DOT-OS-50232

A SYSTEMS ANALYSIS PROCEDURE FOR ESTIMATING THE CAPACITY OF AN AIRPORT: SYSTEM DEFINITION, CAPACITY DEFINITION AND REVIEW OF AVAILABLE MODELS

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RESEARCH MEMO 27

OCTOBER 1975

COUNCIL FOR ADVANCED TRANSPORTATION STUDIES

The University of Texas at Austin

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Prepared for

Council for Advanced Transportation Studies
The University of Texas at Austin
Austin, Texas 78712

In Cooperation With

Department of Transportation
Office of University Research
Washington, D. C. 20590

PREFACE

This is the 27th in a series of research memorandums produced by the Council for Advanced Transportation Studies. It is also the second in a series of research memos describing the findings and activities carried out as a part of the work done under the research project entitled "A Systems Analysis Procedure 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.

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ABSTRACT

This research memo presents results obtained during the period from July 1 through October 1, 1975, in research on a systems analysis procedure for estimating the capacity of an airport in which both airside and landside capacities are studied. A definition of the system is presented including the system boundaries and a description of the subsystems and components of the overall system. A review is made of available analytical models of airport components including air traffic control, runways, gates, passenger processing baggage claim, internal roadways, and parking lots. Also included is a discussion of previous concepts and definitions of capacity, a discussion of relevant units of capacity, and a proposed definition of capacity for the airport system as a whole as well as its subsystems and components.

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I. INTRODUCTION

Purpose

The purpose of this research memo is to present a concise airport system definition, a definition of airport capacity and a review of the available capacity models for specific airport components.

Scope

The system definition identifies the physical and functional components and variables which affect airport capacity. The definition of airport capacity is such that it applies to the airport system as a whole as well as to each of its components and includes consideration of the fact that the four basic subsystems, i.e., the access/egress subsystem, the terminal building subsystem, the apron subsystem and the airside subsystem, each has different capacity constraints.* The review of available models covers all existing analytical capacity models adaptable to airport components regardless of whether or not they were developed specifically for airports. In addition, some aspects of past simulation models are covered.

Background

Heretofore, research and development in airport capacity have been primarily concentrated on the runways and gates of an airport. However, growth in the number of passengers to be processed and an increase in non-flight related activities at airports have shifted the emphasis of the capacity problem. There is increasing evidence that the landside is becoming the constraint on overall airport capacity. For example, the Airport Operators Council International and the American Association of Airport Executives (AOCI? AAAE) recently conducted a survey to determine airport capital development needs to 1980 (Ref. 1). This survey showed that for the 24 large-hub airports

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

sampled, 56 percent of the total projected capital development needs, or almost 2 billion dollars, was for landside improvements. The FAA recently completed a study of airport capacity based on examination of eight major U. S. airports, in which 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 an active program to institute terminal air traffic control improvements, saturation of the airport airside can be postponed a decade, into the mid to late 1980's (Ref. 2). In response to the above evidence, 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 level-of-service methodologies to quantify airport landside capacity, engineering techniques to increase landside capacity, and analytical tools for use in improving landside capacity. The workshop was held in Tampa, Florida, April 28 to May 2, 1975. Research described in this research memo is being carried on cooperatively with the ongoing DOT program on airport landside capacity.

Objective

The objective of this project is to provide an airport capacity estimation method with which balanced improvements to airside and landside components can be planned, through the use of a systems approach rather than the current method of analyzing each component as an independent part of the airport system. The results of this research will provide a valuable tool to airport planners, designers and decision makers. The anticipated users of the airport capacity estimation procedures include the FAA, airport planning consultants, airport sponsors and the airlines. The research results will have application both to the analysis of existing airport capacity and the prediction of capacities of future airports. These applications will take two basic forms: (1) identification and specification of research and capital improvement priorities for the various components of the airport system, and (2) preliminary testing of alternative designs and sizings of each component to assure that its capacity is adequate to meet existing projected demand and is in balance with the capabilities of other airport components.

Research Approach

The current manner in which airport capacity is studied may be termed a "component approach," because each component or subsystem is analyzed as an independent part of the system. This approach can lead to an unbalanced airport system. In our approach, the capacities of individual components of the total airport system are investigated and compared. Interfaces between components are also investigated. This systems approach incorporates a single definition of airport capacity which applies to all components and to the total airport system.

The basic systems approach of our research is summarized in Fig. 1. The five basic steps into which the approach has been broken down are (1) problem recognition, (2) system definition, (3) system description, (4) system capacity definition, and (5) system documentation. These basic steps are further broken down into individual, tasks as shown in the figure.

Report Organization

The next section defines the physical boundaries of the airport system and its components and subsystems. This is the system definition for the study. In section 3 the available models for each component are reviewed. Section 4 presents a review of the available concepts of airport capacity and the formulations of the proposed airport system capacity definition.

PROBLEM RECOGNITION

1. Capacity of Airport may be limited by operation of its weakest component.
2. Lack of models for certain airport components, particularly on the landside.
3. Lack of method for evaluating capacity of airport as a whole.
4. Landside components becoming increasingly critical as constraints to airport capacity

SYSTEM DEFINITION

1. Identify physical components and variables of the airport system and its environment.
2. Identify economic, regulatory, technological, energy, and environmental variables that affect airport capacity.
3. Specify which components and variables will be modeled in Year 1 of research

SYSTEM DESCRIPTION

1. Review available analytical models of airport components.
2. Identify need for model development by attempting to synthesize available models into a systems model of the airport as a whole.
3. Collect data and develop models of selected airport components.
4. Synthesize component models into model of airport system as a whole.

SYSTEM EVALUATION

1. Specify and collect data on level of service measures to be used in model calibration.
2. Estimate maximum throughput rates of airport system components to identify physical components that constitute a bottleneck and to provide input/output flow links between components.

SYSTEM DOCUMENTATION

1. Flexible and integrated modular system model of airport components.
2. Design of input including parameters through which users specify level of service criteria and patterns of demand.
3. Design of output including identification of critical components and sensitivity analysis.
4. Model validation

Figure 1. Research Approach

II. AIRPORT SYSTEM DEFINITION

Background

In recent years the concept of systems engineering has evolved as a rational technique for evaluating large and complex systems in electronics, communications, pavement structures, and the aerosapce industry. This concept provides a means of obtaining a solution to a problem which is so complex and on such a large-scale, e.g., an airport, that the only method of attacking the problem is in a formalized framework which organizes the various segments of the problem into an understandable and coordinated whole.

Ellis and Ludwig define a system as follows:

> "A system is something which accomplishes an operational process; that is, something is operated on in some way to produce something. That which is operated on is usually input, that which is produced is called output, and the operating entity is called the system. The system is a device, procedure, or scheme which behaves according to some description, its function being to operate on information and/or energy and/or matter and/or service ." (Ref. 3).

Airport System

In the case of airport capacity analysis, the airport is the system. For this project the boundaries of the airport system are the airport entrance gate on the landside and the terminal airspace* on the airside. Fig. 2 is a schematic look at the airport system and its input variables from the environment. The airport system transforms the input variables into the outputs of the system. These outputs are depicted in Fig. 3. The airport system, together with the input variables and the outputs, describes the interaction of the airport with its environment.

In order to analyze a complex and large-scale system it is necessary to divide the system into subsystems. 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.

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*The near-terminal airspace under the jurisdiction of the ATC tower is included in the system while approach/departure airspace is not included for purposes of our analysis.

