether a split probability of going directly to the security check from any intervening activity is the same as that from the ticket counter given the same amount of available time.

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[1] Contingency tables are useful for testing independence between a number of sets of attributes, whether orderable or not, and irrespective of the nature of the variable (either continuous or discrete) or of the underlying distribution of the attribute. The construction of contingency tables does not require any particular way of ordering the categories. The results generally yield the same conclusion regardless of how the categories are arranged in the rows and columns.

[2] This test is only an approximate test, and its validity rests on the expected frequencies being fairly large. If the degrees of freedom (d.f.) is greater than 1, the test can be used if fewer than 20 percent of the cells have an expected frequency of less than 5 and if no cell has an expected frequency of less than 1 (Ref 19). When the observed expected frequencies do not meet these requirements, their values can be increased by combining adjacent classifications only if such combining does not rob the data of their meaning.

TABLE 7.2. TWO-WAY CONTINGENCY TABLES FOR TESTING INDEPENDENCE

Available time, min.	Dwell time, min. <15	15-30	>30	Total
<40	6	12	2	20
40-80	7	19	4	30
>80	5	13	6	24
Total	18	44	12	74

(a). Dwell Times at Restaurant at Austin Airport

Available time, min.	Dwell time, min. <2	2-3	>3	Total
<40	5	4	4	13
40-70	12	11	15	38
>70	7	4	9	20
Total	24	19	28	71

(b). Dwell Times at Gift Shop at Austin Airport

(Continued)

Table 7.2.(Continued)

Available time, min.	Dwell time, min. <15	15-25	>25	Total
<45	10	10	10	26
45-75	8	6	14	28
>75	6	12	16	34
Total	24	28	36	88

(c). Dwell Times at Restaurant at San Antonio Airport.

Available time, min.	Dwell time, min. <2	2-3	>3	Total
<30	8	6	2	16
30-50	12	3	5	20
>50	6	6	8	20
Total	26	15	15	56

(d). Dwell Times at Gift Shop at San Antonio Airport.

TABLE 7.3. RESULTS OF PEARSON CHI-SQUARE TESTS FOR INDEPENDENCE

	Pearson χ^2	d.f.	P_I	Conclusion
Restaurant at Austin	2.38	4	0.67	Do not reject
Gift Shop at Austin	0.78	4	0.94	Do not reject
Restaurant at San Antonio	6.71	4	0.15	Do not reject
Gift Shop at San Antonio	6.34	4	0.18	Do not reject

Assume that this probability is approximately constant during short intervals of time, say $\Delta t = 10$ minutes . Let P_i and Q_i be split probabilities of joining the security check from the ticket counter and after visiting one intervening activity, respectively, given that the available time is in the range (δ_i, $\delta_i + t$) in minutes. The probability is defined as a fraction of total passengers who are dispatched from an activity during that time interval.

The assumption of $P_i = Q_i$, for all i , is tested using the two sets of data collected at Austin and San Antonio airports. As noted previously, data are treated on an aggregate basis in that all surveyed flights are combined to calculate probabilities, except for one flight departing at San Antonio airport; only P_i's are obtained for this one flight, however.

The probability Q_i is calculated based on passengers who go directly to the security check after visiting exactly one intervening activity. The split probabilities after two or more intervening activites were not obtained because there were too few data points for these cases to be used for analysis.

Split probabilities for each of ten 10-minute time intervals are tabulated in Table 7.4 as ratios of observed frequencies for which the numerators are the numbers of passengers going directly to the security check and denominators are the total numbers of passengers dispatched from an activity, either the ticket counter or initially visited intervening activites, during the 10-minute

TABLE 7.4. OBSERVED SPLIT PROBABILITIES OF GOING TO THE SECURITY CHECK

Available time, min.	All Flights in Austin P^A	All Flights in Austin Q^A	All Flights in San Antonio P^S	All Flights in San Antonio Q^S	Flight 1 in San Antonio P^1
0-10	20/21, 0.952	8/8 , 1.000	12/13, 0.923	9/9 , 1.000	6/6 , 1.000
10-20	23/27, 0.852	12/14, 0.857	34/40, 0.850	14/16, 0.875	2/2 , 1.000
20-30	38/48, 0.792	16/20, 0.800	52/67, 0.776	21/30, 0.700	7/8 , 0.875
30-40	22/41, 0.537	7/14, 0.500	56/79, 0.709	14/19, 0.737	8/14, 0.571
40-50	15/31, 0.484	10/19, 0.526	32/52, 0.615	11/21, 0.524	3/7 , 0.429
50-60	7/25, 0.280	5/16, 0.313	15/31, 0.484	5/11, 0.455	2/4 , 0.500
60-70	3/11, 0.273	2/9 , 0.222	11/27, 0.407	4/9 , 0.444	5/12, 0.417
70-80	1/9 , 0.111	1/7 , 0.143	8/21, 0.381	6/18, 0.333	3/5 , 0.600
80-90	2/13, 0.154	1/4 , 0.250	6/16, 0.375	7/16, 0.438	0/3 , 0.000
90-100	2/17, 0.118	0/7 , 0.000	9/34, 0.265	3/13, 0.231	0/3 , 0.000

time intervals. Superscripts A , S , and 1 denote Austin, San Antonio, and Flight 1, respectively.

The procedure for testing the similarity between the split probabilities, P_i's and Q_i's , is to fit the observed values to theoretical probability distributions and then to compare estimated parameters of those distributions.

It has been assumed in this research that the decision process of joining the security check is analogous to a stimulus-response process. The stimulus is the amount of available time and the response is whether or not a passenger elects to join the security check. It has been found in a variety of applications, e.g., bio-assay, that the probability of a response as a function of the strength of stimulation can be approximated satisfactorily by a cumulative normal distribution, i.e.,

$$P_i = \frac{1}{2\Pi} \int_{\infty}^{\alpha + \beta \delta i} e^{-y^2/2} dy \qquad (7.1)$$

The kind of relationship in Eq 7.1 similarly holds for Q_i . Notice that P_i is the cumulative normal probability distribution function corresponding to the standard normal deviate $\alpha + \beta\delta_i$.[3] Berkson's Normit analysis was used to obtain estimates α and β . These estimates have excellent small sample properties, such

[3]This normal deviate has been called the Normit which involves the transformation of normal sigmoid curves into straight lines (Ref 20).

as the smallest mean square error (smaller than that of the maximum likelihood estimates or the minimum Chi-Square). To check the normality assumption, the classical Chi-Square goodness-of-fit tests by Karl Pearson were applied.[4] The results of this analysis are presented in Table 7.5 and shown graphically on Figs 7.8(a) and (b) for Austin and San Antonio data, respectively.
From these test results, it appears that split probabilities may be assumed to follow a cumulative normal distribution.

Finally the hypothesis that the P_i's and Q_i's are identical for every time interval was tested. This involves testing the hypothesis that there is no difference between α's and β's . The restricted Chi-Square test by Neyman (Appendix B) was adopted to test this hypothesis for various combinations of Austin and San Antonio data. The results in Table 7.6 suggest that at each airport

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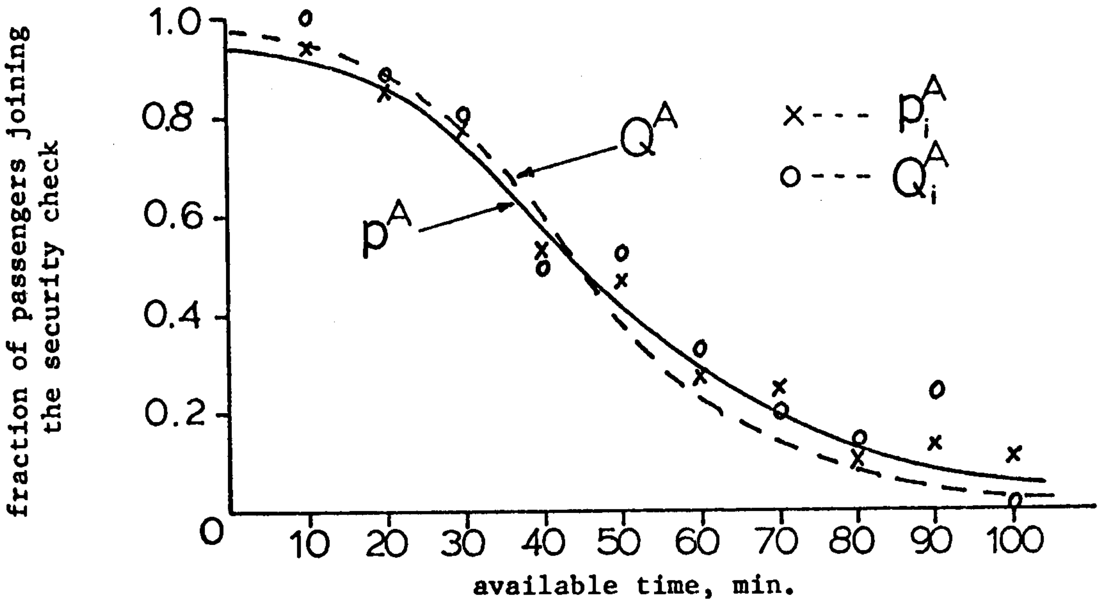
[4] The Normit χ^2 test is available, but classical χ^2 appears to be nearer to the χ^2 -distribution (Ref 21). Note that the decision of joining the security check in each time interval follows a binomial distribution. Therefore, the test statistic to be used is

$$\chi^2 = \sum_{i=1}^{n} \frac{(r_i - n_i P_i)^2}{n_i P_i (1 - P_i)}$$

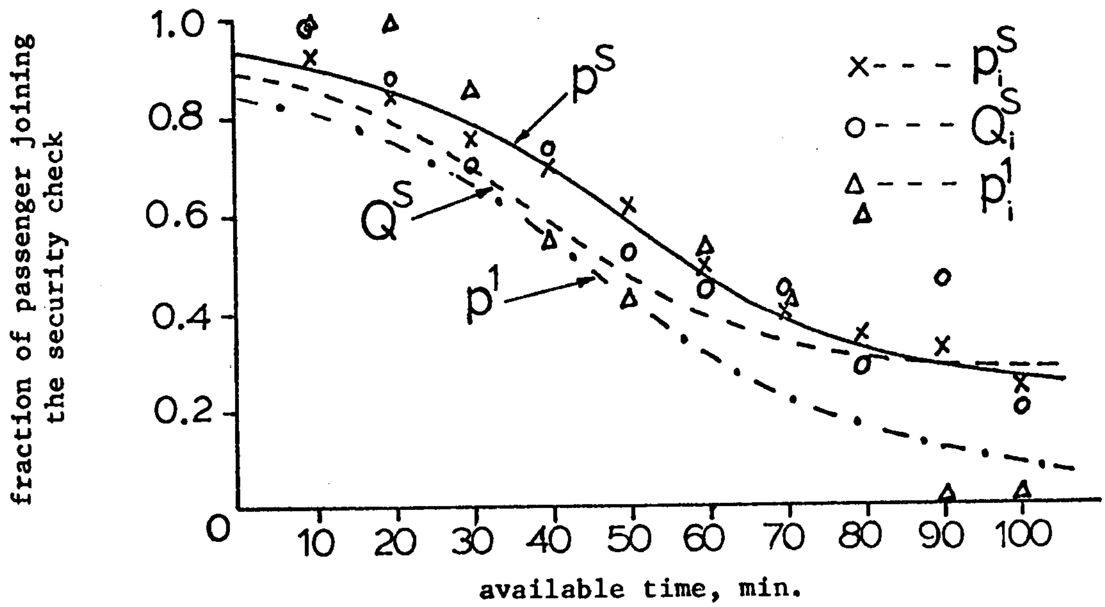
with (m-2) degrees of freedom, where r_i is the number of people going to security check and n_i is the total number of people facing the decision during the $\underline{i}$th time interval.

