Use of an Analytical Queuing Model for Airport Terminal Design

FRANCIS X. MCKELVEY

This paper is an examination of the application of a computer-based model to the airport terminal design process. It includes a discussion of the inherent features of the modeling process as a framework for assessing terminal design alternatives. The paper examines the methodology used by the model and assesses the research needs for improving the model's capabilities to predict terminal performance. A review of an analytical network queuing model that has been developed for analyzing the performance of airport terminal systems for capacity and delay is undertaken. This includes a presentation of the theoretical modeling equations, the mechanism for representing the structure of the passenger processing network, and various measures available within the model for estimating the service quality associated with the terminal design. A simple application of the model to a terminal design that highlights the model's features for its use in evaluating and assessing the terminal design performance is included. The model is critically assessed relative to its capability to present a realistic assessment of the performance of the terminal system. Recommendations are made relative to the types of research and development that might be undertaken to enhance the capability of models to predict terminal performance in the design process to influence and enhance decision making.

This discussion of terminal planning models is confined to the airport area that traditionally is called the airport landside. The landside is the airport subsystem that includes those facilities located within the airport boundary that are necessary to process the inbound and outbound passengers. The airport operator and airlines serving an airport normally have specific issues that must be addressed in what may broadly be called airport landside planning and design. These include master plans to determine the overall facility requirements to meet changing airport needs, design plans to specifically lay out and size construction modifications to airport facilities, operating plans to optimize the use of existing facilities, and cost projections to ascertain the economic and financial viability of airport modifications. The specific focus of this paper is the utilization of modeling procedures to assess the capability of proposed physical or operational changes in the airport terminal design to meet specified objectives.

Considerable attention has been focused on the airport landside in recent years (*1,2*) because of a greater realization of the need to balance both airside and landside capacity to implement effective and efficient airport systems in a rapidly changing environment. Although sophisticated and relatively accurate models exist for an analysis of airside systems, the modeling capabilities for landside systems are very diverse and have had limited application and acceptance (*3–5*). The reasons for this seem clear. The airside is highly systemized, with strict methods of operation greatly simplifying the task of mathematical modeling. The landside system, on the other hand, is not as clearly defined and is subject to a considerable degree of variation in its operation; that makes mathematical modeling a relatively complex problem. A model's ability to simulate accurately the performance of a system is highly dependent on the complexity of the system, which is often characterized by the mathematical rules by which system activity is governed. For this reason, it is doubtful that the modeling of such a system will result in accurate results unless very strict rules are imposed upon passenger behavior and the service capabilities of passenger processors become highly automated. The analyst is therefore faced with the choice of either abandoning the process of modeling the landside system or improving upon existing modeling capabilities. Assuming that the first alternative is not acceptable, a modeling process is presented that offers the potential of responding in a meaningful way to the second alternative.

OVERVIEW OF THE MODEL

The Federal Aviation Administration's (FAA's) Airport Landside Model (*6*) presents a framework within which an airport landside may be analyzed with respect to capacity and delay. This model is a computer-based, analytical queuing model utilizing closed-form mathematical equations and network analysis to study the airport landside. The model represents a first approximation to the analysis of the airport landside. Much of the model's theoretical basis is derived from research conducted by Pararas (*3*). Subsequent research has been performed to improve upon the original model (*7*) and to include a representation of intraairport transportation systems for passengers connecting between flights in different terminal units (*8*). The model is efficiently executable on microcomputers.

The model is configured to analyze the average passenger delay experienced at enplaning terminal facilities, deplaning terminal facilities, and in the ground access system.

Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Mich. 48824-1212.

This paper presents the model's capabilities to assist in the assessment of terminal design alternatives; therefore, a detailed discussion of the ground access component of the model is not undertaken.

The basic premise upon which the model is founded is that the airport terminal can be represented by a series of passenger processors that are linked together to form a sequenced network through which passengers must pass to enplane or deplane aircraft. The processors themselves are mathematically represented as queuing mechanisms in which a unit of demand enters the processor, service is performed, and the unit of demand moves to the next processor. The model computes the average passenger delay and service time at each processor in the network and the average travel time between processors. These three time elements are then added to compute the average passenger processing time through the network. Conceptually, the model is very simple and conforms quite well to the functional nature and operation of the airport terminal building.