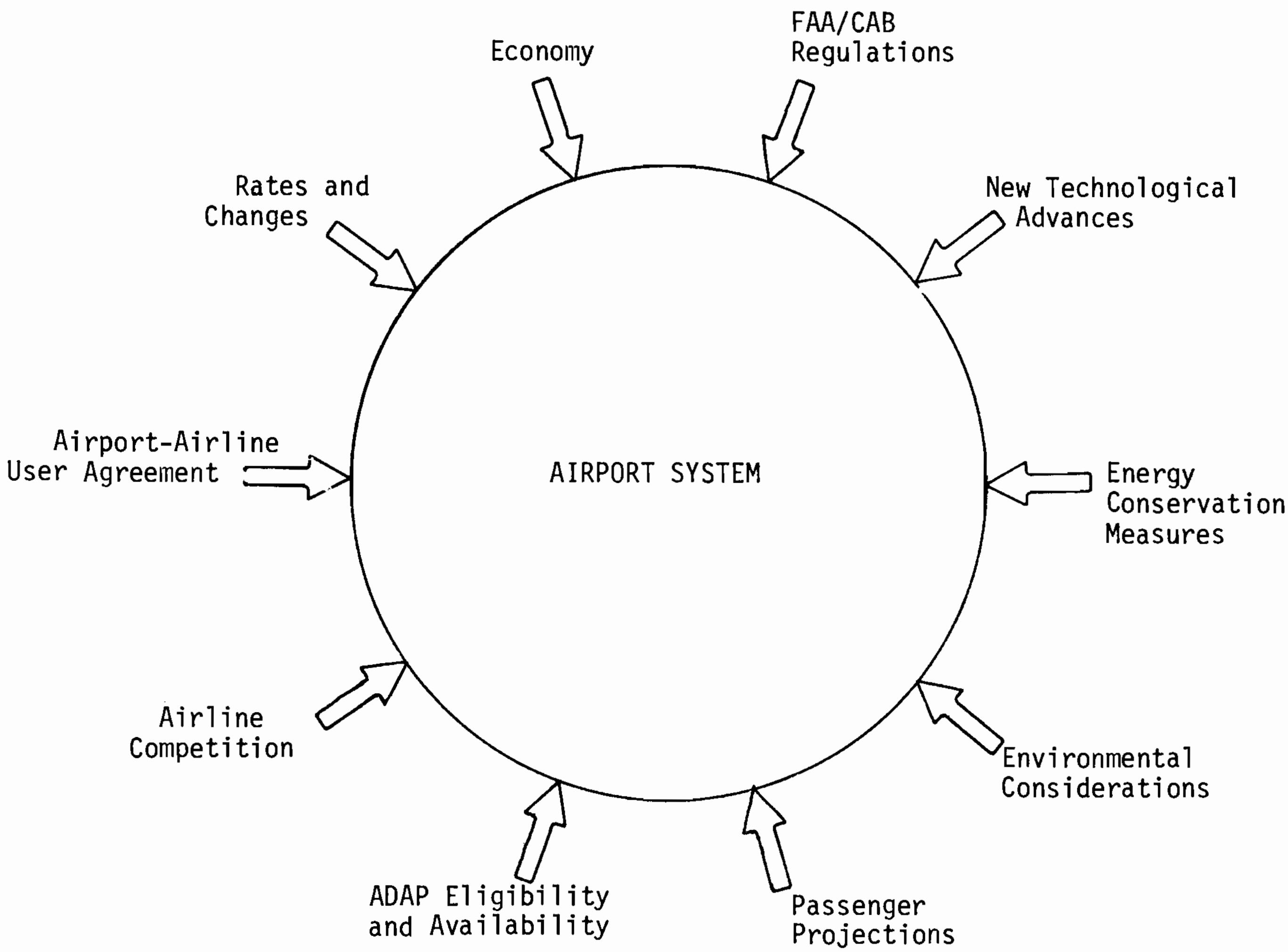

Figure 2. Input Variables from the Environment.

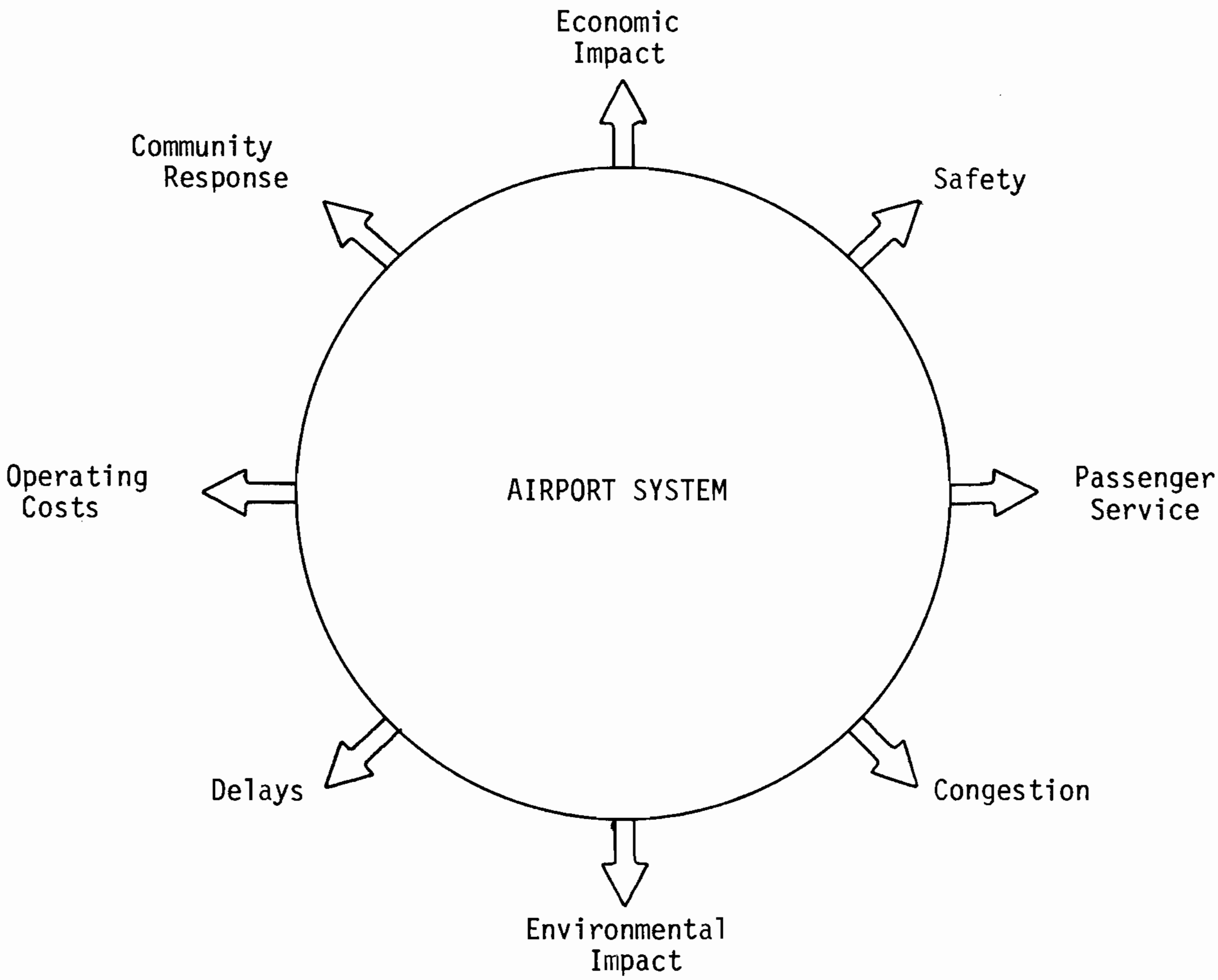

Figure 3. Output Variables to the Environment.

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

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

After being processed through the Terminal Building Subsystem, the passenger and his baggage are loaded into the aircraft parked on the apron. While on the apron, the aircraft interacts with passengers, baggage, and service vehicles. Therefore, it was felt that a good subsystem division 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 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, or 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 element into which the system is divided for nalaysis purposes. In this research a component is used to describe an individual processing or storage unit. Figure 4 is a schematic representation of the airport system with each operational unit employed wherever necessary. In the past most schematic diagrams of an airport depicted an exact functional flow through the different components, especially in the terminal building. Note that Fig. 4 does not have any exact flow representaion. The subsystems are 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 system definition to a particular airport configuration. It is important to realize that within the same subsystem the output of any one particular component is essentially the input to the next component in sequence.