TABLE 7.5. RESULTS OF BERKSON NORMIT ANALYSIS AND GOODNESS-OF-FIT TESTS FOR NORMALITY OF SPLIT PROBABILITIES JOINING THE SECURITY CHECK.

			Pearson χ^2	d.f.	P_I	Conclusion
P^A	1.43	-1.91/60	5.59	8	0.69	Do not reject
Q^A	1.53	-2.04/60	4.13	8	0.83	Do not reject
P^S	1.28	-1.27/60	1.98	8	0.98	Do not reject
Q^S	1.18	-1.20/60	5.15	8	0.74	Do not reject
P^1	1.12	-1.23/60	6.90	8	0.55	Do not reject



(a). Cumulative Normal Approximations of Split Probabilities Observed at Austin Airport.



(b). Cumulative Normal Approximations of Split Probabilities Observed at San Antonio Airport.

Fig 7.8. Normal curve fitting by Berkson Normit Analysis.

TABLE 7.6. RESULTS OF RESTRICTED CHI-SQUARE TESTS FOR EXACT SIMILARITY OF SPLIT PROBABILITIES

	Restricted χ^2	d.f.	P_I	Conclusion
P^A and Q^A	0.054	2	0.97	Do not reject
P^S and Q^S	0.187	2	0.91	Do not reject
P^S and P^1	0.675	2	0.72	Do not reject

split probabilities from intervening activites can be replaced by those from the ticket counter, i.e., $P_i = Q_i$ for all i. It is also suspected that passenger split behavior is independent of flights and follows the overall trend, although this was not tested.

For actually calculating the split probabilities at any time interval, it is suggested to use estimates of α and β estimated from the initial probability distributions at each airport. The probabilities of joining component $j+1$ at two airports are:

$$P^A_{j+1} = \Phi\left[1.43 - \frac{1.91}{60}(t_o - t)\right] \tag{7.2}$$

and

$$P^S_{j+1} = \Phi\left[1.28 - \frac{1.27}{60}(t_o - t)\right] \tag{7.3}$$

where Φ denotes the cdf of the standard normal distribution; these values are widely tabled. Recall that t_o denotes the flight departure time and t is the time at which a passenger is dispatched from either a ticket counter or any intervening activity.

It is possible to compare two airports with the foregoing parameters. By equating Eq 7.2 and 7.3, it is calculated that the available time of approximately 15 minutes is the point at which $P^A_{j+1} = P^S_{j+1}$. Austin passengers seem more sensitive to short available time left in joining the security check. Beyond this point of time, however, San Antonio passengers appear to be quicker than Austin passengers. The security check at Austin airport is expected to have a sharp peak near the departure times whereas the security check demand at San Antonio airport spreads over time.

Probability of Joining Intervening Activites. Similarly to the assumption stated under the previous heading, it is also desired to test whether a split probability of joining a certain intervening activity from any intervening activity is identical to that from the ticket counter given the same amount of available time. Let $F_{k,i}$ and $G_{k,i}$ be the split probabilities of going to intervening activity k from the ticket counter (T.C) and from the first intervening activity (I.A), respectively, given the available time of δ_i. The observed probabilities in 10-minute time intervals at Austin and San Antonio airports are tabulated in Table 7.7(a) and (b).

It is noticed from the table that split probabilities concerning restaurants and gift shops at both airports are slowly increasing functions of the available time whereas those from other intervening activites appear somewhat constant and are in the same order for a given intervening activity although there are minor fluctuations. Since the magnitudes of split probabilites concerning these relatively insignificant activities are negligible, it seems quite reasonable to assume that these probabilities are identical to the others. The hypothesis is, therefore, tested only for the probabilities associated with restaurants and gift shops for which more data points are available.

TABLE 7.7. OBSERVED SPLIT PROBABILITIES OF JOINING INTERVENING ACTIVITIES

Available time, min.	to Restaurant		to Gift Shop		to Restroom		to Vending		to Telephone	
	F^A	G^A	F^A	G^A	F^A	G^A	F^A	G^A	F^A	G^A
0-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.048	0.0
10-20	0.0	0.0	0.037	0.071	0.074	0.071	0.037	0.0	0.0	0.1
20-30	0.104	0.0	0.042	0.05	0.021	0.1	0.0	0.0	0.042	0.05
30-40	0.171	0.214	0.171	0.143	0.073	0.071	0.024	0.0	0.024	0.071
40-50	0.194	0.105	0.129	0.105	0.097	0.105	0.032	0.053	0.065	0.105
50-60	0.16	0.25	0.28	0.188	0.12	0.125	0.04	0.063	0.12	0.063
60-70	0.231	0.222	0.364	0.222	0.091	0.111	0.0	0.222	0.0	0.0
70-80	0.333	0.286	0.444	0.286	0.111	0.143	0.0	0.143	0.0	0.0
80-90	0.615	0.25	0.231	0.25	0.0	0.0	0.0	0.0	0.0	0.25
90-100	0.529	0.429	0.294	0.286	0.0	0.143	0.0	0.0	0.159	0.143

(a). Observed Fractions at Austin Airport

(Continued)

TABLE 7.7. (Continued)

available time, min.	to Restaurant		to Gift Shop		to Restroom		to Lounge		to Telephone	
	F^S	G^S	F^S	G^S	F^S	G^S	F^S	G^S	F^S	G^S
0–10	0.0	0.0	0.077	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10–20	0.05	0.0	0.025	0.063	0.05	0.063	0.025	0.0	0.0	0.0
20–30	0.06	0.167	0.09	0.067	0.03	0.033	0.03	0.0	0.015	0.033
30–40	0.101	0.158	0.063	0.105	0.038	0.0	0.051	0.0	0.025	0.0
40–50	0.154	0.095	0.135	0.095	0.019	0.095	0.058	0.095	0.019	0.095
50–60	0.161	0.273	0.129	0.182	0.129	0.0	0.097	0.091	0.0	0.0
60–70	0.259	0.333	0.111	0.0	0.037	0.111	0.148	0.111	0.137	0.0
70–80	0.286	0.222	0.19	0.111	0.095	0.111	0.0	0.167	0.048	0.056
80–90	0.25	0.313	0.188	0.188	0.063	0.0	0.125	0.063	0.0	0.0
90–100	0.324	0.538	0.147	0.077	0.088	0.154	0.088	0.0	0.088	0.0

(b). Observed Fractions at San Antonio Airport

Again by assuming the stimulus-response process for joining the intervening activites, tests are performed similar to those used under the previous heading. Results of the tests are shown in Tables 7.8 and 7.9, and Fig 7.9.

The probabilities of joining the restaurants and gift shops at the two airports are:

$$F_r^A = \Phi\left[-1.88 + \frac{1.29}{60}(t_o - t)\right]$$

$$F_g^A = \Phi\left[-1.76 + \frac{0.98}{60}(t_o - t)\right] \qquad (7.4)$$

and

$$F_r^S = \Phi\left[-1.83 + \frac{0.93}{60}(t_o - t)\right]$$

$$F_g^S = \Phi\left[-1.64 + \frac{0.47}{60}(t_o - t)\right] \qquad (7.5)$$

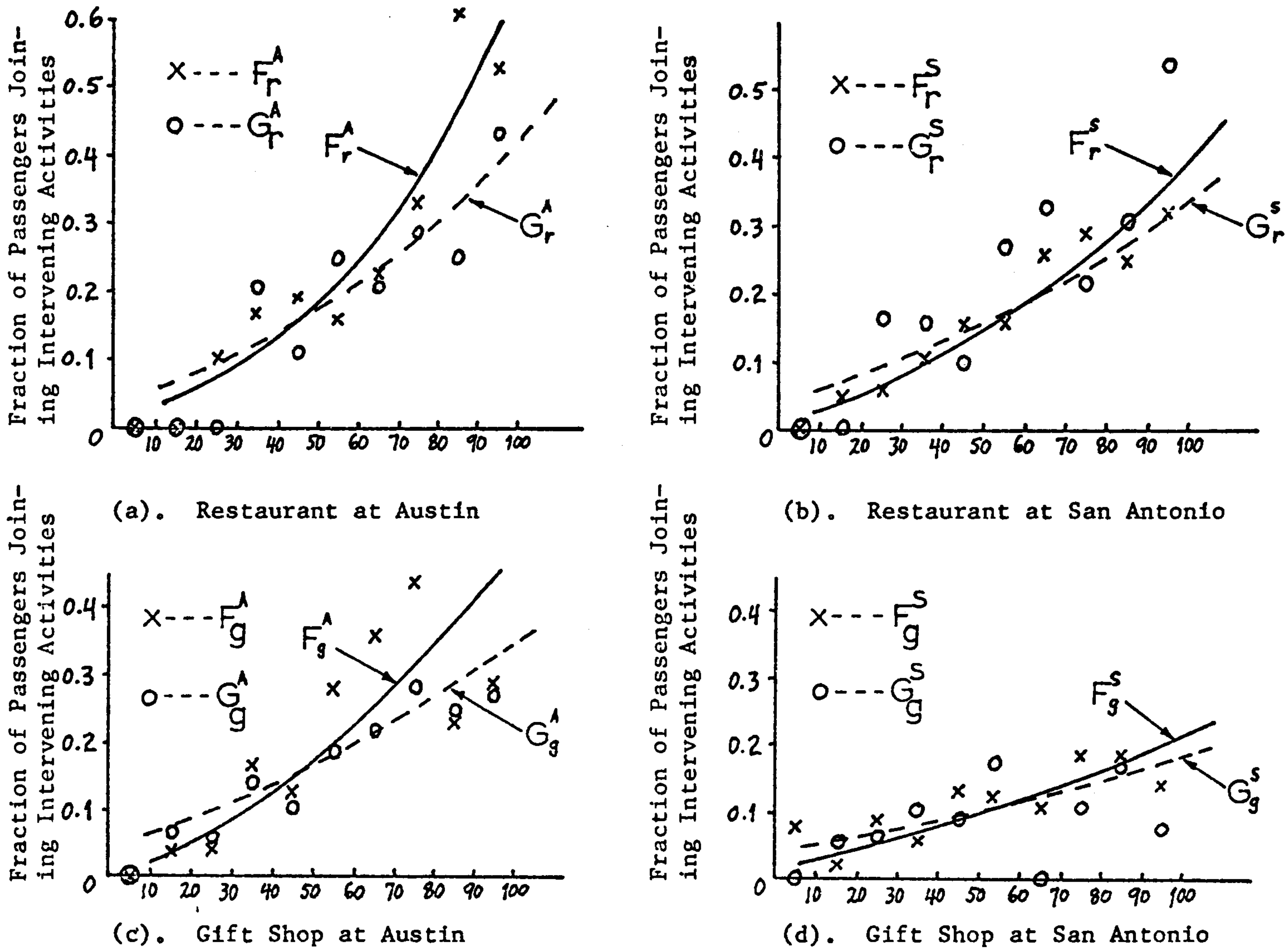
where the subscripts r and g stand for restaurants and gift shops, respectively. Equations 7.4 and 7.5 reveal that the utilization of intervening activites at Austin Airport is higher than that at San Antonio Airport. This result was expected, because there exists another set of intervening activites at San Antonio airport beyond the survey area while there is no other area at Austin Airport.