Modeling Equations

Most of the passenger processors within the terminal building are modeled through the use of two closed-form mathematical queuing equations (*7*). The models are multiple-channel queuing models with a first-in first-out (FIFO) queuing mechanism. Both models assume that the demand is random and may be characterized by a Poisson arrival distribution. The first model assumes that the service rate at a processor is random and is characterized by an exponential distribution, the MMK model. This type of model is normally used in situations where the service time is influenced by individual passenger characteristics. In design studies at Fort Lauderdale-Hollywood International Airport (FLL) it was found to reasonably approximate delays in situations where the passenger service time is relatively small, such as at security locations.

The second model assumes that the service rate is a general random variable characterized by its mean and variance, the MMG model. This type of model is useful in situations where service times are similar for all passengers and therefore lie within clearly defined limits. It was found at FLL that this model form presented reasonable delay approximations at processors where a discrete service time was required for passengers, such as at ticketing. The average delay for the MMK model is given by

$$W_{\mathrm{MMK}} = D^k S^{k+1} \Bigg/ \left[(k-1)!\,(k-DS)^2 \sum_{n=0}^{k-1} \frac{(DS)^n}{n!} + \frac{(DS)^k}{(k-1)!\,(k-DS)} \right] \quad (1)$$

and for the MMG model by

$$W_{\mathrm{MMG}} = \frac{v + S^2}{2} W_{\mathrm{MMK}} \quad (2)$$

where

D = the mean passenger arrival rate;
S = the mean processor service time;
v = the variance of the mean processor service time; and
k = the number of processors.

By collecting data at various processors within the airport terminal, the average service time and the variance of the average service time at processor may be determined and Equation 2 used to model the terminal system. The preceding equations are valid only when the average demand rate, D, on a processor is less than the average service rate, k/S, of the processor. When the demand rate approaches the service rate, the delay approaches infinity and the processing system becomes saturated. To account for periods of saturation when the queues would continue to grow as additional demand enters the system, an additional delay term was derived using a deterministic model. This model assumes that the demand and service rates remain constant over the saturation period; therefore, the delay may be represented as the area that exists between the demand and delay curves over this period (*6*). It was assumed that the saturation period would be relatively short since additional personnel would normally be assigned to alleviate these queues. This delay term, W_S, is

$$W_S = \frac{T(D - k/S)}{2k/S} \quad (3)$$

where T is the period of time over which saturation occurs. The average delay at the baggage claim device, W_B, is computed through another relationship that defines passenger delay as the time difference between the arrival of the passenger at the claim area and the point at which the passenger claims all baggage. Therefore, the average delay at the baggage claim is given by

$$W_B = T_B + T_U - T_T \quad (4)$$

where

T_B = the average time to unload baggage from the aircraft and transport it to the claim area;
T_U = the average time to unload baggage from the transport vehicles to the claim device; and
T_T = the average time for a passenger to travel from the aircraft to the baggage claim device.

When the results of Equation 4 are negative, the model assigns no passenger delay at the baggage claim facility. The first term in Equation 4, T_B, is fixed in the model based upon studies conducted at several airports. The second term is given by the relationship

$$T_U = \frac{n}{n+1} \frac{B}{rc} \quad (5)$$

where

n = the average number of pieces of checked baggage per passenger;
B = the total number of pieces of checked baggage on the flight;
r = the baggage unloading rate from the transport vehicles to the claim device; and
c = the number of baggage devices used for the flight baggage.

The last term in Equation 4 represents the time for the average passenger to move from the aircraft to the baggage claim area. This time is a function of the distance from the aircraft to the claim device and the speed at which a passenger travels to the device. The model assumes an average passenger walking speed of three feet per second.

Network Representation

As noted earlier the model considers the airport terminal a series of linked and sequenced passenger processors. Figure 1 illustrates a typical representation of the passenger movement through the enplaning network in a terminal building. The passenger enters the terminal building through the terminal doors, D, proceeds to the passenger check-in facilities for ticketing only, T, or ticketing and baggage checking, B, through the security checkpoint, X, and to the gate area for seat selection, S, and boarding, G. Each of these processors serves the passenger demand imposed upon it; therefore, passenger delays and waiting lines may occur at each. The links between these processors indicate the possible paths that passengers may take from one processor to another. The percentage of total passengers at one processor proceeding directly to the next processor and the average distance between these processors are also shown in Figure 1.