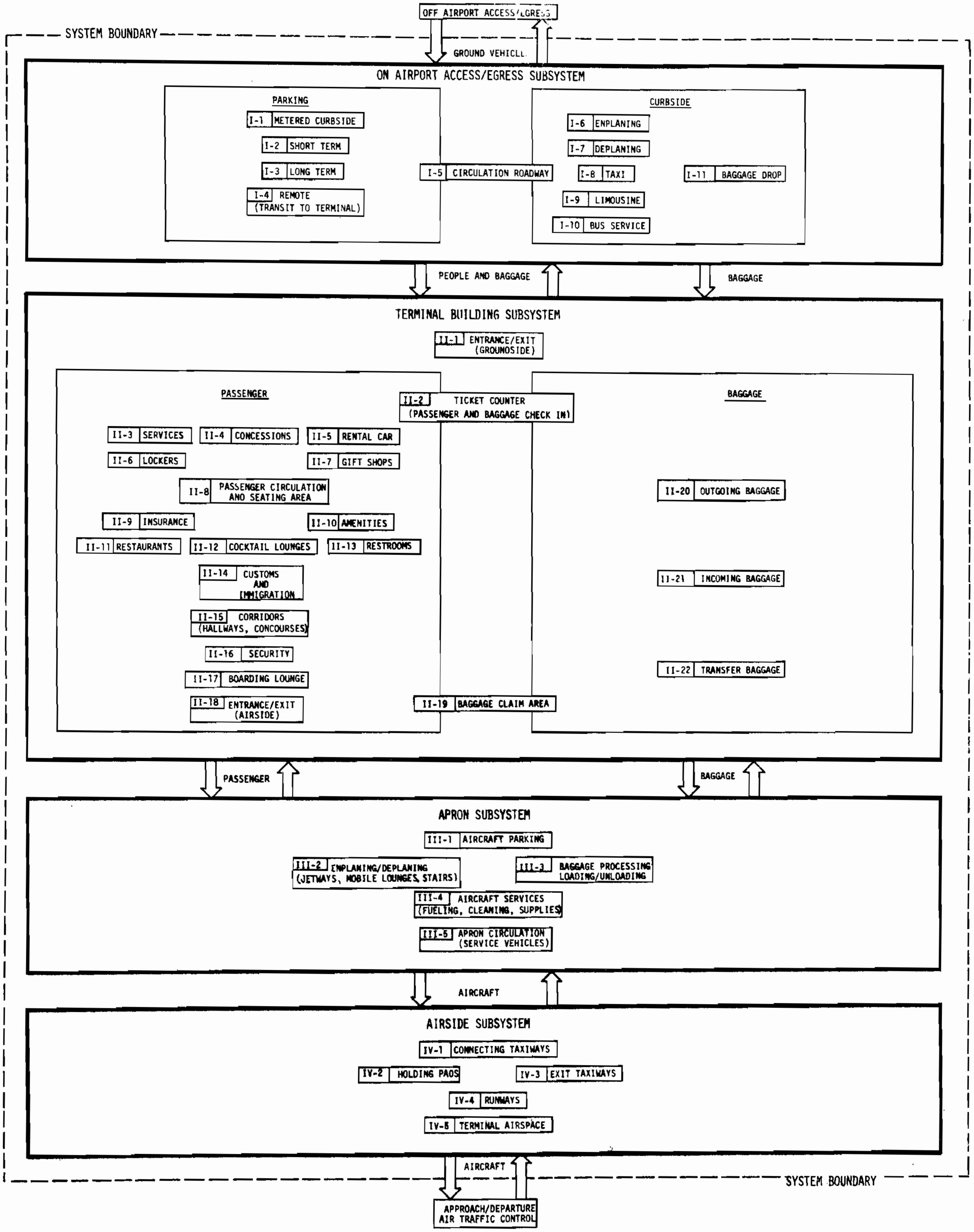

Figure 4. The Airport System.

Terminology

A vital step in the development of a systems approach to a problem is a clear understanding and agreement on terminology. In describing the components of the airport system (Fig. 4) some illustrative terms have been used which require further clarification and definition as follows:

Metered Curbside Parking: parking, usually with the highest cost, located adjacent to the terminal building, used mainly for stops that are very short.

Short Term Parking: parking available within convenient walking distance to the terminal building at a lower cost than metered curbside parking.

Long Term Parking: parking with a longer walking distance to the terminal building than short term parking and at a lower cost than short-term.

Remote Parking (transit to terminal): parking located farthest from the terminal building that uses some form of transfer device to deliver people to or from the terminal building at the lowest cost of all the parking types.

Circulation Roadway: way on which vehicles circulate within the airport system.

Enplaning Curbside: curbside specifically for the purpose of delivering passengers.

Deplaning Curbside: curbside specifically for the purpose of picking up passengers.

Taxi Curbside: curbside designated for taxicab use only.

Limousine Curbside: curbside designated for limousine use only.

Bus Service Curbside: curbside designated for use by buses only.

Baggage Drop Curbside: curbside area designated for the purpose of checking baggage in.

Passenger Circulation and Seating Area: space available to people within the terminal building for moving about the different passenger conveniences.

Corridors: hallways, concourses, and passageways within the terminal building which connect several separate parts of the terminal.

Entrance/Exit (airside): portal through which passengers enter or exit the terminal building.

Outgoing Baggage: baggage being processed from the terminal building to the aircraft.

Incoming Baggage: baggage being processed from the aircraft to the terminal building.

Transfer Baggage: baggage that is separated from incoming baggage and assigned to a departing flight.

Aircraft Parking: operation in which the aircraft is positioned with respect to the terminal building and the manner in which the aircraft maneuvers in and out of the parking area.

Apron Circulation: movement of service vehicles around the aircraft to prepare it for flight.

Connecting Taxiways: pattern of taxiways joining the runway area with the apron.

Exit Taxiways: taxiways used to depart from the runway.

Terminal Airspace: Airspace within approximately 5 miles of the airport, which is under the jurisdiction of the airport control tower.

System Components

Before models can be developed it is necessary to: (1) determine which activities occur at each component that would impede its operation, (2) develop methods to measure the activity and (3) determine which variables influence this activity. This is accomplished in Table 1. In this table only the critical components are discussed, along with the activity occuring at the component, the level of service measure, and the primary variables influencing the level of service measure. Again it is necessary to define the terminology used:

Activity: service or function performed by a specific component.

Level-of-Service Measure: physical appraisal of how a component, subsystem, or system performs.

An example of the table's interpretation is provided below to aid in the understanding of its purpose. As the passenger enters the terminal building and proceeds to the ticket counter, component No. II-2, he will either be processed by an agent immediately or, if no agent is free, will wait in the line or queue that has developed. Thus, the length of the queue and the waiting time are assessments of the component's performance, or its level of service

TABLE 1. AIRPORT SYSTEM COMPONENTS

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
I-1	Metered Curbside	Storage	Holding capacity Space availability	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 Walking distance 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	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

TABLE 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	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	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	1) Effective dimensions of each corridor 2) Passenger (and visitor) accumulation rate 3) Walking rate of passengers

TABLE 1. (Continued)

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
II-16	Security	Processing	Queue length at entrance Waiting time Congestion	1) Passenger flow thru rate 2) Size of security force
		Storage	Holding capacity	1) Passenger flow to aircraft 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	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	Queue length Waiting time Congestion	1) Width of doorway 2) Walking rate of passengers 3) Space requirements per passenger
II-19	Baggage Claim Area	Storage	Queue length Waiting time Congestion	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.)

TABLE 1. (Continued)

NO.	COMPONENT	ACTIVITY	LEVEL OF SERVICE MEASURE	PRIMARY VARIABLES INFLUENCING PERFORMANCE
II-20	Outgoing Baggage	Processing	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	Waiting time and queue length at baggage claim area	1) Time required to unload, sort and convey to baggage claim areas
II-22	Transfer Baggage	Processing	Delay to 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)

TABLE 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 Taxiiing 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

TABLE 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

measure. The passenger processing rate per agent is a primary variable influencing the level of service measure. The number of agents available is also a primary variable influencing the level of service measure.

Also of interest at the ticket counter is the total area or storage space available in the event that long queues develop. The corresponding level of service measure would be the holding capacity which would be affected by the peak-hour passenger arrival and processing rates and the minimum space necessary for each passenger standing in line. Knowing the storage and processing input data will facilitate development of a model to predict the capacity of the ticket counter component.

Summary

Using a systems engineering approach, the airport system, along with appropriate subsystem and components, has been defined for capacity analysis. Figure 4 is a schematic representation of the airport system. The figure is arranged so that an exact flow can be specified for each particular airport configuration. Terminology has been defined wherever necessary.

To facilitate model development, activities at each component that would hinder its operation have been defined, along with a method to measure the activity and level of service provided by the variables which influence its operation (Table 1).

III. REVIEW OF AVAILABLE MODELS--SYSTEM DESCRIPTION

A systems study typically begins with hypothesizing the real system into a simplified version 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 tool for describing and understanding the system in a desirable fashion. Therefore, models that describe the system provide information on the organization, the physical components, or the operations of the system and, through a continuous feedback between the analysis and the implementation phases, a better understanding of the system itself.

Models that were developed under an airport environment are presented, based on the list of components defined in the previous section. General capacity models of other modes which are also applicable to the airport are not discussed in detail.

There are two major types of models for analyzing airport capacity, 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 compatability in application.

For airport capacity analysis, simulations have been much more widely used than analytical methods. The main reasons for this is that they are relatively easy to develop (although expensive) and the airport itself is a very complex system. However, in this research the main analysis was be 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 use as an input to the simulation, whenever appropriate. Thus, the following discussions of available models emphasize analytical models.

There are many references which include capacity models. In this memo, an attempt is made to cover as many models as possible which are reasonably significant to the research purpose. Due to the inaccessibility to some literature, however, some portions of the discussion are still incomplete.

The available models of airport components are reviewed in the following discussion.

Terminal Airspace Component

According to the system boundary described in Section II the terminal airspace component bounds the airport on the airside. Its major role is to connect the enroute sectors to the runway component by feeding aircraft to the runway. Thus, the terminal airspace component's capacity influences subsequent component operations to a large extent.

The Federal Aviation Administration, based on the controller workload approach, developed a simulation model for the New York Metropolitan Area airspace system (Ref. 4). Using real-time simulation, total workload times were computed for various levels of aircraft demand. The total workload time WLT was defined as

$$WLT = nW_1 + nW_2 + CW_3 \qquad (1)$$

Where n = number of aircraft per hour,

C = number of potential conflicts per hour,

W_1 = routine communications workload measured in seconds per aircraft,

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

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. (1), one can determine a capacity range for each terminal sector by limiting the workload time to a predetermined value, say 2000-2500 seconds per hour, and finding the corresponding demand level, say n. To compute the capacity, two inputs are required: the maximum allowable value of WLT and the number of potential conflicts C.