TABLE 7.8. RESULTS OF BERKSON NORMIT ANALYSIS AND GOODNESS-OF-FIT TESTS FOR NORMALITY OF SPLIT PROBABILITIES JOINING INTERVENING ACTIVITIES.

	α	β	Pearson χ^2	d.f.	P_I	Conclusion
$F^A_{\text{restaurant}}$	-1.88	1.29/60	5.65	8	0.69	Do not reject
$G^A_{\text{restaurant}}$	-1.77	0.99/60	5.27	8	0.72	Do not reject
$F^A_{\text{gift shop}}$	-1.76	0.98/60	9.15	8	0.35	Do not reject
$G^A_{\text{gift shop}}$	-1.71	0.81/60	1.52	8	0.99	Do not reject
$F^S_{\text{restaurant}}$	-1.83	0.93/60	2.16	8	0.98	Do not reject
$G^S_{\text{restaurant}}$	-1.32	0.60/60	7.41	8	0.49	Do not reject
$F^S_{\text{gift shop}}$	-1.64	0.47/60	3.50	8	0.90	Do not reject
$G^S_{\text{gift shop}}$	-1.54	0.31/60	3.58	8	0.89	Do not reject

TABLE 7.9. RESULTS OF RESTRICTED CHI-SQUARE TESTS OF IDENTICAL SPLIT PROBABILITIES

	Restricted χ^2	d.f.	P_I	Conclusion
$F^A_{restaurant}$ and $G^A_{restaurant}$	1.51	2	0.48	Do not reject
$F^A_{gift\ shop}$ and $G^A_{gift\ shop}$	0.44	2	0.82	Do not reject
$F^S_{restaurant}$ and $G^S_{restaurant}$	2.55	2	0.36	Do not reject
$F^S_{gift\ shop}$ and $G^S_{gift\ shop}$	0.34	2	0.87	Do not reject



(a). Restaurant at Austin

(b). Restaurant at San Antonio

(c). Gift Shop at Austin

(d). Gift Shop at San Antonio

Fig 7.9. Normal curve fitting by Berkson Normit Analysis.

Estimation of Demand Patterns

In this chapter, it is attempted to estimate input demand patterns at the security check from the output patterns of previous components. The scope of this demand estimation is limited in that only passenger flows which are dispatched from the ticket counter are considered. As discussed in Chapter 6, the basic principle for passenger flow analysis can be extended for visitors and transfers through an appropriate use of conversion factors. The same procedure may be extended to any pair of components involving intervening activities.

Equation 6.10 in Chapter 6 is used for the estimation of demand patterns. To estimate the total expected time shift, $E\{T\}$, three inputs are required:

(1) transfer time matrix,

(2) dwell time at each individual intervening activity, and

(3) split probabilities.

Shown in Table 7.10 are the transfer time matrices constructed from the geometric configurations of the terminal buildings and observed mean walking speeds. It is interesting to note that transfer times are considerably higher than the given distances divided by commonly known pedestrian walking speeds. The observed mean walking speeds were 2.1 ft/sec. and 2.7 ft/sec. for Austin and San Antonio passengers, respectively.

The dwell times at individual intervening activities shown previsously on Figure 7.6 are listed again in Table 7.11. Dwell

TABLE 7.10. TRANSFER TIME MATRICES FOR THE TWO AIRPORTS

	Vending Machine	Telephone	Gift Shop	Restroom	Restaurant	Security Check
ticket counter	1.1	1.2	1.5	1.9	2.1	2.2
Vending machine		0.1	0.3	0.8	1.1	0.8
telephone			0.2	0.7	0.9	0.9
gift shop				0.4	0.6	1.2
restroom					0.7	1.6
restaurant						1.4

(a). Transfer Times at Austin Airport, min.

(Continued)

TABLE 7.10. (Continued)

	Lounge	Telephone	Gift Shop	Restroom	Restaurant	Security Check
ticket counter	3.5	2.7	2.8	2.7	3.1	3.9
lounge		1.7	0.6	1.7	0.6	0.3
telephone			1.2	0.2	1.2	2.3
gift shop				1.1	0.4	0.8
restroom					1.2	2.0
restaurant						0.8

(b). Transfer Times at San Antonio Airport, min.

TABLE 7.11. DWELL TIMES AT INTERVENING ACTIVITIES

	Austin Airport		San Antonio Airport	
	Mean	Standard Deviation	Mean	Standard Deviation
restaurant	23.67	13.37	22.84	11.62
gift shop	3.86	3.30	3.91	6.42
restroom	3.02	3.15	2.69	2.64
telephone	5.15	4.67	4.40	3.51
Vending	1.64	0.92	-	-
lounge	-	-	12.41	12.88

times are fairly stable around their mean values. Mean dwell times are used for the estimation of demand patterns.

Equations 7.2 and 7.3 are used for the split probabilities concerning the flow directly joining the security check from the ticket counter. The split probabilities of joining restaurants and gift shops are calculated from Eqs 7.4 and 7.5. Therefore, given the available time of $(t_o - t)$, the probabilities of joining the remaining activities are

$$F_w^A + F_v^A + F_t^A = \begin{cases} 1 - P_{j+1}^A - F_r^A - F_g^A , \\ \quad \text{if } P_{j+1}^A + F_r^A + F_g^A < 1 \\ 0, \text{ otherwise} \end{cases} \tag{7.6}$$

$$F_w^S + F_L^S + F_t^S = \begin{cases} 1 - P_{j+1}^S - F_r^S - F_g^S , \\ \quad \text{if } P_{j+1}^S + F_r^S + F_g^S < 1 \\ 0, \text{ otherwise} \end{cases} \tag{7.7}$$

where, the subscripts w , V , L , and t denote restrooms, vending machine, passenger lounge, and telephones.

The residual probabilities in above equations are then allocated to the remaining intervening activities in proportion to their contributions. The best estimates for these contributions seem to be the fractions of passengers that used a particular intervening activity over the entire time intervals. For each airport, estimated probabilities are:

$$F_w^A = \frac{14}{243}(1 - P_{j+1}^A - F_r^A - F_g^A)$$

$$F_V^A = \frac{4}{243}(1 - P_{j+1}^A - F_r^A - F_g^A) \qquad (7.8)$$

$$F_t^A = \frac{10}{243}(1 - P_{j+1}^A - F_r^A - F_g^A)$$

and

$$F_w^S = \frac{19}{380}(1 - P_{j+1} - F_r^A - F_g^A)$$

$$F_L^S = \frac{9}{380}(1 - P_{j+1}^S - F_r^S - F_g^S) \qquad (7.9)$$

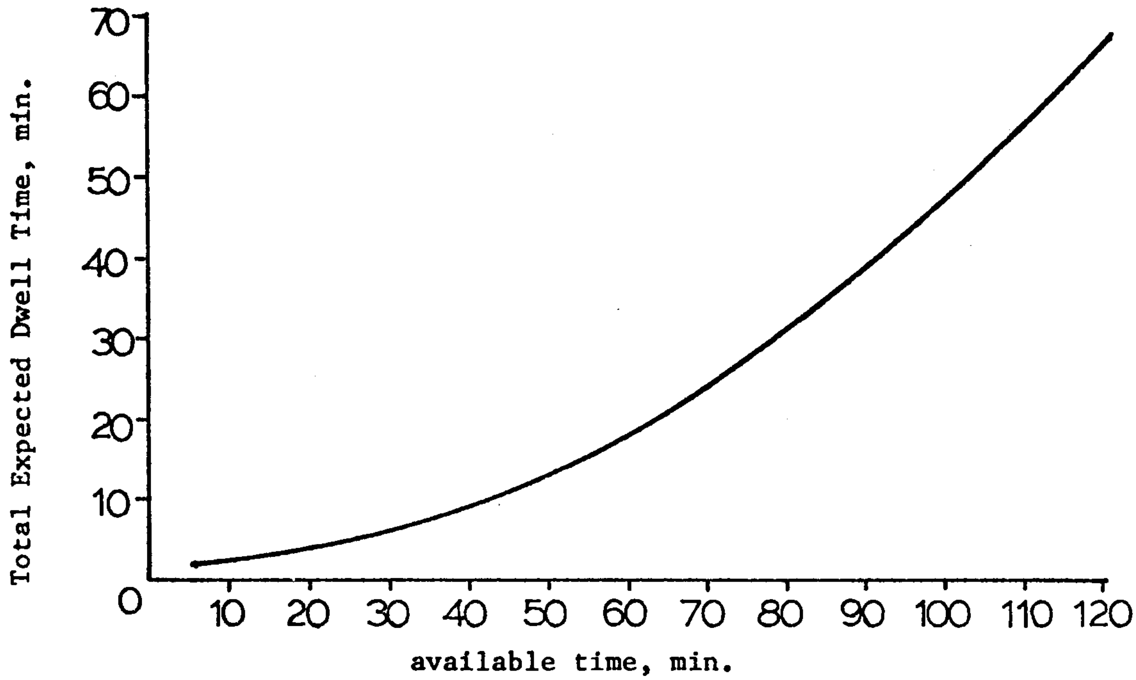
$$F_t^S = \frac{22}{380}(1 - P_{j+1}^S - F_r^S - F_g^S)$$

The total expected time shifts are calculated by the use of Eq 6.9 in Chapter 6 for Austin and San Antonio, respectively, and they are listed in Table 7.12 for every 10-minute time interval (See Appendix C for sample calculations). As shown in Fig 7.10, the total expected dwell time is a convex function of the available time. It is important to note that the function is not valid beyond a certain limit of available time (approximately 100 to 120 minutes) because probability functions were obtained through regression analysis. As noted earlier, the time shift at San Antonio Airport is less than that at Austin Airport. This difference is due to the existence of another set of intervening activities beyond the security check at San Antonio Airport.

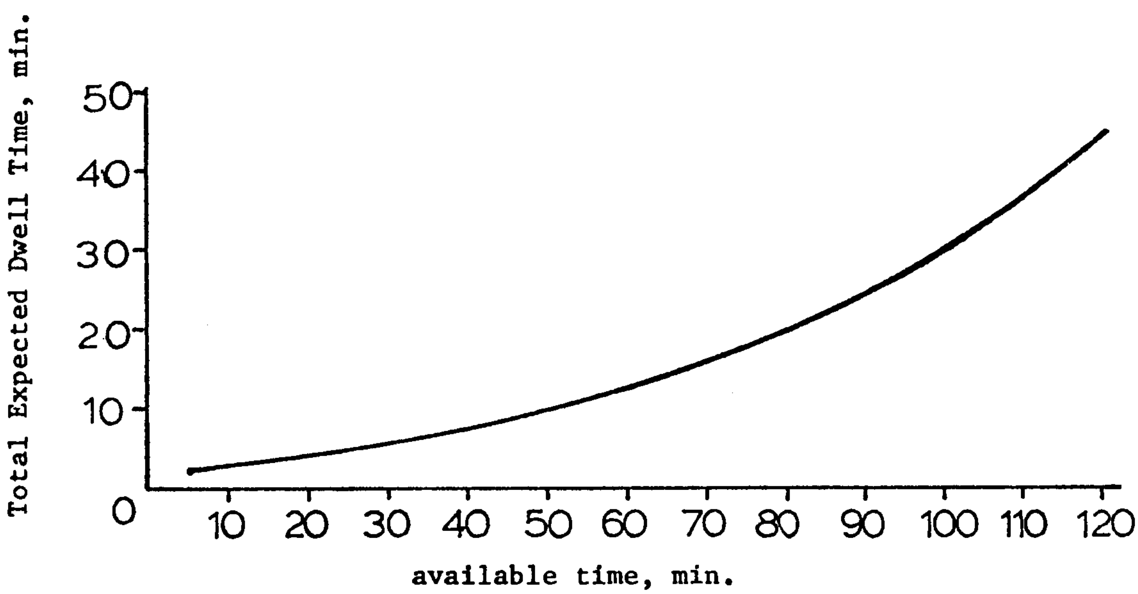
The estimated time shifts are applied to the output curves from the ticket counter in order to estimate input patterns to the

TABLE 7.12. TOTAL ESTIMATED TIME SHIFTS

Available Time, min.	Austin Airport	San Antonio Airport
5	2.11	1.94
15	4.38	4.25
25	5.32	4.82
35	8.34	6.96
45	11.96	8.85
55	15.88	11.04
65	21.42	13.95
75	28.08	17.60
85	35.48	21.60
95	43.66	26.32
105	53.01	33.26
115	62.64	40.12
125	71.63	47.87



(a). Total Expected Dwell Time at Austin Airport.