In the model the various passenger paths through the network, as shown in Figure 1, are represented by a transition matrix indicating the passenger splits between components and the travel distances between components. This transition matrix is computationally efficient for determination of the total passenger demand on each of the passenger processors. An example of the transition matrix for the passenger splits between the components shown in Figure 1 is illustrated in Table 1. A specific row of the transition matrix indicates the percentage of passengers at one component proceeding directly to the next component. Therefore, the first row of the transition matrix shown in Table 1 indicates that of all the passengers entering the terminal through the terminal doors, D, 60 percent proceed directly to ticketing, T; 30 percent proceed directly to ticketing and baggage check-in, B; and 10 percent proceed directly to security, X. A unique feature of the transition matrix representation of the network is that the passenger demand on the system may be varied without reconstructing the network. This allows the analyst to determine service quality parameters for the given system under various levels of demand.

In a similar manner, the distances passengers travel between components may also be represented by the transition matrix, as shown in Table 2.

An example of a typical deplaning passenger network is shown in Figure 2. In this figure passengers arrive on aircraft, A, and proceed from the aircraft to the gate area, G, down the concourse to an escalator, E. From the escalator, passengers proceed either to the baggage claim device, B, rental car areas, R, or directly to the terminal doors, D. The percentage of passengers and the distances between the processors are also shown in Figure 2.

AN EXAMPLE OF MODELING RESULTS

The model may be used to evaluate the performance of an airport's enplaning and deplaning network. Using an airport enplaning about 1 million passengers annually with a total peak-hour passenger demand of 700 passengers, the model was run for the enplaning passenger network shown in Figure 1 and the deplaning network shown in Figure 2. Typical values for the service rates for the various processors were used in this example. Sources may be consulted for reasonable estimates of facility service characteristics (*6, 7, 9*), or original data collection may be performed to arrive at these values. The results of the analysis are displayed in Tables 3 and 4.

As may be seen from the information in Tables 3 and

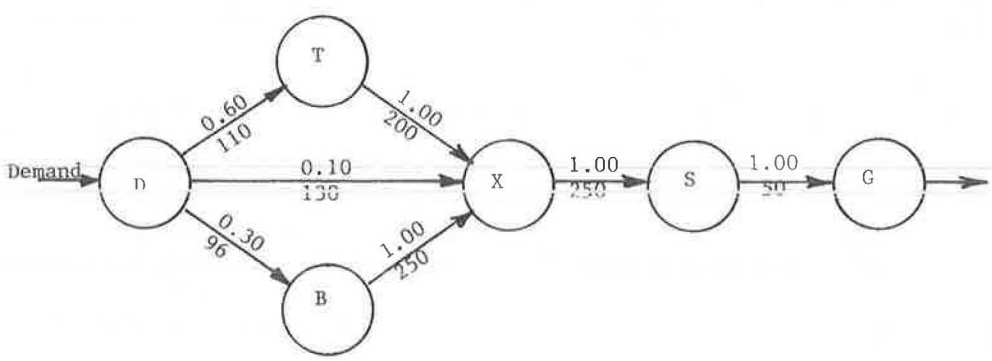

FIGURE 1 Typical representation of the enplaning network.

TABLE 1 TRANSITION MATRIX FOR PASSENGER FLOWS BETWEEN PROCESSORS FOR A TYPICAL ENPLANING NETWORK

	To	D	T	B	X	S	G
From	D		0.60	0.30	0.10		
	T				1.00		
	B				1.00		
	X					1.00	
	S						1.00
	G						

TABLE 2 TRANSITION MATRIX FOR AVERAGE DISTANCE BETWEEN PROCESSORS FOR A TYPICAL ENPLANING NETWORK

	To	D	T	B	X	S	G
From	D		110	96	130		
	T				200		
	B				250		
	X					250	
	S						50
	G						