A complexity rating approach was employed by the Airborne Instruments Laboratory (Ref. 5). This method, known as the TRANSAIR model, relates aircraft movements to a set of relative complexities of controlling various types of aircraft operations and interactions. After assigning a complexity weighting factor for each type of aircraft interaction, a steady-state stochastic model computes the total complexity ratings resulting from the given demand on the terminal sector in question. Knowing the weighting factors for each interaction type and the number of interactions for each type, the model gives the total complexity rating as follows:

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

where CR = complexity rating,

n_i = number of interactions of type i,

W_i = weighting factor for interaction type i.

With this approach, capacity is defined as the aircraft movement which causes 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 evaluate sectors (Ref. 6). Although the model is for enroute sectors, it can be applied in principle to the terminal airspace as well. In the SRI procedure, estimates are computed for the number of ATC events associated with a given pattern of traffic. These estimated numbers of events are determined using analytical models of air traffic operating within the sector. Their assertion was that workload is related to the frequency of events which require decisions and actions by a controller team and to the time required to accomplish 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):

$$CDI = \sum_i W_i E_i \qquad (3)$$

where W_i = weighting factor for event i,

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. From this upper limit a capacity estimate can be made.

Recent studies by SRI and Dunlay pointed out the stochastic nature of controller workload and suggested possible alteration to methods of computing airspace capacity (Refs. 7 and 8).

Runway Component

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

The early analytic investigations were concerned mainly with landing delays using models of queueing theory, although the principles involved are also applicable to the take-off problem. Using Poisson arrivals with constant service time, Bowen and Pearcy computed steady-state average landing delays (Ref. 9). Under the same assumption, delay distributions were further pursued by Pearcy (Ref. 10). In the earlier work, the assumption of arrivals corresponding to a Poisson distribution was generally accepted and actual validations were reported by Bower and Pearcy, Bell, and Berkowitz and Doering (Refs. 9, 11, and 12). This class of early M/G/1 queueing* 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. 13).

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

where λ = mean arrival rate,

$1/\mu$ = mean service time,

σ^2 = variance of service time,

ρ = is traffic intensity.

Using a similar queueing model, Galliher and Wheeler derived nonstationary delay distributions for landing aircraft (Ref. 14). The effect of approach path separation on landing delays was analyzed by Oliver (Ref. 15).

The most widely applied model in the U. S. for mixed operations was developed by the Airborne Instruments Laboratory (AIL). Several documents

*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. It is customary to use the conventional codes M, G, and D to represent Poisson, general, or deterministic distributions, respectively.

for use by airport planners have evolved from this effort (Refs. 16 and 17). With its final versions based on the practical capacity concept, FAA issued advisory circulars AC 150/5060-1A and AC 150/5060-3A, which have been widely used in airport planning. Essentially there were two models. While one model exclusively for runway use, follows the form of Eq. 4, the other, for mixed operations, is based on the preemptive spaced arrival queueing process. In this 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 processes that takeoffs encounter at the runway are not assumed Poisson but are modeled to behave more like the output of an airborne queueing process. Galliher modified this general model by inclusion of spaced arrivals, i.e., he used a displaced exponential gap distribution. Under steady-state conditions, the average delay for mixed operations was expressed as

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

where W_d = average delay to departure,

λ_a = average arrival rate,

λ_d = average departure rates,

j = average interval of time between two successive departures,

σ_j = standard deviation of interval,

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

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 lengths of time intervals are used for defining capacity. One, known as the practical hourly capacity (PHOCAP), is defined as the number of aircraft movements that the runways can accept that corresponds to some fixed limit on the level of average delay (4 minutes is commonly used). The other, known as the practical annual capacity (PANCAP), allows for an overload on the airfield during short periods over a year's time. An overload is defined as a period of time when demands exceeds

PHOCAP*. PANCAP was empirically defined as that level of operation (for a given demand pattern) at which 10% of the operations or 5% of the time the demand on the runways exceeds PHOCAP and that the average delay during those overload periods is 8 minutes. AIL has applied its models to a number of airport configurations and aircraft populations for both VFR and IFR conditions.

As a means of increasing the capacity, the effect of runway-use priority rules on aircraft delays during mixed operations was investigated by Pestalozzi (Ref. 18). 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, varying load factors and a mixture of both.

Models of runway capacity using the ultimate capacity concept were initiated by Blumstein (Ref. 19). 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 include the lengths of common approach paths, aircraft speeds, separation times, and runway occupancy times among which the aircraft separation time was found to be most important. Using a deterministic model Baran computed ultimate capacity for various types of operations (Ref. 20).

The National Bureau of Standards introduced stochastic service times and analyzed capacity for various random distributions of the service time (Ref. 21). A major contribution for computing ultimate capacity was made by Harris, who introduced time separation buffers to account for errors in navigation and air traffic control (Ref. 22). Capacity was first calculated for the error-free system as simply the reciprocal of the minimum weighted service time t:

$$t = \sum_{i,j} P_i M_{ij} P_j \qquad (6)$$

where P_i = percent of aircraft of speed class i,

M_{ij} = (i,j) element of matrix M where

*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.

M = matrix of minimum interarrival times at the runway threshold, T_{ij} 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. (6) where B is the buffer matrix. Hockaday and Kanafani extended the work of Harris for studying the effect of wake turbulances and derived optimal operating strategies for specific proportions of arrivals and departures in the mix (Ref. 23).

Recently, Douglas Aircraft Co. and Peat, Marwick, Mitchell & Co. (DAC/PMM) et al. developed a new approach for analyzing runway capacity (Refs. 24). Using analytical models for determining capacity and computer simulations based on Monte Carlo sampling determining aircraft delay, hourly capacity was computed (ultimate capacity concept) along with annual capacity based on 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. 24). For this reason, models for determining the capacity of a taxiway network have not been developed extensively.

Recently, DAC/PMM et al. developed deterministic taxiway capacity models for each taxiway network segment (Ref. 24). From these initial models, it was concluded that taxiway segments are not a significant constraint on airfield system capacity. But in the case of runway-taxiway intersections, since they can affect airfield capacity, the 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,

D. Selected cases of close parallel runway crossings.

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

$$TICAP = \sum_{ij,klm} P_{ij} \; P_k P_l P_m N_{ij}(klm) \; T(AA) \qquad (7)$$

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 j.

P_k = proportion of aircraft class k,

T(AA) = weighted average interarrival time = $\sum_{ij} P_{ij} T_{ij}(AA)$

For cases of close parallel runway crossings, Eq. (7) is applied with the appropriate changes.

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 for this component has been the determination of space requirements to accomodate demand imposed on the apron area. The major factors affecting apron sizing are the layout of aircraft gate positions, type 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. 25). 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 the capacity of the apron as a whole except for the gates.

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. 24). To determine under what conditions gate configurations are not a constraint on 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 taxilanes 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:

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

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 A and B, appropriate changes were made to Eq. (8).

Based on a balanced design concept between the apron/gate and the runway and taxiway configurations, the DAC/PMM et al. study suggests 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. 26). Braaksma and Shortreed proposed a network model using the critical path method to analyze aircraft service times (Ref. 27). They showed how to reduce gate occupancy times by identifying the critical activities for servicing an aircraft on an apron. A simple diagrammatical method shown by Ralph M. Parsons Co. was to suggest a systematic approach to analyze the overall apron terminal system components, which include the apron service functions and could be used for a simulation model (Ref. 28).

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 and his work was extended by Brantley (Ref. 29 and 30):

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

where G = number of gate positions required,

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

T = weighted average gate occupancy time in hours,

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.

Russian researchers formulated the model of gate capacity in relation to the daily demand of aircraft (Ref. 31):

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

where I = number of flights per day,

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

T = average gate occupancy time in minutes.

The two models, Eq. (9) and (10), are essentially the same, and several variations of these models exist in practice. For example, Eastern Airlines uses (Ref. 32)

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

where G_E = number of gate positions required by Eastern Airlines,

C_I = IFT 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 facotr, e.g., 1.2,

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

Stafford, et al., pioneered the method for calculating gate requirements in relation to the annual passenger volume (Ref. 33). The formula developed from this study was

$$\text{Future gates} = \left[(\text{present gates} - 2) \cdot \frac{\text{future passengers}}{\text{present passengers}}\right] + 2 \tag{12}$$

A set of curves, one for gates required by the schedule and one for gates required by operations, were developed from Eq. (12), as documented in an ICAO manual (Ref. 34).

For early arrivals and late departures, Stafford and Stafford made a suggestion to allow additional capacity which varies around 15 percent of gate requirements (Ref. 35).