(b). Total Expected Dwell Time at San Antonio Airport.

Fig 7.10. Total expected time shift as a function of available time.

security check. Two individual flights, each of which were scheduled at two airports, respectively, during the survey periods, are used for demonstration. Figs 7.11(a) and (b) show comparisons of estimated input patterns with actually observed patterns at Austin and San Antonio, respectively. The result shows that the model can predict the actual patterns very closely. As is clear from the figures, however, the model exhibits a general tendency of under-estimating the total time shifts. This is probably due to the variation of dwell times which have been assumed constant in the model. Whereas, the observed demand at Austin is fluctuating around the predicted demand, the relationship at San Antonio is quite stable; the observed input rate is slightly faster than the expected input rate most of the time. This has been somewhat expected. One likely reason is that San Antonio passengers were not as cooperative as expected during the survey, and, therefore, many cards may have not been flashed at intervening activity facilities although they were turned in at the security check. In summary, the intervening activities model gives fairly reliable results.

Summary

The flash-card technique for collecting intervening activities data has been briefly discussed. Its advantage is that is does not significantly affect dwell time or passenger flows, but possible recording errors and a low data collection rate appear to be its shortcomings.

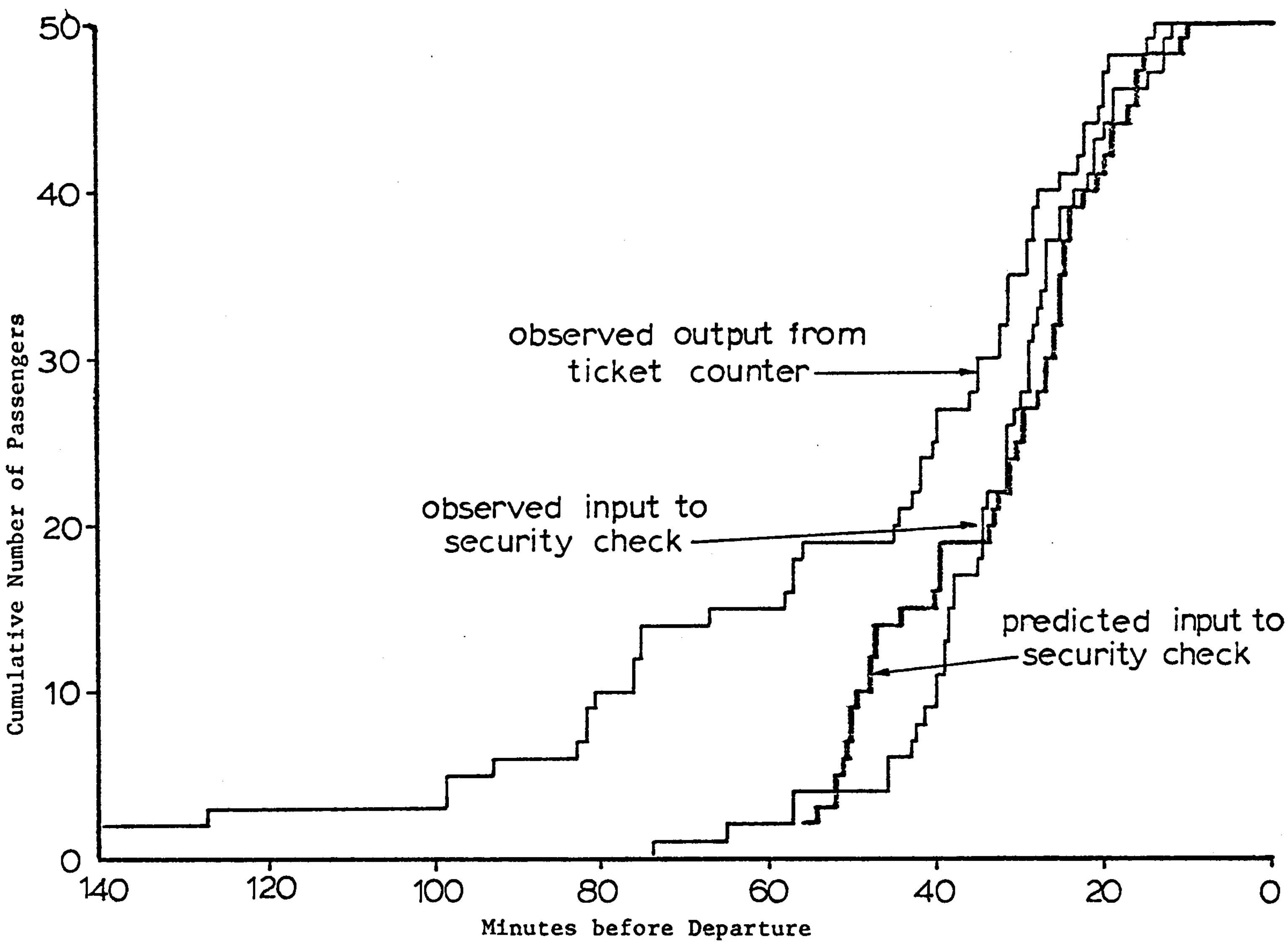


Fig 7.11(a). Estimated and observed input patterns at Austin Airport.

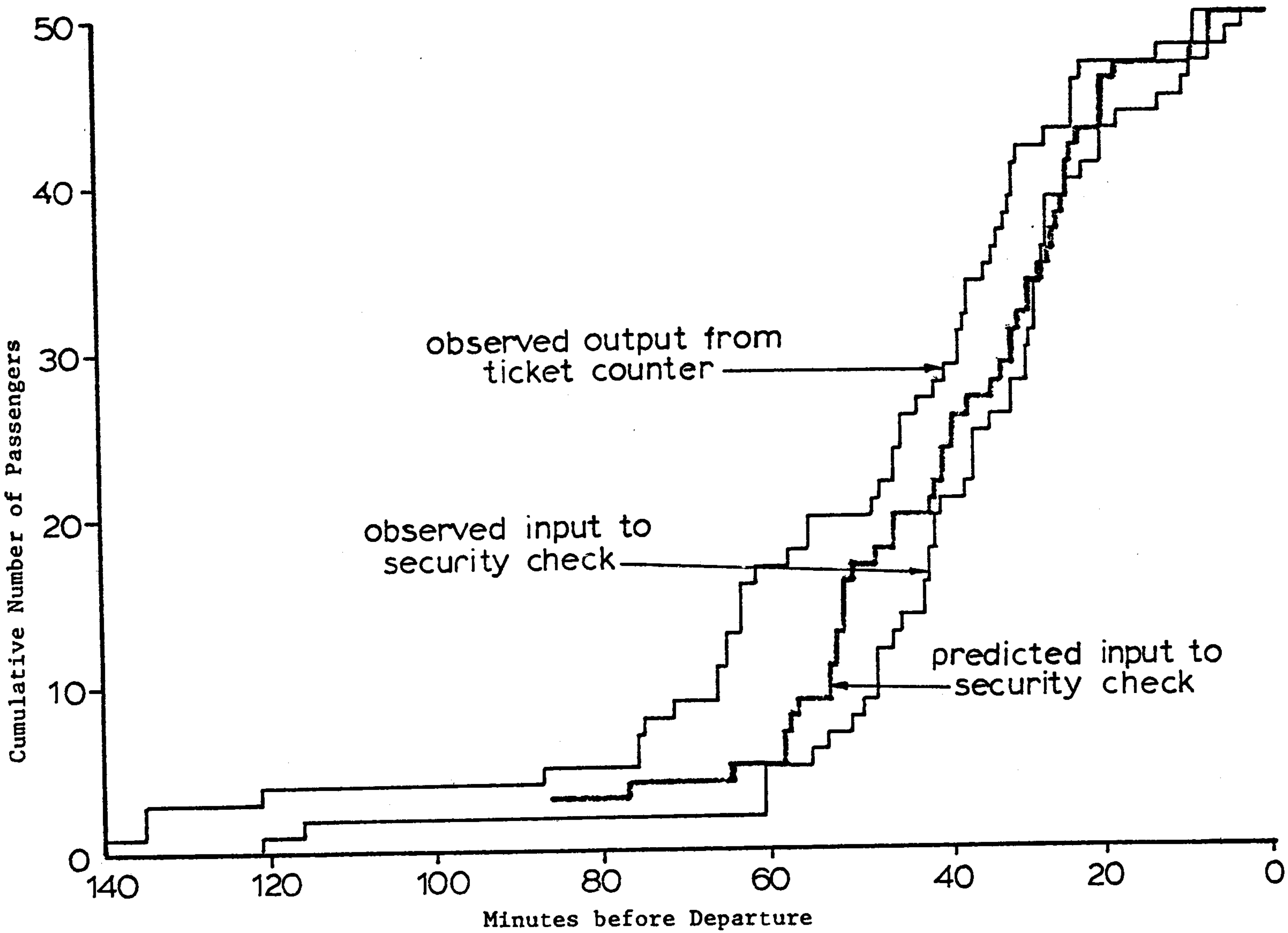


Fig 7.11(b). Estimated and observed input patterns at San Antonio Airport.

The intervening activities model was successfully verified against two sets of data collected at Austin and San Antonio airports. The results indicate, as postulated, that behavior of a passenger is likely to be governed largely by his available time. The model was tested for small and medium hub airports. To apply the model to a large airport which has usually a large number of intervening activities, a much larger sample size would be required. This will provide a successful estimation of model parameters. It is recommended that a required sample size be in the order of 100 times the number of intervening activities.

CHAPTER 8. CONCLUSIONS AND EXTENSIONS

Summary and Conclusions

Past airport capacity studies have taken a component approach which treats system components in isolation, irrespective of the effect of other system component capacities. A combination of existing component models, therefore, does not adequately estimate overall airport capacity, mainly because it is incapable of predicting input rates to a component as a function of output rates from the previous components.

The airport system has been defined with the aid of a flow chart. One of the unique features of this systems definition is that the exact flows within the airport system are not specified. This allows greater flexibility in modeling the airport system necessary to allow desirable component models to be applied to a variety of airport configurations.

Existing definitions of airport capacity are reviewed and a definition is developed which is applicable to any airport system hierarchy. Level-of-service concepts are used in the definition in order to include qualitative as well as quantitative measures of the service provided by the airport.