4, the model determines several performance measures for the individual processors and the overall performance of both the enplaning and deplaning networks. The average passenger delay time and average waiting line length during the peak hour may be used to measure the performance or service quality afforded by individual processors. The average total passenger delay time, service time, travel time, and total processing time may be used as measures of the overall performance or service quality of the enplaning and deplaning system. As noted earlier, this model's approach lends itself very well to changes in the service features of the network's processors without modification of the network itself. Therefore, if the performance of one or more processors does not meet design standards, the number of processors or their service features may be modified and the results of these modifications readily ascertained. Similarly, if the system does not meet design standards, the demand on the system may be modified to determine the level of demand at which unacceptable performance is reached. This is a measure of the capacity of either the processors or the system itself and indicates those processors most susceptible to degraded performance at higher levels of passenger demand.

APPLICATIONS OF THE MODEL

The model just described presents an interesting conceptual framework for the analysis of terminal building performance. It is well suited for three types of applications. In the first, the model may be used to analyze the performance of an existing terminal building and compare the results to those of problem areas observed within the airport. In this context, design or operational modifications may be made to the number, orientation, or service features of processors to alleviate congestion. It was found, by utilizing this model, that high levels of congestion experienced in the main terminal building at Palm Beach

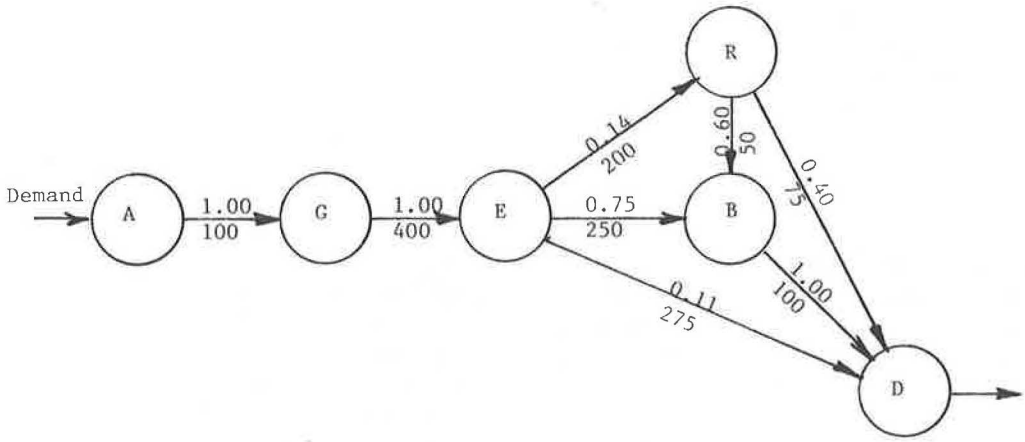

FIGURE 2 Typical representation of the deplaning network.

TABLE 3 TYPICAL MODEL OUTPUT FOR AN AIRPORT ENPLANING TERMINAL UNIT

AIRLINE ENPLANING NETWORK

PROC	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (MIN)	LINE LENGTH WAITING (PERSONS)
DOOR	2	.0959	.200	.48	0.	0.
EXCH	3	.0585	.050	1.17	2.	3.
TIX	6	.0293	.020	1.46	6.	2.
XRAY	2	.1111	.100	1.11	8.	27.
SEAT	8	.1128	.178	.63	0.	0.
GATE	8	.1128	.800	.14	0.	0.

PEAK HOUR SUMMARY

DELAY TIME:	10.8 MIN	4365. PAX-MIN
SERVICE TIME:	3.2 MIN	1300. PAX-MIN
TRAVEL TIME:	3.3 MIN	1360. PAX-MIN
TOTAL TIME:	17.3 MIN	7025. PAX-MIN

International Airport (PBI) could be reduced considerably and the useful life of this facility extended by reallocating leased airline terminal space (*10*).

In the second type of application, the model may be used to examine the performance of proposed terminal designs in both the conceptual development and schematic design phase of the design process. In the recent terminal design study conducted at Fort Lauderdale-Hollywood International Airport, the model was used to examine the validity of the facility space allocations obtained from secondary sources (*11–14*) and the orientation of these facilities for the various airlines serving the airport. The model enabled a response in a timely manner in evaluating the impact of modifications to facilities proposed by the airport operator, the airlines, and the design team. The model also proved helpful in this study in determining the passenger volumes that would occur in different areas of the airport. This information was of considerable value in establishing the location of specific concession activities within the terminal complex.