Rallis proposed a stochastic queueing model in which arrivals are assumed Poisson distributed and gate occupancy exponentially distributed (Ref. 36). Steuart developed a stochastic model considering the relationship between the underlying airline schedule and the loads on the gate positions (Ref. 37). It was also reported by Steuart that in the absence of a schedule, gate requirements could be estimated from an infinite channel queueing system with Poisson arrivals.

$$G = \frac{\overline{\lambda}}{\overline{\mu}} + 2\sqrt{\frac{\overline{\lambda}}{\overline{\mu}}} \tag{13}$$

where G = estimated number of gate positions required,

$\overline{\lambda}$ = average arrivale rate,

$1/\overline{\mu}$ = average occupancy time.

Belshe provided simulation results for gate utilization under several alternatives (Ref.38). Using a practical capacity concept, a simulation model was developed by Van Ginkel Associates for the Canadian Ministry of Transport (Ref. 39).

Recently, DAC/PMM et al. developed a new gate capacity model based on the ultimate capacity concept (Ref. 24). Two analytical models were developed with gate capacity calculated as the inverse of a weighted average gate occupancy time of all aircraft being served. One model assumed that all aircraft can use all the gates available at an airport. This ideal capacity N (aircraft per hour) is given by

$$N = \frac{G}{\sum_i P_i T_i} \tag{14}$$

where G = total number of available gates,

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

T_i = gate occupancy time of aircraft type i.

In the second model, it is assumed that not all aircraft desiring service can use all the available gates. Assuming that a gate for a large aircraft can be used by all smaller size aircraft, the constrained capacity C is

$$C = NX \tag{15}$$

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, $i = 1,2,\ldots,n$,

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

Considering excess gate minutes, the model in Eq. (15) was slightly revised by Dunlay (Ref. 40) who showed that the constrained capacity is

$$C = \sum_i \min(N_i, C_i) \tag{16}$$

where N_i is the number of aircraft type i served per hour under ideal condition, and C_i is computed by the following series of equations:

$R_i = N\ T$

$A_i = G\ (60) + E_{i-1};\ E_0 = 0$

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

$C_i = A_i/T_i$

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.

Baggage Claim Component

One of the early models for sizing baggage claim areas was suggested by FAA (Ref. 41). Based on the FAA graphical relationship a regression equation was fitted by Zaniewski for space requirements in terms of passenger flow rate, measured as typical peak-hour passengers (TPHP) (Ref. 42):

$$TPHP = 33 + .190x \tag{17}$$

or

$$x = 5.26\ TPHP - 173.68$$

where x = baggage areas, ft.^{2}

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

Barbo and Horonjeff showed a deterministic queueing model for space requirements (Refs. 43 and 44). The model was based on experimental data taken at San Francisco International Airprot and the capacity figures were obtained by a graphical method. The required size of the baggage display is obtained by the simple equation

$$Q_b(t) = N_b \left[F_b(t) - F_p(t)\, F_b(t) \right] \tag{18}$$

where $Q_b(t)$ = number of bags in the queue,

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.

Eq. (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 required size of the passenger movement area was obtained accordingly. In general, when some passengers have more than one bag, it was shown by Newell (Ref. 45) that

$$Q_p(t) = N_p F_p(t) \left[1 - \sum_{i-1}^{n} P_i F_b^i(t) \right] \tag{19}$$

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, $\sum_{i=1}^{n} P_i = 1$,

$F_b^i(t)$ = fraction of bags to arrive by time t raised to the i^{th} 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 arrival time difference between bags and passengers, Horonjeff suggested from the experimental study that average waiting times be introduced and $F_p(t)\, F_b(t)$ be displaced by that amount. His study shows that the displacement is 1/2 to 1 minute if bags are displayed on a carousel (Ref. 44).

Browne et al. developed a mathematical model to compute expected maximum queue lengths of both passengers and baggage (Ref. 46). 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 variables,

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

where

N = number of passengers,

n = 1, a, b, d, N variables ,

a = arrival rate of passengers,

b = arrival rate of bags ,

d = delay in the start of baggage arrivals.

By assuming that passengers and baggage are each mixed randomly, that neither a passenger nor his bag leaves the system until they are joined up, and that 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 ,

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 the purpose of baggage analysis, it is reasonable to assume uniform processing speeds for baggage. For example, in a baggage assembly one man can shift 20 bags/min. without sorting or 4 to 5 bags/min. with sorting. With automation, this speed can be increased to about 70 bags/min.

For outbound baggage, Karash constructed a simulation model for Logan Airport in Boston and Tanner proposed a deterministic queueing model (Refs. 47 and 48). Several studies were made as to general aspects of the baggage handling (Refs. 49 and 50).

For the baggage analysis in general one precaution by Beinhaker et al. is that the provision of capacity and space must be determined by the flows and queues and not by averages or generalized standards (Ref. 51).

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. 52, 53, 54, 55, 56, and 57).

Passenger Processing

Because of the complexity of the problem or lack of attention to this area, only a few analytical models have been developed. In the past several years, simulation models have been developed emphasizing landside elements of an airport. Most of the models are programmed in GPSS. Nanda et al. developed a model for simulating passenger arrivals (Ref. 55). Passengers and bags are generated from each flight. Allowing inspection components for international flights, the major output 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. 54). The TAMS model is similar to the Bechtel model (Ref. 58). The MIT simulation model generates passengers with respect to flight schedules and includes the curbside and transit station platform (Ref. 59). The Battelle model includes various landside passenger terminal components (Ref. 56). The Canadian model depicts flow capacities from the curbside to the gate, but its use is limited (Ref. 57). 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. 60).

As for analytical models, FAA suggested graphic models for several basic functions of the terminal building (Ref. 41). The FAA graphical relationships were converted by Zaniewski into a set of regression equations (Ref. 42). 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. They are

$$\text{Ticket counter, ft:} \quad TPHP = -80 + 3.370x$$
$$\text{Waiting area, ft}^2\text{:} \quad TPHP = -31 + 1.751x$$
$$\text{Operations area, ft}^2\text{:} \quad TPHP = -24 + 13.5x + 0.15\,(x/1000)^2$$
$$\text{Eating facilities, ft}^2\text{:} \quad TPHP = -71 + 41.9\,(x/1000) + 0.73\,(x/1000)^2$$
$$\text{Women's Restrooms (closet and lavatories):} \quad TPHP = -2.6 - 28x + 1.27x^2 \qquad (21)$$
$$\text{Men's Restrooms (closet and urinals):} \quad TPHP = 132 + 1.56x$$
$$\text{Men's Restrooms (lavatories):} \quad TPHP = 9 + 0.306x$$
$$\text{Lobbies, ft}^2\text{:} \quad TPHP = 39 + 0.101x$$

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

In the above equations, TPHP is derived from the projected annual passengers and is treated as the independent variable.

While the FAA method is to estimate spatial requirements directly from peak-hour volumes, Johnson's approach is another method for computing required floor areas in the passenger terminal (Ref. 61). His model calculates the required terminal size by first estimating the 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 min., 19 min., and 82 min. are allocated to outbound, inbound, and transfer passengers in the peak hour, respectively. By applying specified standards such as 15 sq. ft./person, the floor areas are estimated. In its recent study, Battelle suggested similar square foot requirement standards for various landside elements (Ref. 56).

The FAA and Johnson's approaches are methods which only estimate space requirements, but it is not difficult to see that capacity models can be reduced by simply reversing the procedure. Given the spaces of various terminal components, the holding capacities, for example, can be computed by applying square foot standards that correspond to desirable levels of service.

Since the development of the above models, there have been no significant models developed especially for measuring flow capacities. One reason for this is that one can always apply one of the already developed standard queueing models to such problems. For example, one can use M/M/c or M/D/c queues with various queueing disciplines. Lee and Longton studied passenger check-in systems with combinations of four queueing processes of different types (Ref. 62). Basically using M/M/c queues with first in and first out discipline, they computed mean waiting times and showed how to obtain the optimum system by using both theoretical and empirical methods. Fisher, et al., and Worral, et al., developed analytical models of ticket counters, which are also based on stochastic queueing approaches (Refs. 63 and 64). 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. A recent study by Roman and Jackson shows the influence of sexual differences on security processing speeds (Ref. 65).

For passenger circulation, Fruin (Refs. 66 and 67) and Henderson, et al. (Refs. 68, 69, 70 and 71) provided extensive information on passenger movements, although their papers are primarily for general planning purposes rather than for capacity estimates. Fruin suggested various design standards for walkways, stairways, and people moving systems and theparticular feature of his work is that the standards 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 must be tested (Ref. 72, 73, 74, 75, 76, 77, 78, and 79).

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. 80) and Smith and Murphy performed a similar study at San Francisco Airport (Ref. 81). In addition, Baron developed a simulation model for evaluating terminal efficiency in terms of operational distances (Ref. 82). Analytical models are yet to be developed. Based on the stochastic queueing approach, a recent preliminary effort by Dunlay analyzes corridor flows of linear and pier-finger terminals (Ref. 83). A manual recently released by Ralph M. Parsons, Co. provides corridor geometrics (Refs. 28 and 84). It also includes desirable geometrics for various landside components.

An empirical method by Battelle estimates the passenger distribution within the terminal with respect to the flight schedule (Ref. 56). The distribution was observed with 10 min. lead time segments and the results indicated that the distribution was skewed to the aircraft departure time. Similar results were obtained for visitors.