A tandem-queue algorithm has been proposed in which a conceptual scheme of relating input and output demand patterns of individual components is developed based on a deterministic approach. This is a desirable approach for airport capacity studies. The algorithm facilitates overall airport capacity estimation and evaluation as a function of user-specified level of service criteria. The model is intended to produce a capacity figure as a scaled pattern of flow over a finite time interval. As a continuing effort of this research is in progress, the model will provide a valuable tool by which developed component models can be modularized to form a system capacity model.

Special attention has been given to a component resulting in the disrupted order of flow due to the existense of intervening activities. The intervening activities model has been successfully validated and has provided conclusions that

(1) dwell time is independent of the available time,

(2) the split probability of joining a component beyond intervening activites is a decreasing function of the available time only, and follows a cumulative normal distribution, and

(3) probabilities of joining intervening activities are slowly increasing functions of the available time. It has been asserted that passenger split behavior is explainable with respect to the available time only.

It has been found from the survey results that intervening activites have a profound effect on the passenger flow pattern. The intervening activites model quantifies this effect and provides a component model which is connectable to other system component models.

The flash card technique provides a complete trace of the airport user. Since the technique is simple and not expensive to use, it can be extended for studying airport system components simultaneously. This will define paths of passengers for a specific flight and facilitate the development of flow conversion factors concerning route splits and spatial distributions of visitors and transfer passengers. A possible recording error and low data collection rate are its major drawbacks.

Future Research Needs

The following appear to be immediate research topics in the near future:

(1) definition of level-of-service regarding airport capacity; To determine the most appropriate dimensions in which to express levels-of-service, it is recommended that attitudinal surveys be conducted to explore the attributes of airport service;

(2) election of adequate level-of-service criteria for evaluating overall airport capacity;

(3) development of component capacity models which are able to predict output rates and provide maximum service rates;

(4) validity of a constant service time assumption for processing the flow; for many airport components, this assumption appears to be quite reasonable. However, this may constitute a drawback in applying the model for an entire airport system. If individual service times are subject to large variances, then the input estimation to the next component has to suffer unusually large variances. This is because individual variances are multiplying under a series of dependent queues. Future research should be aimed at estimating the effect of individual variances on the total variance;

(5) validity of constant dwell time assumption;

(6) effect of intervening activites on arriving/deplaning flows; The intervening activites model has been developed for departing/enplaning flows since these are the ones that are given some excess times to be used for other than essential processings. It will be interesting to investigate, to what extent (if any), intervening activities affect arriving/deplaning flows.

In addition, the following constitute research areas to be developed further:

(1) development of conversion factors;

(2) effect of employee travel on airport capacity;

(3) interaction of bi-directional flows, boarding and deboarding;

(4) effect of transfer passengers;

(5) effect of visitors on passengers' intervening activity usages.

APPENDIX A. REVIEW OF AVAILABLE MODELS

Introduction

A systems study typically begins with hypothesizing a simplified version of the real system which can be described and analyzed more easily. This abstraction of the real world whether it is a mathematical, physical, or conceptual model, serves as a convenient tool for describing and understanding the system.

Models development for airport components are presented in this Appendix according to the list of components defined in Chapter 2. General capacity ideas developed for other modes, which are also applicable to an airport, are not discussed in detail.

There are two major types of models of airports, analytical models and simulation models. The choice of model depends on such factors as reliability of *a priori* assumptions, complexity of the problem, cost and time required to develop the information, and its compatibility with the intended application of the model.

For airport capacity analysis, simulations have been more widely used than analytical methods. The main reason for this is that they are relatively straightforward to develop (although expensive) for a very complex system like an airport. However, in this research the analysis is based on analytical models because their use can lead to a better understanding of the important system parameters. That is, with analytical models one can investigate specific interactions which are of particular interest and study parameter combinations more clearly, quickly, and cheaply than with simulation. Another advantage is the flexibility of using analytical models input to a larger simulation model, whenever appropriate. The following discussions of available models emphasize analytical models.

Terminal Airspace Component

According to the system boundary described in Chapter 2, the terminal airspace component bounds the airport on the airside. Its major role is to connect the enroute sectors to the runway component. Thus, the termianl airspace components's service rate may influence subsequent component operations.

The Federal Aviation Administration developed a simulation model based on the controller workload approach for the New York Metropolitan Area airspace system (Ref 22). Using real-time simulation, total workload times were computed for various levels of aircraft demand. The total workload time WLT was defined as:

$$WLT = nW_1 + nW_2 + CW_3 \tag{A.1}$$

where

n = number of aircraft per hour,

C = number of potential conflicts per hour,

W_1 = routine communications workload measures in seconds per aircraft,

W_2 = non-conflict control and control-support communications worklaod measured in seconds per aircraft, and

W_3 = conflict-control workload measured in seconds per conflict.

The value of C is determined from the total demand by considering the physical layout of the airspace system. Using Eq A.1, one can estimate a capacity for each terminal sector by limiting the total workload time to a predetermined value, say 2,000 - 2,500 seconds per hour, and finding the corresponding demand level, say n'. To compute the capacity, two inputs are required: the maximum tolerable value of WLT and the number of potential conflicts C for a given pattern of air traffic.

A complexity rating approach to airspace capacity was employed by the Airborne Instruments Laboratory (Ref 23). This method, known as the TRANSAIR model, related aircraft movements to a set of relative complexities of controlling various types of aircraft operations and interactions. After assigning a complexity weighting factor to each type of aircraft interaction, a steady-state stochastic queueing model computes the total complexity rating (CR) resulting from the given demand on the terminal sector in question as follows:

$$CR = \sum_i n_i W_i \qquad (A.2)$$

where

CR = total complexity rating,

n_i = number of interactions of type i , and

W_i = weighting factor for interaction type i .

With this approach, capacity is defined as the aircraft movement pattern which results in a complexity rating which by the controller's assessment corresponds to about the largest amount of traffic he can handle in a particular terminal airspace.

More recently, Stanford Research Institute (SRI) developed a model to estimate controller workload and to evalute sectors (Ref 24). Although the model is for enroute sectors, it can be extended in principle to the terminal area sectors. In the SRI procedure, estimates are computed for the number of ATC events associated with a given pattern of air traffic. These estimated numbers of events are determined using analytical models of air traffic operating within the sector. Their assertion is that workload is related to the frequency of events which require decision and actions by a controller team and to the time required to comprehend and execute the tasks associated with these events. A workload index was computed by aggregating event frequencies and task execution times into a single numerical index called a control difficulty index (CDI):

$$CDI = \sum_i W_i E_i \tag{A.3}$$

where

W_i = weighting factor for event i and

E_i = expected number of type i events per hour.

This CDI index can be transformed into decision making time, which is shown by SRI to have a limiting value of approximately 44 man-minutes per hour for all levels of present or future ATC automation. The number and pattern of aircraft corresponding to this upper limit constitutes a capacity estimate for the sector in question.

Recent studies by Dunlay point out the stochastic nature of air traffic and controller workload and suggest possible alteration to methods of computing airspace capacity to account for this stochastic nature (Ref 25).

Runway Component

Previous capacity analyses have concentrated on the runway component the airport system. Therefore, this is the most developed area and satisfactory models are available.

Early analytic investigations of runway operations were concerned mainly with estimating landing delays using models of queueing theory. The principles involved are also applicable to take-off operations. Using Poisson arrivals with constant service time, Bowen and Pearcy computed steady-state average landing delays (Ref 26). Under the same assumption, delay distributions were further pursued by Pearcy (Ref 27). In these earlier works, the assumption of Poisson arrivals was generally accepted and actual validations were reported by Bowen and Pearcy, Bell, and Berkowitz and Doering (Refs 26, 28, and 29). This class of early M/G/1 queueing[1] problems is solved by using the imbedded Markov chain. Assuming that the arrivals are Poisson distributed and the service time a random variable with a first-come-first-serve discipline, Kendall expressed the average delay as (Ref 30)

$$W = \frac{\lambda(\sigma^2 + 1/\mu^2)}{2(1 - \rho)} \tag{A.4}$$

where

λ = mean arrival rate,

$1/\mu$ = mean service time,

σ^2 = variance of service time, and

ρ = traffic intensity = λ/μ .

Using a similar queueing model, Galliher and Wheeler derived stationary delay distributions for landing aircraft (Ref 31). The effect of approach path separation on landing delays was analyzed by Oliver (Ref 32).

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[1]A queueing system is often characterized by three-symbol notations, e.g., M/G/1 representing the input distribution, service time distribution, and number of parallel servers in the system, respectively. It is customary to use the conventional codes M, G, and D to represent Poisson, general, or deterministic distributions.

Until just recently, the most widely applied capacity model in the U. S. for mixed operations was developed by the Airborne Instruments Laboratory (AIL). Several documents for use by airport planners have evolved from the AIL (Refs 14 and 33). AIL based their capacity models on the practical capacity concept. FAA has issued advisorty circulars AC 150/5060-A1 and AC 150/5060-3A based on AIL's results, and these have been widely used in airport planning. There were essentially two models: one exclusively for landings followed the form of Eq A.4, the second for mixed operations was based on a preemptive spaced arrival queueing process. In the second model, priority for service is given to landing aircraft and departures can be released only when a sufficient time gap occurs between landings. The take-off demand process is assumed to be Poisson; however, the arrival process that takeoffs encounter at the runway are not assumed Poisson, but instead are modeled to behave like the output of an airborne queueing process. Galliher modified this general model inclusion of spaced arrivals, i.e., he used a displace exponential gap distribution. Under steady-state conditions, the average delay for mixed operations was expressed as:

$$W_d = \frac{\lambda_d(\sigma_j^2 + j^2)}{2(1 - \lambda_d j)} + \frac{g(\sigma_v^2 + v^2)}{2(1 - \lambda_a v)} \tag{A.5}$$

where

W_d = average delay to departures,

λ_a = average arrival rate,

λ_d = average departure rate,

j = average interval of time between two successive departure,

σ_j = standard deviation of interval j ,

g = average rate at which gaps occur between successive arrivals,

v = average value of an interval of time within which no departure can be released,

σ_v = standard deviation of v .

In the AIL model, two different capacities are defined according to the lengths of time periods under consideration. One, known as the practical hourly capacity (PHOCAP), is defined as the maximum number of aircraft movements that the runways can accept in one hour that corresponds to some tolerable limit on the level of average delay (4 minutes is commonly used). The other, known as the practical annual capacity (PANCAP), allows for specified amount of overloaded hour and is defined as one during which demands exceeds PHOCAP.[2] PANCAP was empirically defined as that level of operation (for a given demand pattern) at which 10 percent

[2]The AIL model does not consider the airspace and the runways as one system. The output of the airborne process is observed and becomes an input into the runway models. The models therefore predict delays due to runway congestion but not due to airspace delays.

of the operations or 5 percent of the time the demand on the runways exceeds PHOCAP and that the average delay during those overloaded periods is 8 minutes. AIL's model can be applied to a number of airport configurations and aircraft populations for both VFR and IFR conditions.

As a means of increasing runway capacity, the effect of runway-use priority on aircraft delays during mixed operations was investigated by Pestalozzi (Ref 34).

He compared several priority rules numerically by means of a steady-state queueing model with non-preemptive priorities. This M/G/1 queueing model raised the issue of applying certain priority rules to different aircraft mixes and evaluating their effects on capacity.