Paullin developed a mathematical model for sizing the departure lounge (Ref. 85). To analyze this, he presented two models. One model 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 least-squares regression analysis of actual data and expressed as the polynominal function:

$$F(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 \tag{22}$$

where

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

t = minutes before departure,

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:

$$G(t) = b\ (t - t_b),\ t_b < t < t_2 \tag{23}$$

where

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

b = capacity flow rate into aircraft,

t_b = time the aircraft doors are opened,

t_2 = time the queue dissapates.

A graphical method is employed for the analysis of departure lounge operation. Similar types of models largely based on graphical methods were developed to provide walkway capacity with respect to flight schedules.

The effect of seat assignments on enplaning and deplaning rates was studied by Kaneko (Ref. 86). IATA suggested a very simple method for sizing the passenger lounges (Ref. 87). Space requirements of 9.7 sq. ft. per standing passenger and 15 sq. ft. per seated passenger were recommended.

No mathematical models have been developed for 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. To develop analytical models one possibility is to employ a series of graphical methods of tandem queueing approaches (Ref. 88).

Curbside Component

The curbside component is probably one of the most neglected areas of the airport system. Curbside methods have been mainly concerned with the computation of required curbspace 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 recommended length of curb for 1980 was about 0.6 ft. per 1,000 annual enplaned passengers (Ref. 89). The required length of curb for 1980 is increased to over 1.2 ft. per 1,000 annual enplaned passengers for airports such as Maiquetia Airport in Venezuela, which serves a large amount of overseas travel and virtually no transfer passengers (Ref. 58).

As noted earlier in the passenger processing component, 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 don't reflect demand characteristics imposed on the curbside component. No analytical models have been developed in this respect.

Tilles provided a nomograph method for calculating the required impact of curbspace using a simple M/M/c queueing process (Ref. 90). Another method was suggested by Whitlock and Clearly, who considered a modal split on the internal roadways and related it to the number of peak-hour vehicles to compute the length of curbside required (Ref. 91). One study which is remotely related to the curbside is pursued by Yu who studied the effect of the curb parking maneuver on the roadway capacity (Ref. 92). Simulation models such as MIT's, Battelle's, etc. 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 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. Piper shows a simple analytical model for computing the required number of short and medium-term parking spaces (Ref. 93):

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

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,

T_i = average parking duration (in hours) of car type i.

Equation (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. 41). For self-parking structures it is generally agreed that angle parking (approximately 60°) with clear spans of approximately 55 ft. 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", requires 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. 94). Yu consideres the level-of-service for designing parking facilities through the method of trial and error (Ref. 95). There are also simulation models and queueing models available to analyze airport parking facilities.

Internal Roadway Component

Some simulation models are available to analyze the roadway capacity of an airport. 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, most of the current practices have been the result of applying the methods specified in the Highway Capacity Manual (HCM) or other traffic engineering publications. Some example applications based on the Highway Capacity Manual were shown by Zaniewski (Ref. 42).

Piper introduces a simple model to assess the demand level on the roadways considering the modal split (Ref. 93):

$$Z = qS \frac{1.1 z_p + z_t}{a} + \frac{2 z_b}{a_b}$$

where

Z = traffic load 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,

a_b = passengers per bus.

Summary

The available models of airport components are reviewed and listed in Table 2. From the table it can be seen that the models concerning the airside component are relatively complete. For purposes of this research, the only problem on the airside is to select a desirable set of models and tie them together into a series for investigating various interactions among airside components. Because the airside component interdependencies are not yet clear, putting the set of models in a modular form may present some difficulties. The weak areas of the airside are the apron subsystem and the taxiway component.

Although available models can be found for the passenger terminal component, these models are considered incomplete in their present forms for our purposes. Most of the models concerning flow capacities are largely dependent upon the readily available queueing models, but details of the specific airport environment have not been introduced. There are various standards for sizing the facilities, but these were assumed independent of the adjacent components' processing capabilities. This deficiency may be erased by analyzing the terminal component capacities simultaneously in a series format. However, no analytical models of this type are available. This may be due to difficulties

PASSENGER TERMINAL	Baggage Claim	FAA & Zaniewski (Refs. 41 & 42) Barbo & Horonjeff (Refs. 43 & 44) Browne, et al (Ref 46)	graphic and regression deterministic queueing deterministic queueing
	Overall Space Requirement	FAA & Zaniewski (Refs. 41 & 42) Johnson (Ref. 61)	graphic & regression empirical
	Ticket/Check-In	Lee & Longton(Ref.62) Fisher, et al (Ref.63) Worral, et al (Ref.64)	stochastic queueing stochastic queueing stochastic queueing
	Security	Roman & Jackson(Ref.65)	stochastic queueing
	Passenger Circulation	Fruin (Ref. 66) Henderson (Ref. 70)	empirical-deterministic empirical-deterministic
	Corridor Flow	Reese (Ref. 80) Smith&Murphy(Ref. 81) R. M. Parsons, Co. (Ref. 28) Dunlay (Ref. 83)	simulation-deterministic simulation-deterministic empirical stochastic queueing
	Departure Lounge	Paullin (Ref. 85) IATA (Ref. 87)	deterministic queueing empirical
ACCESS/EGRESS	Curbside	Tilles (Ref. 90) Whitlock&Clearly (Ref. 91)	stochastic queueing empirical-deterministic
	Parking	FAA Recommendation (Ref. 41) Piper (Ref. 93) Others	deterministic deterministic stochastic queueing,etc
	Internal Roadways	Highway Capacity Manual Method Piper (Ref. 93)	empirical deterministic

in estimating changing demand patterns on facilities in a series and their corresponding peaking characteristics. The available models for the ticket/ check-in component are weak in that they consider only a limited number of alternative systems. In the passenger terminal the weakest areas are the security 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 in highway traffic engineering. 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 complete.

In summary, the analysis of airport capacity as a whole will require a hierarchical procedure. It is first necessary to consider subsystem interactions at the major interface components. The second step is to analyze component interactions within each subsystem. The revision of existing models or development of new models will center around these interactions.

IV. AIRPORT SYSTEM CAPACITY DEFINITION

Previous Concepts of Airport Capacity

Until recently, the capacity of an airport was assumed to be limited by the airside operation. Airside capacity has been defined in two ways. One definition, referred to as practical capacity, is the "number of aircraft operations during a specified interval of time corresponding to a tolerable level of average delay" (Ref. 16). Another definition is that 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. 24). The second definition has been referred to in several ways: ultimate capacity, saturation capacity, and throughput rate.

A review of papers presented at the Airport Landside Capacity workshop conference and others shows that it is becoming increasingly common to consider capacity with a corresponding level of service (Refs. 96, 97, 98, 99, and 100). For example, Heathington and Jones point out that "... capacity is the physical provisions required for a given demand at a given time at a specified level of service" (Ref. 96). In these terms, "Capacity or at least ultimate or maximum capacity may be associated with the lowest level of service" (Ref. 96). This is similar to the concept of highway capacity. Also pointed out is that "different levels of service can occur at different times; however, it is generally assumed that the lowest level of service which occurs at peak design period determines the overall operating level of service for a given facility" (Ref. 96).

Some definitions and concepts are also presented by Beinhaker (Ref. 97) as follows:

Nominal (or Rated) Capacity is the amount of demand (traffic) the facility can handle if there is a continual flow.

Practical Flow Rate is a function of the demand pattern and the service level.

Achievable Flow Rates for individual processors 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.

Beinhaker concludes 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 acceptable to the user and which is economically justifiable, and dwell times which reflect the holding capacities required at each processor" (Ref. 97).

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 the measurement of the capacity of the airport system as a whole.

According to Beinhaker, "The service level must be expressed in terms of percent of demand subject to more than a specific amoung of delay or in some other similar manner" (Ref. 97). On the other hand, Heathington and Jones point out "in general, the dimensions best suitable for levels of service appear to be time, distance, area, cost, comfort and convenience." (Ref. 96). Hockaday and Horonjeff agree with this last categorization of the best dimentions for levels of service.

A paper based on work done by Klingen for Eastern Airlines presents level of service standards for various functional areas in a terminal (Ref. 97). 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.

Hockaday and Horonjeff point out that "...with the current lack of information or methodology to obtain valid measures of passenger terminal level-of-service, there are hazards associated with the use of such a measure" (Ref. 98). But 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. 99).

It is possible to say that almost every author of the reviewed papers defends the usefulness of the level-of-service concept, although pointing out the difficulty in establishing the level-of-service criteria for airport components, as well as for the airport system as a whole. In terms of measuring capacity of the airport system, Heathington and Jones report that all the participants of the related workshop at Tampa indicated that each segment on the landside of the airport should have a capacity and level-of-service rating (Ref. 96). Also, "...the majority of the workshop participants felt that a given airport should have a single capacity and level of service rating. There was a minority of participants that felt that this could not be accomplished" (Ref. 96).