Models of runway capacity using the ultimate capacity concept were initiated by Blumstein (Ref 15). Using a uniform speed distribution of aircraft with varying means and speed ranges, a parametric study was made to identify the factors that affect capacity. The major factors tested include:

(1) length of common approach path,

(2) aircraft speeds,

(3) minimum separation times, and

(4) runway occupancy time.

Among these factors, aircraft separation time was found to be most important. Using a deterministic model Baran also computed ultimate capacity for various types of operations (Ref 35).

The National Bureau of Standards introduced stochastic service times and analyzed capacity for various random distribution of the runway service time (Ref 36). A major contribution for computing ultimate capacity was made by Harris, who introduced time-separation buffers to account for errors in navigation and allowances made by air traffic controllers (Ref 13). Capacity was first calculated for the error-free system as simply the reciprocal of the minimum expected service time t :

$$t = \sum_{i,j} P_i M_{ij} P_j \tag{A.6}$$

where

P_i = proportion of aircraft of speed clas i ,

M_{ij} = (i,j) element of matrix M where M is a matrix of minimum interarrival times at the runway threshold, M , for an aircraft of speed class j followed by an aircraft of speed class i .

Assuming normally distributed errors in aircraft interarrival times at the entry gate or the runway threshold, capacity was computed from an interval and buffer matrix. This was done by substituting $(M + B)_{ij}$ for M_{ij} in Eq A.6 where B is the buffer matrix. Hockaday and Kanafani extended the work of Harris to account for the effect of wake turbulances and optimal operating strategies for specific proportions of arrival and departures in the mix (Ref 39).

Recently, Douglas Aircraft Co. and Peak, Marwick, Mitchell, and Co., et al (DAC/PMM), refined the approach to analyzing runway capacity (Ref 11). Their method uses analytical models for estimating aircraft delay. Hourly capacity is computed (ultimate capacity concept) and so is annual capacity on the basis of 16 hours of operation per day at ultimate capacity.

Taxiway Component

It has been argued that, in general, the capacity of the taxiway component is much greater than the capacities of either the runway or the apron/gate component (Ref 11). For this reason, models for determining the capacity of a taxiway network have not received much emphasis.

Recently, DAC/PMM et al. developed deterministic taxiways capacity models for each taxiway network segment (Ref 11). From these initial models, it was concluded that taxiway segments are not a significant constraint on airfield system capacity except for the case of runway-taxiway intersections, because these can affect runway capacity.

Runway crossing models for the following cases were developed for fair and poor visibility conditions by a deterministic approach:

A. single runway crossing, arrivals only,

B. single runway crossing, departures only,

C. single runway crossing, mixed operations, and

D. selected cases of close parallel runway crossings.

The intersection capacity for taxiing aircraft was then obtained by the following equation

$$\text{TICAP} = \left[\sum_{ij,klm} P_{ij} \; P_k P_l P_m N_{ij}(klm) \right] \left[T(AA) \right] \quad (A.7)$$

where

TICAP = Capacity of single runway-taxiway intersection,

$N_{ij}(klm)$ = total number of taxiing aircraft which can cross the runway between arrivals of class i and j, where potential departures are in classes k, l, and m,

P_{ij} = probability of an arrival pair with leading aircraft of class i and trailing aircraft of class j,

P_k = proportion of aircraft in class k, and

$T(AA)$ = weighted average interarrival time

$$= \sum_{ij} P_{ij} T_{ij}(AA) \,..$$

For cases of close parallel runway crossings, Eq A.7 is applied with appropriate modifications.

Apron Component

The major function of the apron component is to hold or circulate aircraft between the gates and taxiways and to provide space for aircraft parking maneuvers. Therefore, the major concern in previous models of this components has been the determination of space requirements to accommodate demand imposed on the apron area. The major factors affecting apron sizing are the layout of aircraft, gate positions, types of aircraft parking, and circulation and taxiing patterns dictated by the relative locations of the terminal buildings and the runway system.

Horonjeff has pointed out that the size of the apron-gate area depends on the number of aircraft gates, required size of the gates, and aircraft parking configuration at each gate (Ref 38). Therefore, the capacity of a given apron/gate system can be obtained by applying simple geometry to the changing mix of aircraft types and their durations on the apron areas. However, there is no general model available for estimating the capacity of the apron as a whole.

Although it was not directed toward the apron component as a whole, a recent DAC/PMM et al study considered the effects of apron/gate capacity on aircraft circulation on the apron (Ref 11). To determine under which conditions gate configurations are not the constraint on the apron capacity, analytical models were developed for the following three basic apron/gate configurations:

A. Single taxilane feeding gates on one side,

B. Single taxilane feeding gates on both sides,

C. Two-way taxilane feeding gates on both sides.

As a result the following equation was proposed for case A to compute the reduction of apron/gate capacity due to aircraft circulation on the apron:

$$R = \frac{S + M_o + M_i}{T} \qquad \text{(A.8)}$$

where

S = gate service time,

M_o = maneuvering time out of a gate,

M_i = maneuvering time into a gate,

T = time between successive operations at a gate in the constrained situation.

The value of T, which is a function of the aircraft platoon cycle time on the apron and number of gates, was computed by trial and error and the relationship between the number of gates and R was derived. For cases B and C appropriate modifications were made to Eq A.8. Based on a balanced design concept between the apron/gate and the runway and taxiway configurations DAC/PMM, et al suggest that the airport designer be concerned primarily with the number and type of gates and the classes of aircraft using the gates, rather than the geometry of the apron.

A study by Van Wyen considered apron maneuvering times for the nose-in parking method compared with those of other parking methods and provided data which may be used to approximate the number and duration of airplane conflicts in the apron areas (Ref 39). Braaksma and Shortreed proposed a network model using the critical-path method to analyze aircraft service times on the apron (Ref 40). They showed how to reduce gate occupancy times by identifying the critical activites for servicing an aircraft on an apron. A simle diagrammatic method by Ralph M. Parsons Co., which suggests a systematic approach to analyze the overall apron/

terminal system components, includes the apron service functions and could be used in simulation model (Ref 41).

Gate Component

In early days gate capacity was measured by deterministic models. Horonjeff suggested the number of gate positions be balanced with the capacity of the runways (Ref 42). Both Horonjeff and Brantley (Ref 43) suggest a model of the form:

$$G = \frac{V\,T}{u} \tag{A.9}$$

where

G = number of gate positions required,

V = design volume of arrivals and departures in aircraft per hour,

T = weighted average gate occupancy time in hours, and

u = utilization factor.

The gate utilization factor is a measure of the amount of time the gate positions are occupied in relation to the total amount of available time. The above Eq A.9 can be turned around and solved for V, say capacity, as a function of G.

Russian researchers formulated the model for gate requirements in relation to the daily demand of aircraft (Ref 44).

$$G = \frac{2\,(IKT)}{24 \times 60} \tag{A.10}$$

where

I = number of flights per day,

K = coefficient of nonconformity (ranges from 2.4 to 4.0),

T = average gate occupancy time in minutes.

The coefficent of nonconformity measures the degree at which the mix of aircraft and the available gates are incompatible.

The two models, Eq A.9 and A.10, are essentially the same, and several variations of these models exist in practice. For example, Eastern Airlines uses (Ref 45)

$$G_E = \frac{C_I}{u} \, d \, e \, s \tag{A.11}$$

where

G_E = number of gate positions required by Eastern Airlines,

C_I = IFR air carrier capacity in movements per hour,

u = utilization factor, e.g., 1.1 aircraft/hour for through stations,

d = delay factor, e.g., 1.35,

e = exclusive use factor, e.g., 1.2, and

s = Eastern's share of airport traffic, e.g., 20 percent of JFK.

Stafford, et.al., pioneered the method for calculating future gate requirements as a function of annual passenger volume (Ref 46). The formula developed from this study was

$$\text{Future gates} = (\text{present gates} - 2)\left(\frac{\text{future annual passengers}}{\text{present annual passengers}}\right) + 2 \tag{A.12}$$

A set of two curves (one for gates required by a schedule and one for gates required by operations) were developed from Eq A.12 and are contained in an ICAO manual (Ref 47).

For early arrivals and late departures, Stafford and Stafford made a suggestion to allow additional capacity which amount to about 15 percent of gate requirements (Ref 48).

Rallis proposed a stochastic queueing model in which arrivals are assumed Poisson distributed and gate occupancy time is assumed exponentially distributed (Ref 49). Steuart developed a stochastic model considering the relationship between the underlying airline schedule and the loads on the gate positions. (Ref 50). It was also reported by Steuart that in the absence of a schedule, gate requirements could be estimated from an infiite channel queueing system with Poisson arrivals.

$$G = \frac{\bar{\lambda}}{\bar{\mu}} + 2\sqrt{\frac{\bar{\lambda}}{\bar{\mu}}} \tag{A.13}$$

where

G = estimated number of gate positions required,

$\bar{\lambda}$ = average arrival rate, and

$1/\bar{\mu}$ = average gate occupancy time, i.e., $\bar{\mu}$ = average service rate.

Belshe provided simulation results for gate utilization under several alternatives (Ref 51). Using a practical capacity concept, a simulation model was developed by Van Ginkel Associates for the Canadian Ministry of Transport (Ref 52).

Recently, DAC/PMM et al. developed a new gate capacity model based on the ultimate capacity concept (Ref 11). Two analytical models were developed with gate capacity calculated as the inverse of the expected value of gate occupancy time computed for the set of aircraft being served. One model assumed that all aircraft can use all the available gates at an airport. This ideal capacity N (aircraft per hour) is given by

$$N = \frac{G}{\sum_i P_i T_i} \qquad \text{(A.14)}$$

where

G = total number of available gates,

P_i = proportion of aircraft of type i , ($\Sigma P_i = 1$),

T_i = gate occupancy time of aircraft type i .

Equation A.14 is identical in concept to equation A.9 except for the utilization factor. In their second model, DAC/PMM assumed that not all aircraft desiring service can be used by all smaller size aircraft, the constrained capacity C is

$$C = NX \qquad \text{(A.15)}$$

where

$$X = \min (g_1/t_1, g_1 + g_2/t_1 + t_2, \ldots, g_1 + g_2 + \ldots + g_n/t_1 + t_2 + \ldots + t_n),$$

g_i = fraction of total gates that can accommodate aircraft of class i ,

t_i = fraction of total gate time required for aircraft of class i , $i = 1, 2, \ldots, n$.

The model in Eq A.15 was slightly revised to take into account more completely excess gate minutes by Dunlay (Ref 53) who showed that the constrained gate capacity can be expressed:

$$C = \sum_{i}^{n} \min(N_1, C_i) \qquad (A.16)$$

where N_i is the number of aircraft type i served per hour under idea condition, and C_i is computed for each aircraft class i , $i = 1, \ldots, n$, by the following series of equations:

$$N_1 = N P_i$$

$$R_i = N_i T_i$$

$$A_i = G_i(60) + E_{i-1} \text{ ; NOTE: } E_0 = 0$$

$$E_i = \max (0, A_i - R_i)$$

$$C_i = A_i/T_i$$

where

R_i = required gate minutes per hour for type i ,

A_i = available gate minutes for type i ,

E_i = excess gate minutes for type i .

Dunlay's method Eq A.16 given slightly greater capacity estimates than the DAC/PMM method (Eq A.15).

Baggage Claim Component

One of the early models for sizing baggage claim areas was suggested by the FAA (Ref 54). Based on the FAA method a regression equation was developed by Zaniewski for space requirements in terms of passenger flow rate, measured as typical peak-hour passengers (TPHP) (Ref 55):

$$TPHP = 33 + .190x \qquad (A.17)$$

or

$$x = 5.26\ TPHP - 173.68$$

where

$$x = \text{baggage areas, ft}^2.$$

The relationship in Eq A.17 is valid only when the value of TPHP exceeds 200.

Barbo and Horonjeff showed a deterministic queueing model for space requirements (Refs 1 and 6). The model was based on experimental data taken at San Francisco International Airport and the capacity figures were obtained by a graphical method. The required size of the baggage display is obtained from the equation:

$$Q_b(t) = N_b \{F_b(t) - F_p(t)\ F_b(t)\} \qquad (A.18)$$

where

$Q_b(t)$ = number of bags in the queue, i.e., on the baggage display, at time t,

N_b = total number of bags,

$F_b(t)$ = fraction of bags to arrive by time t,

$F_p(t)$ = fraction of passengers to arrive by time t.

Equation A.18 is valid even if some passengers have more than one bag provided that the customer removes a bag from the display (carousel in this case) immediately even if he must still wait for a second bag.

The size of the passenger queue is also of importance. In general, when some passengers have more than one bag, it was shown by Newell (Ref 56) that

$$Q_p(t) = N_p F_p(t) \{1 - \sum_{i=1}^{n} P_i F_b^i(t)\} \tag{A.19}$$

where

$Q_p(t)$ = number of passengers waiting at time t,

N_p = total number of passengers,

P_i = fraction of passengers who have i bags, $\sum_{i=1}^{n} P_i = 1$, and

$F_b^i(t)$ = fraction of bags to arrive by time t raised to the ith power.

In this method, the average waiting times can be obtained by computing the area between the two curves $F_p(t)$ and $F_p(t)F_b(t)$. To account for the delay that occurs on the displace device itself, Horonjeff suggested from an experimental study that average waiting times be introduced and the curve $F_p(t)F_b(t)$ be displaced by that amount. His study shows that displacement is 1/2 to 1 minute if bags are displayed on a carousel (Ref 1). This is approximately the time of one carousel revolution.

Browne et al. developed a mathematical model to compute expected maximum queue lengths of both passengers and baggage (Ref 7). The model is based on the assumption of uniform arrival rate of passengers and baggage. The models were obtained for the following three cases:

(1) $n = 1$, $d = 0$; a, b, N variable,

(2) $n = 1$, a, b, d, N variable,

(3) $d = 0$; a, b, n, N variable.

where

N = number of passengers,

n = number of bags per person,

a = arrival rate of passengers,

b = arrival rate of bags, and

d = delay in the start of baggage arrivals.

By assuming that passengers and baggage are each mixed randomly, neither a passenger nor his bag leaves the system until they are joined up, and passengers remove their bags from the display area as soon as the bags arrive, the expected maximum inventories for passengers and baggage are computed for each of the above three cases. For example, for case (1) above:

$$I_p = \begin{cases} aN/4b & \text{if } a/b<1/2 \\ aN/4b & \text{if } 1/2\leq a/b\leq 2 \\ (1-b/a)N & \text{if } a/b>2 \end{cases}$$

$$I_b = \begin{cases} (1-a/b)N & \text{if } a/b<1/2 \\ bN/4a & \text{if } 1/2\leq a/b\leq 2 \\ bN/4a & \text{if } a/b>2 \end{cases}$$

where

I_p = expected maximum number of passengers, and

I_b = expected maximum number of baggage.

The above models are concerned only with the passenger/baggage interface. That is, the models deal with space requirements for baggage claim areas. To increase the capacity, it is necessary to increase processing speeds of passengers and baggage from aircraft to claim areas and vice versa, which needs hardside engineering development. For this purpose of baggage analysis, it is reasonable to assume uniform processing speeds for baggage. For example, in a baggage assembly one man can shift approximately 20 bags/minute without sorting and 4 to 5 bags/minute with sorting. With automation the speed without sorting can be increased to about 70 bags per minute.

For outbound baggage, Karash (Ref 57) constructed a simulation model for Logan Airport in Boston and Tanner (Ref 58) proposed a deterministic queueing model. Several studies have been made of general aspects of baggage handling (Refs 59 and 60).

One precaution by Beinhaker et al, of the baggage analysis in general, is that the provision of capacity and space must be determined by the flows and queues and not by averages or generalized standards (Ref 61).

Numerous simulation models have been developed for analyzing the baggage component and most of them are available in the computer packages that simulate overall landside functions of an airport (Refs 62, 63, 64, 65, and 66).

Passenger Processing

Because of the complexity of passenger processing and the relative lack of attention it has received, only a few analytical models have been found in this area. In the past several years, simulation models have been developed which emphasize landside elements of an airport. Most of the models are programmed in GPSS. Nanda et al developed a model for simulating passenger arrivals (Ref 65). Passengers and bags are generated from each flight. The major output of Nanda's model describes the passenger-baggage interface. The Bechtel model is a time-oriented queueing model that simulates passenger and baggage functions inside the terminal and the surface traffic on the airport internal roadways (Ref 64). The TAMS model is similar to the Bechtel model (Ref 69).

The MIT simulation model generates passengers with respect to flight schedules and includes the curbside and transit station platform (if any) (Ref 68). A Canadian model depicts flow capacities from the curbside to the boarding gate (Ref 66). These models are either in the process of development or in the validation process. An overview of the above simulation models is presented by McCabe and Carberry (Ref 4).

As for analytical models, FAA suggested graphic models for sizing several basic components of the terminal building (Ref 54). The FAA graphical relationships were converted by Zaniewski into a set of regression equations (Ref 55). The equations are expressed in terms of passenger flow rate measured as typical peak-hour passengers TPHP and are derived for a minimum passenger flow of 200 TPHP. Zaniewski's equations are listed below:

$$
\begin{aligned}
&\text{Ticket counter, ft:} && \text{TPHP} = -80 + 3.370x \\
&\text{Waiting area, ft}^2\text{:} && \text{TPHP} = -31 + 1.751x \\
&\text{Operations area, ft}^2\text{:} && \text{TPHP} = -24 + 13.5x + 0.15\,(x/1000)^2 \\
&\text{Eating facilities, ft}^2\text{:} && \text{TPHP} = -71 + 41.9\,(x/1000) \\
& && \qquad + 0.73\,(x/1000)^2
\end{aligned}
\tag{A.21}
$$

Women's Restrooms (closet and lavatories): $\text{TPHP} = -2.6 - 28x + 1.27x^2$

Men's Restrooms (closet and urinals): $\text{TPHP} + 132 + 1.56x$

Men's Restrooms (lavatories): $\text{TPHP} = 9 + 0.306x$

Lobbies, ft^2: $\text{TPHP} = 39 + 0.101x$

where

x = the dependent variable representing space requirements for the corresponding facilities in appropriate units.

In the above equation, TPHP is derived from the projected annual passengers.

Johnson has presented another method for computing required floor areas in the passenger termianl (Ref 69). His model calculates the required terminal size by first estimating instantaneous occupancy in an element of the terminal and multiplying that by a specified standard. Passengers are categorized into three classes, and occupancy times of 43 minutes, 19 minutes, and 82 minutes are allocated to outbound, inbound, and transfer passengers in the peak hour, respectively. By applying specified standard such as 15 sq. ft./person, required floor areas are estimated.

The FAA and Johnson approaches are designed to estimate space requirements but it is not difficult to see that capacity models can be obtained by simply reversing their procedures. For example, given the sizes of various terminal building components, one can estimate corresponding holding capacities by applying square foot standards associated with desirable levels-of-service.

One can always apply one of the already developed standard queueing models to passenger flow problems. For example, one can use M/M/c or M/D/c queues with various queueing disciplines with well-known results. Lee and Longton studies passenger check-in systems with combinations of four queueing processes of different types (Ref 70). They used M/M/c queues with first-in, first-out queue discipline to compute mean waiting times and showed how to obtain the optimum system by using both theoretical and empirical methods. Fisher, et al and Worral developed analytical models of ticket counters based on a stochastic queueing approach (Refs 71 and 72). There is no universally accepted model for check-in components. Probably for the same reason mentioned above no adequate models exist for security, customs, or inspection components except one study by Roman and Jackson which explores influence of sexual differences on security processing speeds (Refs 73).

For passenger circulation, Fruin and Henderson, et al., (Refs 74, 75, 76, 77, 78, and 79) provided extensive information on passenger movements, although their papers are primarily for general planning purposes rather than for estimating capacity. Fruin suggests various design standards for walkways, stairways, and people moving systems and the particular feature of his work is that the standard are expressed as a function of level-of-service. Numerous studies for pedestrian flow have been made in traffic engineering literature but their application to airport terminals has not been tested (Refs 80, 81, 82, 83, 84, 85, 86, and 87).

A limited number of models are available for analyzing corridor flow, all of which rely to a large extent on simulation. Reese constructed a model for studying passenger flow in a concourse at O'hare Airport (Ref 88) and Smith and Murphy performed a similar study at San Francisco Airport (Ref 89). In addition, Baron developed a simulation model for evaluating terminal efficiency in terms of operation distances (Refs 90). Analytical models are yet to be developed. A recent preliminary effort by Dunlay, based on a stochastic queueing approach, analyzed corridor flows of linear and pier-finger terminal corridors (Ref 91). A manual recently released by Ralph M. Parsons, Company provides corridor geometrics (Refs 92). It also includes desirable geometrics for various landside components.

Paullin developed a mathematical model for sizing the departure lounge (Ref 8). He presented two models: one describes the flow of passengers into the departure lounge and the other explains the flow into the aircraft. The first model is based on a polynomial regression analysis of actual arrival data and is expressed as

$$F(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 \qquad (A.22)$$

where

$F(t)$ = fraction of passengers who arrive at the lounge by time t,

t = minutes before departure, and

a_n = regression coefficients, $n = 0, 1, 2, 3, 4$.

From the observations, the following linear model was adopted by Paullin for the second model:

$$G(t) = b(t - t_b), \quad t_b < t < t_2 \qquad (A.23)$$

where

$G(t)$ = cumulative flow of passengers into aircraft,

b = capacity flow rate into aircraft,

t_b = time the aircraft doors are opened, and

t_2 = time the queue dissapates.

Paullin employed a graphical method for the analysis of departure lounge operation.

The effect of seat assignments on enplaning and deplaning rates was studied by Kaneko (Ref 93). IATA suggested a very simple method for sizing the passenger lounges (Ref 94): namely 9.7 sq. ft. per standing passenger and 15 sq. ft. per seated passenger.

No mathematical models have been developed for simultaneously analyzing the overall passenger processing subsystem due to the difficulty of estimating the demands on successive components, given the peak hour volume and surges of flows imposed on the system. Simulation methods are the only available ones in this area.

Curbside Component

The curbside component is probably one of the most neglected areas of the airport system. Previous curbside models have been mainly concerned with the computation of required curb-space through rules of thumb which relate linear feet of curbspace to some readily available measure of airport activity, such as aircraft operations, number of gates, annual passengers, etc. Examples of applying standards unique to particular airports can be found in recent studies. It was shown for the Greater Pittsburgh Airport, a medium-hub airport with a high proportion of business travel and a high number of transfer passengers, that the length of curb recommended for 1980 was about 0.6 feet per 1,000 annual enplaned passengers (Ref 95). The length of curb required for 1980 is approximately 1.2 ft. per 1,000 annual enplaned passengers at other airports such as Maiquetia Airport in Venezuela, which serves a large amount of overseas travel and virtually no transfer passengers (Ref 67).