Hom and Orman treat airport airside and landside interaction (Ref. 100). They recognize that in order to realize the maximum capacity of an airport, airside and landside must be balanced. However, they also point out that there is not a 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" (Ref. 100). They also state that "...application of the concept of balance typically reduces to a determination of how the individual components of the airside and landside should be 'appropriately' sized and configured to satisfy demands placed upon them" (Ref. 100). In summary, the literature surveyed does not provide a concrete airport system capacity definition.

Alternative Concept of Capacity

The currently used method of analyzing the capacity of an airport may be termed a component approach. In this method analytical models or simulations are used to determine the capacity of a component or subsystem independent of the rest of the airport system. Such an approach does not provide a way to balance all the components of the system.

An alternative approach to the problem of determining airport capacity in the systems approach. In this method, the capacity of the components are computed and compared. Interfaces between components are also investigated. This method allows a comparison and balance between components.

Proposed Definitions of Capacity

In order to develop a level-of-service related capacity concept, we need the following definitions:

Level-of-Service Measure: a physical measure of how a component, subsystem or system performs.

Level-of-Service Criterion: a specified maximum tolerable limit on the level of service measure.

The capacity of the airport system, as well as of its subsystems and components, is a strong function of

(1) the level-of-service criteria for the system, subsystems, and components of the airport in question. These criteria are to be specified by the decision maker. Notice that one decision maker may specify only level-of-service criteria for the entire system, while others may specify level-of-service criteria for each component, or subsystem.

(2) the interval of time over which the capacity is to be determined, for example, a one-hour period, day, year, etc., and

(3) the pattern of demand of passengers, aircraft, baggage and ground vehicles for the airport in question.

In this research, the following definitions have been adopted:

Airport System Capacity: 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.

Airport Subsystem Capacity: the maximum level of demand of a given pattern that can be imposed on a subsystem in a given interval of time, without violating any specified level-of-service criteria for the particular subsystem or any of its components.

Airport Component Capacity: the maximum level of demand of a given pattern that can be imposed on a component in a given interval of time, without violating a specified level-of-service criterion for that component.

A special case of the above definitions under conditions of continual flow (demand) and corresponding to a minimum level of service is the ultimate (or maximum) capacity of the system, subsystem, or component in question.

Units of Capacity

We have to choose the units in which to express capacity in such a way as to facilitate the task of comparing and balancing subsystem and component-limited capacities. The most natural units for expressing the various subsystems' capacities (and hence for all the components of each subsystem) are ground vehicles for access-egress subsystem, aircraft for the apron and air-side subsystems, and passengers for the terminal building subsystem. Of course, it is possible to convert from one of the mentioned 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, total passenger (enplaning and deplaning) demand rate is proposed. The proposed expression of capacity of the 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 has to be taken in using passenger rate as the common subsystem capacity unit. The process is complicated by the fact that at some points in the terminal building only passengers are being served, e.g., the security check, while at other points both passengers and visitors (and perhaps even some employees in corridors and lobbies) must be processed. Whether a particular component handles only passengers or passengers plus their visitors may depend on the particular terminal building layout and airline 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, some corridors. On the other hand, 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 transfer be used as the common unit. The actual passenger demand rate on any component is then obtained by taking the airport demand and factoring in (or out, depending on the component) transfer passengers, visitors and employees where appropriate.

In order to estimate total airport system capacity it is necessary to transform the total airport passenger demand rate into the actual demands on 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) is a function of the service rate or output of either off-airport access/egress system on the landside or the output of the approach/departure air traffic control on the airside.

(2) Demand on Airport Subsystem (at subsystem boundary) is a function of the service rates of preceding subsystems and the fraction of airport passenger demand using the subsystem.

(3) Demand on Airport Component (at component boundary) is 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 service rate of each component, which is in a sense the ultimate capacity or the throughput rate of the component. The relationships among the above three levels of capacity illustrated conceptually by the schematic representation in Figs. 5, 6, and 7.

Figure 5 illustrates how to relate component capacity to overall airport capacity, given the relationship between the airport demand and the component demand, level-of-service measure, and level-of-service criterion. Thus, it is possible to obtain, for a particular component, the kind of relationship illustrated in Fig. 6 , where, for a given component level-of-service criterion, it is possible to obtain the corresponding component-limited airport capacity. Figure 7 illustrates the way to obtain subsystem and overall airport system capacity from a comparison of the various component capacities. The limiting airport demand rate will be imposed by the first component that, receiving this demand as an input, reaches its specified level-of-service criterion--see line D-D in Fig. 7 . Any demand rate above this limiting one will violate the level-of-service criterion of that particular component.

Note that all of the level of service criteria in Figs. 5 to 7 apply to individual components. It may also be possible to specify a level of service criterion for an entire subsystem, or even for the total airport system. The level-of-service criterion related to the limiting component may be less restrictive than a specified subsystem level-of-service criterion or an

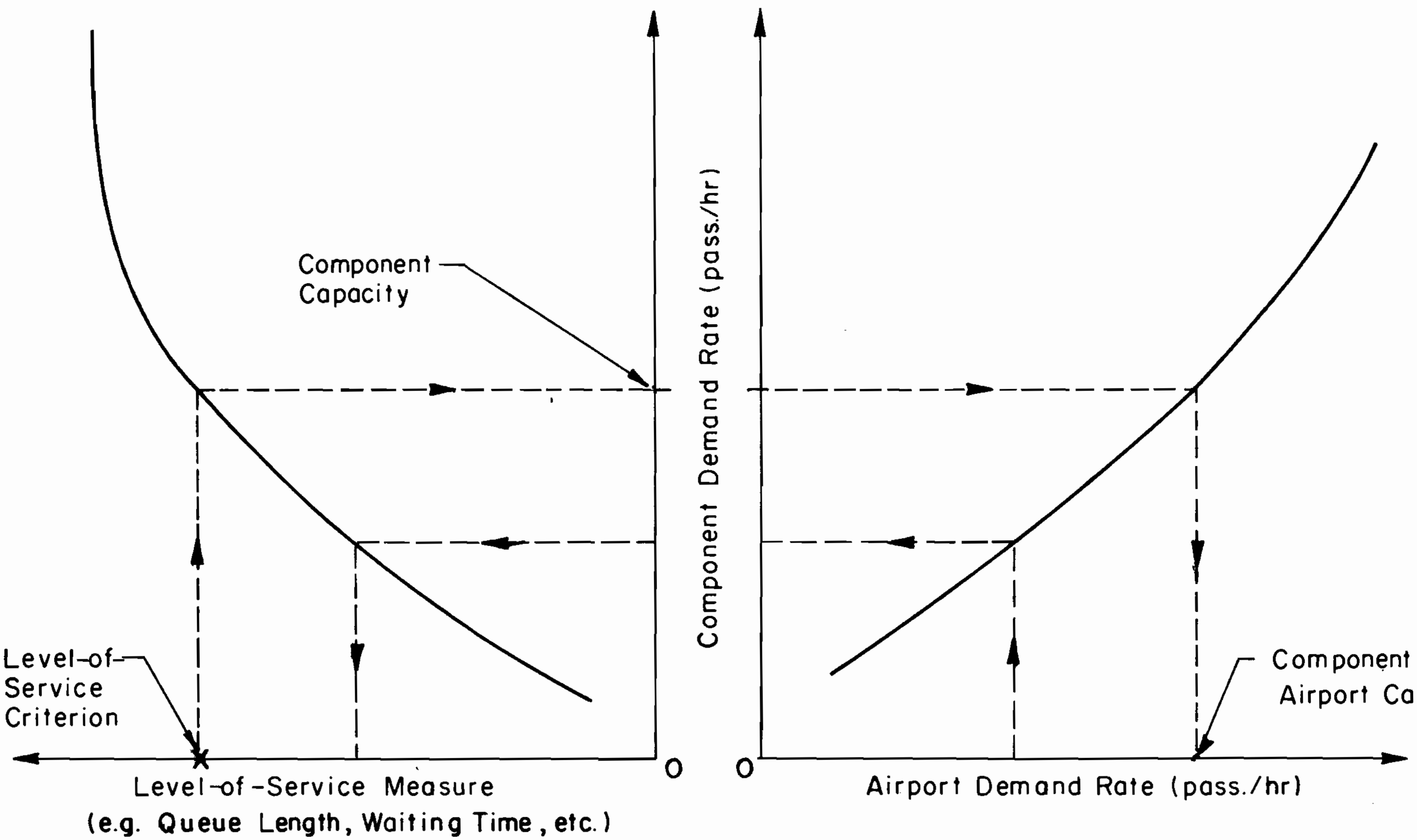

Figure 5. Relationships Between Airport Demand and a Particular Component's Demand and Level of Service.