As noted earlier for passenger processing components, the method of computing the curbside requirements can be reversed to provide a capacity model. However, if such a procedure employs averages or standards, the reversed model may not be adequate in that averages do not reflect demand characteristics imposed on the curbside component. No analytical models have been developed to explicitly estimate curbside capacity.

Tilles provided a nomograph method for calculating the required impact of curbspace using a simple M/M/c queueing process (Ref 96). Another method was suggested by Whitlock and Clearly, who considered a model split on the internal roadways and related it to the number of peak-hour vehicles for which to compute the length of required curbside (Ref 97). One study which is remotely related to the curbside is pursued by Yu who studies the effect of the curb parking maneuver on the roadway capacity (Ref 98). Several simulation models such as MIT's, Battelle's etc., do consider the curbside component.

Parking Component

Parking lot capacity is largely governed by the composition of users and their characteristics. Once these are known one can apply standard models developed by traffic engineers. The FAA recommendation is that 1.2 spaces be provided per peak-hour passenger, but the actual ratio varies greatly depending on the particular airport. Pipler shows a simple deterministic model for computing the required number of short and medium-term parking space (Ref 99).

$$P_i = S \frac{q}{a} z_i T_i \tag{A.24}$$

where

- P_i = number of parking spaces for car type i ,
- S = passenger volume per hour,
- q = proportion of passenger using parking spaces,
- a = average car occupancy,
- z_i = proportion of passengers using car type i , and
- T_i = average parking durination (in hours) of car type i .

Equation A.24 is generalized for sizing the long-term parking spaces by setting $q = 0.5$ and converting hourly volumes to daily demand.

FAA recommended the provision of parking-lot capacities with respect to the geometric arrangement (Ref 54). For self-parking structures it is generally agreed that angle parking (approximately 60°) with clear spans of approximately 55 feet is the most efficient and economical. This limits the aisles to one way traffic operation and expedites both parking and traffic flow. Using a space width of 8'8" required a net parking area, including aisle, of 275 sq. ft. per car, which allows about 158 cars per acre, which is equivalent to the FAA criteria (Ref 100). Yu considers level-of-service in designing parking facilities through a trial and error method (Ref 101). There are also simulation models and queueing models available for analyzing airport parking facilities.

Internal Roadway Component

Some simulation models are available to analyze the capacity of airport roadways. However, no adequate analytical models have been developed for airport planning purposes. One probable reason is that airport roadway characteristics are quite similar to those of off-airport roads. Therefore, current practice has been to apply the methods specified in the Highway Capacity Manual or other traffic engineering publications. Some example applications of the Highway Capacity Manual to airport roadways were shown by Zaniewski (Ref 55).

Piper derived a simple deterministic method to assess the demand level on the roadways considering model split as follows:

$$Z = qS \left\{ \frac{1.1 z_p + z_t}{a} + \frac{2 z_b}{a_b} \right\} \qquad (A.25)$$

where

Z = traffic laod on access roads,

S = passenger volume during a typical peak hour,

q = ratio of departing passengers to total passengers,

z_p = fraction of passengers using private cars,

z_t = fraction of passengers using taxis,

z_b = fraction of passengers using buses:

$$z_p + z_i + z_b = 1 ,$$

a = passengers per private car or taxi, and

a_b = passengers per bus.

Summary and Assessment

The models for the airside component are relatively complete. The weak areas of the airside are the apron subsystem and the taxiway component.

Available models for passenger terminal components are considered incomplete in their present forms with respect to the objective of this thesis. Most of the models concerning flow capacities are largely dependent upon readily available queueing models, but details of the corresponding airport environment have not been introduced. There are various standards for sizing the facilities, but these have been assumed indpendent of adjacent components processing capabilities in previous research. This deficiency may be erased by analyzing terminal components successively in a series format. This will involve estimating changing demand patterns on facilities in a series and their corresponding peaking characteristics.

The available models for the ticket-counter check-in component are weak in that they consider only a limited number of factors. In the passenger terminal the weakest areas are the security-check and corridor components. The baggage component is fairly complete, but a slight revision may be required in terms of passenger-baggage interface criteria. The existing models do consider the time lag between passengers and baggage arrival times. However, since most of the models are based on deterministic approaches, there may be some problems in applying the models to a variety of passenger terminal configurations.

The internal roadway component in the access/egress subsystem has not been adequately modeled. However, it may be possible to use models developed for highways. There is no doubt that it will be necessary to develop a model for the curbside component, as existing models of the curbside are not adequate.

In summary, the analysis of airport capacity as a whole will require improvements to existing models. It will be necessary to consider subsystem interactions at the major interface components and to analyze component interactions within each subsystem.

APPENDIX B. NEYMAN'S RESTRICTED CHI-SQUARE TEST

Neyman's restricted Chi-Square test (Ref 102) is a useful tool for testing the difference between sets of discrete observations. Consider n independent observations, and let X_i be the number falling in the i^{th} cell for $i = 1, 2, \ldots, m$ mutually disjoint and exhaustive cells. Further, let P_i be the probability of an observation falling in the i^{th} cell. Neyman considered that even under the class Ω of admissible hypotheses, there are restrictions on the probabilities of falling in the specified cells, that is, on P_1 , P_2 , ... P_m . The hypothesis tested H will impose further restrictions among them. For example, under the model Ω , the probabilities may depend in a particular way on some unknown parameters $\theta = (\theta_1, \theta_2, \ldots, \theta_s)$ so that one can write $P_i(\theta)$ which denotes $P_i(\theta_1, \theta_2, \ldots, \theta_s)$ under Ω . Then H may specify that $\theta_1 = \theta_2$. The Chi-Square criteria now should test the hypothesis H against $\Omega - H$ and not against the most general possible alternatives. The restricted Chi-Square test achieves this; the test criterion is the difference $\chi^2_H - \chi^2_\Omega$. Heuristically, this difference measures the increase in χ^2 due to the additional restrictions imposed by H , over those already imposed by Ω .

Assume that under Ω the probability of any observation falling in the i^{th} cell is $P_i = P_i\ (\theta_1, \theta_2, \ldots, \theta_s)$ and the probability is $\Pi_i(\theta) = \Pi_i(\theta_1, \theta_2, \ldots, \theta_s)$ under H. Let $\hat{\theta}_i$ be an estimate of θ_j under Ω and $\hat{\hat{\theta}}_j$ be the corresponding estimate under H. The restricted Chi-Square is defined as

$$\chi^2_f = \chi^2_H - \chi^2_\Omega = \sum_{i=1}^{m} \frac{\{X_i - n\Pi_i(\hat{\hat{\theta}})\}^2}{n\Pi_i(\hat{\hat{\theta}})} - \sum_{i=1}^{m} \frac{\{X_i - n\, P_i(\hat{\theta})\}^2}{n\, P_i(\hat{\theta})}$$

with

degrees of freedom $f = f_H - f_\Omega$

where f_H is the number of degrees of freedom in χ^2_H and f_Ω is the number in χ^2_Ω. Thus f_Ω is the total number of independent cells after grouping minus the number of indpendent parameters under Ω estimated from the data; and f_H is the same under the hypothesis H. Thus $f = f_H - f_\Omega$ is the decrease in the number of independent parameters under H, compared to under Ω, provided the grouping is the same.

Note that the classical Chi-Square test may also be used to test the difference. This test is relatively simple to apply, is consistent against all alternatives to the hypothesis tested, and possesses the property of being about equally sensitive to alternatives in all directions. In any particular problem, however, the test may have much less power than the best test. In many cases, only certain alternatives are of interest and for these the power is unnecessarily low. Because of this drawback in the classical Chi-Square test, the restricted Chi-Square test was proposed by Neyman to deal with particular classes of alternatives.

APPENDIX C. TOTAL EXPECTED TIME SHIFT - SAMPLE CALCULATIONS

Suppose that there are only two ancillary activites, A and B , between components j and j+1 . Also assume that one is given the following information:

Transfer times, ${}_i\Delta_j$, minutes:

	A	B	j+1
j	2	4	7
A	-	2	5
B	2	-	3

Expected dwell times, minutes:

dwell time at A , $D_A = 20$

dwell time at B , $D_B = 30$

Split Probabilities, $P = \Phi(\alpha + \beta\delta)$:

to component j+1 , $P_{j+1} = \Phi(1.5 - \frac{2.0}{60}\delta)$

to activity A , $P_A = \Phi(-3.0 + \frac{2.0}{60}\delta)$

to activity B , $P_B = 1 - P_{j+1} - P_A$

where

δ = the available time.

The following Eq 6.9 in Chapter 6 is used to compute the total expected time shift:

$$E\{T\} = {}_j\Delta_{j+1}\, P_{j+1}(t_o - t)$$

$$+ \sum_k ({}_j\Delta_k + D_k + {}_k\Delta_{j+1})\, P_k(t_o - t)\, P_{j+1}(t_o - t - {}_j\Delta_k - D_k)$$

$$+ \sum_k \sum_{k+1} \ . \ . \ .$$

Consider the value of δ and compute $E\{T\}$ by the above equation as follows:

(1) For $\delta = 20$ minutes, $E\{T\} = 7\, P_{j+1}(20) = 7\,\Phi\,(0.83)$

$= 5.58$ minutes. Only the first term of the equation is computed, as the remaining terms are not defined.

(2) For $\delta = 40$ minutes, $E\{T\} = 7\, P_{j+1}(40)$

$$+ (2 + 20 + 5)\, P_A(40)\, P_{j+1}(40 - 2 - 20)$$

$$+ (4 + 30 + 3)\, P_B(40)\, P_{j+1}\,(40 - 4 - 30)$$

$$= 7\,\Phi\,(0.17) + 27\,\Phi\,(-1.67)\,\Phi\,(0.9)$$

$$+ 37\{1 - \Phi\,(0.17) - \Phi\,(-1.67)\}\Phi\,(1.3)$$

$= 18.27$ minutes.

For different value of δ , the corresponding time shifts can be computed similarly to the computation shown above by the use of given information and a cumulative normal distribution table.

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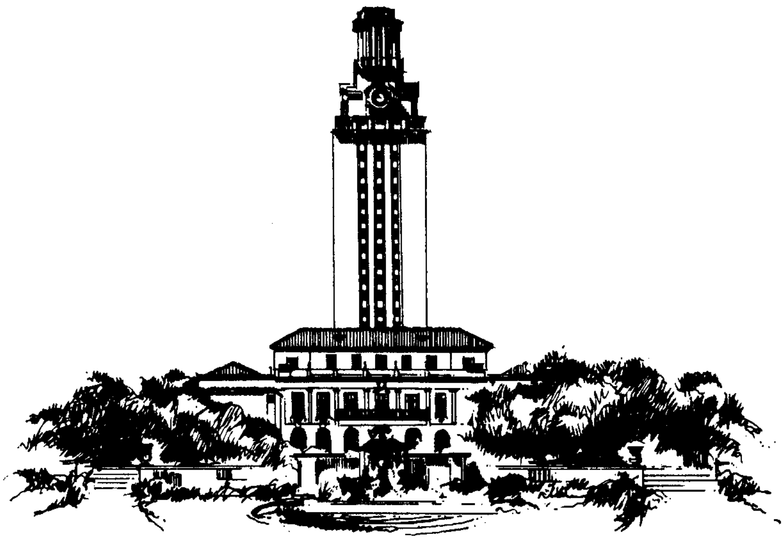

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