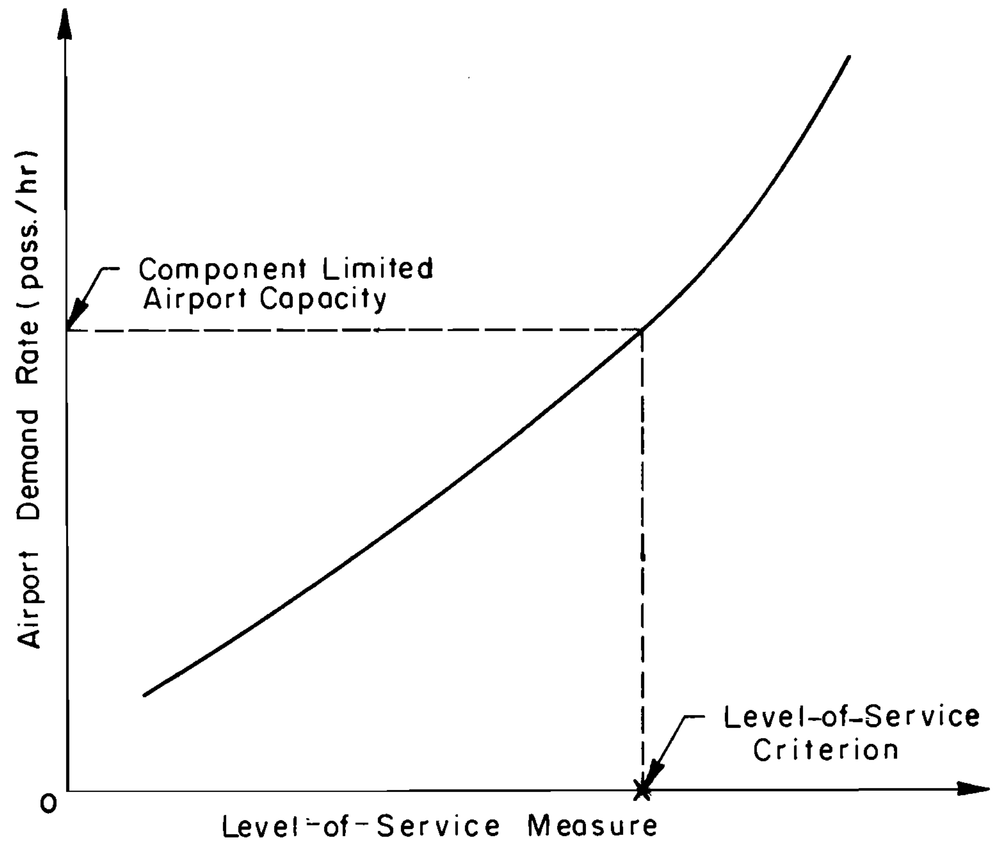

Figure 6. Derived Relationship Between Airport Demand and a Particular Component's Level of Service.

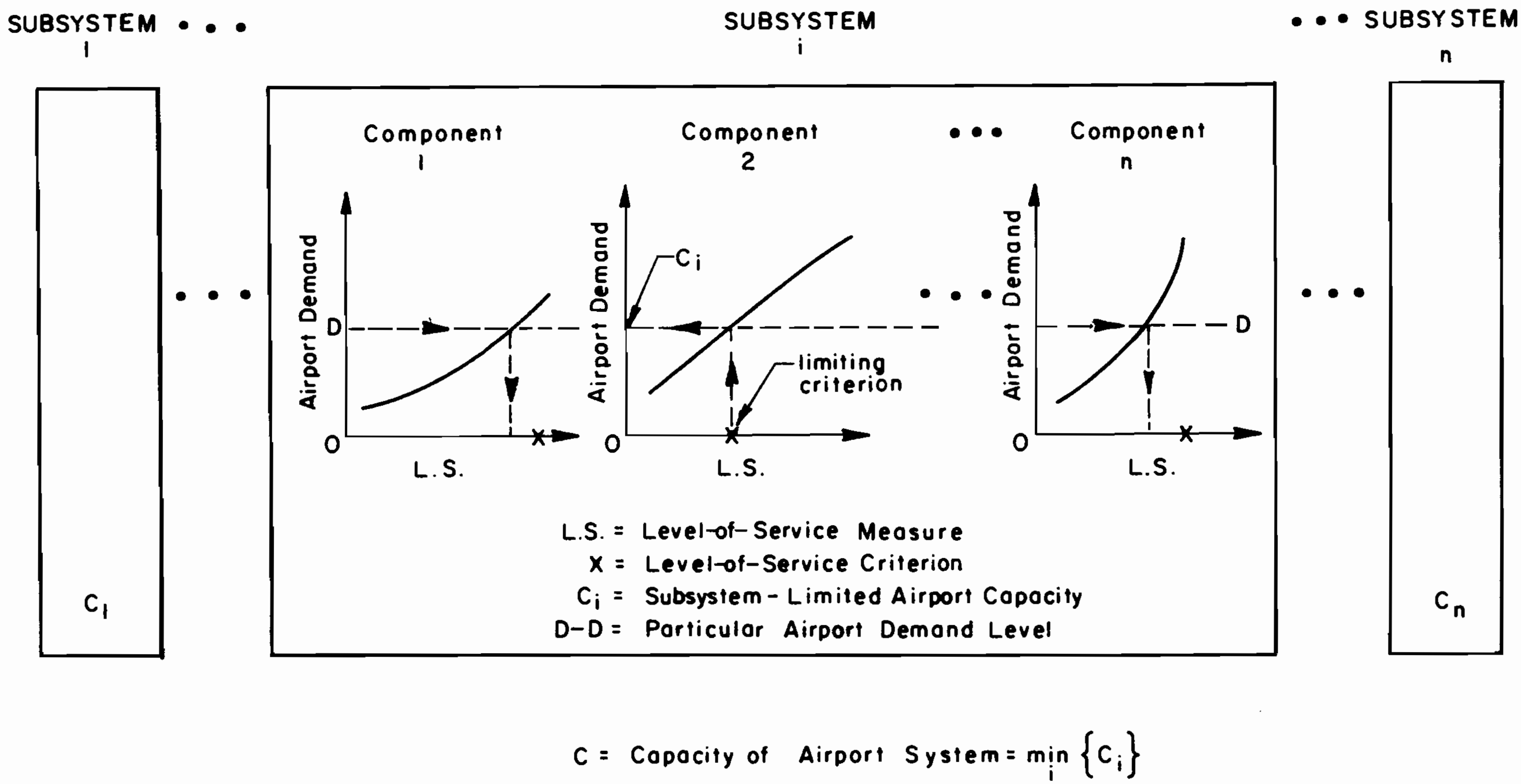

Figure 7. Concept of Airport System Capacity as Minimum of Various Component-Limited Airport Capacities.

overall system criterion. Subsystem and system level-of-service measures and criteria will be investigated in this research.

V. SUMMARY AND CONCLUSIONS

The purpose of this research memo is to present a definition of the airport system as it applies to this study, review available models for analyzing airport capacity, and develop a definition of airport capacity which applies to the whole airport system as well as the individual components. In Section II, the airport system has been defined with the aid of a flow chart. This definition of the airport system specifies the physical boundaries of the airport system, and the subsystems and components within the airport system. 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 the models developed during this project to be applied to a variety of airport configurations.

In Section III, the available models for the various components within the airport system are reviewed. This review shows that the vast majority of previous research on airport capacity has been concerned with the airside facilities of the airport. From this review, it is apparent that in order to develop a systems analysis procedure for airport capacity, it will be necessary to develop some models for components within the terminal building and access/egress subsystems.

In Section IV, the existing definitions of airport capacity are reviewed and a definition is developed for airport capacity which applies 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 quantative measures of the service provided by the airport.

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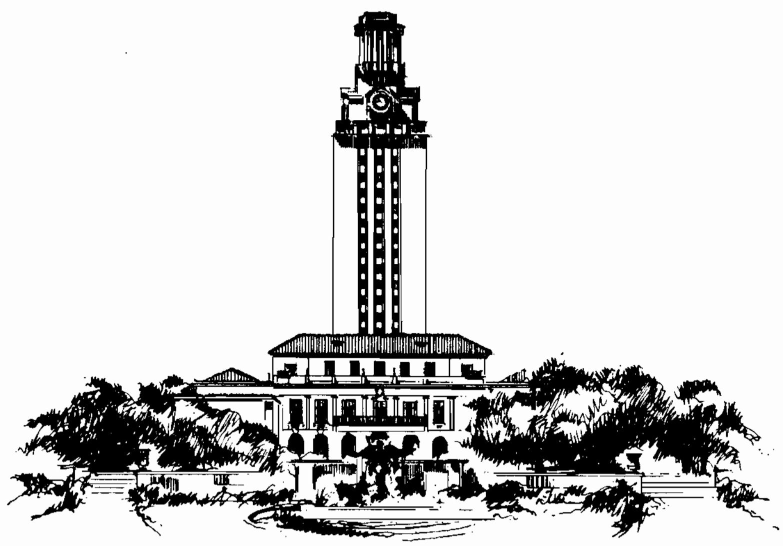

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