In the third type of application, the facilities, service rates, and network representation are considered fixed and the peak-hour passenger demand is increased until unacceptable measures of service quality are exhibited at individual processors or for the enplaning or deplaning network as a system. Although there are no universally accepted measures of service quality, such metrics as queue length and waiting time at a processor, or overall passenger processing time through the network, may be considered valid indicators of performance.

CRITICAL ASSESSMENT OF THE MODEL AND FURTHER RESEARCH NEEDS

It is not the intent of this paper to propose that this specific model present the definitive procedure by which airport terminal buildings should be analyzed in terms of capacity, delay, or service quality. On the contrary, the model has several deficiencies that need to be addressed in future research. The model does, however, present an effective methodology through its use of a sequenced network of passenger processors that offers a unique and conceptually realistic approach to the study of the airport terminal system.

The model does not explicitly consider the variation of demand on downstream processors that might occur because of delays at earlier processors in the sequence. The model assumes that the demand on each processor is the maximum peak-hour demand proportioned to each processor and that this demand is independent of delays at previous processors. This is a deficiency in the model that can be addressed only by assessing the variations in downstream demand associated with such delays. At both FLL and PBI, it was found that the demand on downstream processors was typically more uniform and of lesser magnitude than that represented by the model, resulting in an overestimate of delay. It was also found, however, that the overstatement of such delays was not large enough to affect component design.

The network through which passengers proceed is normally chosen so as to represent all of the facilities through

TABLE 4 TYPICAL MODEL OUTPUT FOR AN AIRPORT DEPLANING TERMINAL UNIT

AIRLINE DEPLANING NETWORK

PROC	NUMBER OF SERVERS	ARRIVALS PER SEC	TOTAL SERVICE PER SEC	UTILIZ. FACTOR	PER PAX DELAY (MIN)	LINE LENGTH WAITING (PERSONS)
ARCF	6	.1128	1.000	.11	0.	0.
GATE	6	.1128	.600	.19	0.	0.
ESCR	2	.1128	.333	.34	0.	0.
RENT	4	.0134	.013	1.01	4.	1.
BAGS	3	.0799	.960	.08	22.	35.
DOOR	2	.0959	.200	.48	0.	0.

PEAK HOUR SUMMARY

DELAY TIME:	15.9 MIN	6460. PAX-MIN
SERVICE TIME:	1.1 MIN	463. PAX-MIN
TRAVEL TIME:	4.7 MIN	1889. PAX-MIN
TOTAL TIME:	21.7 MIN	8812. PAX-MIN

which passengers proceed for a given airline or group of airlines located in a particular gate complex. When depicted in this manner, the network considers all paths between processors so that parallel paths that might be taken to bypass peak period delays are included in the network. Similarly, the proportioning of demand between network processors should represent those percentages associated with peak period activity.

Considerable research should be undertaken to study the overall functional performance of airport passenger processing facilities for the purpose of formulating more accurate mathematical relationships for describing these processors. The degree of variation between the operating procedures and the state of automation used by the various airlines indicates that the type of mathematical model used to represent a specific type of facility is subject to change. The limited database upon which the queuing relationships and service parameters are formulated should be expanded and analyzed to decrease the margin of error inherent in the existing modeling process. One approach that has been recommended is to attempt to model component performance through regression models (*4*). Another would assume a generalized service distribution, a family of distribution functions, representing the performance of a service mechanism in the system. The service mechanism could be represented by the Erlang distribution given in Equation 6.

$$f(t) = C_x \, t^{(x-1)} \, e^{-xt/S} \tag{6}$$

where

$f(t)$ = the frequency with which service time, t, occurs;
S = the mean service time;
e = a constant, the base of natural logarithms; and
x = an integer related to the Erlang parameter C_x, which defines the dispersion of distribution.

The Erlang constant, C_x, is given by Equation 7.

$$C_x = \frac{x^x/S}{(x-1)!} \tag{7}$$

The variance of the service time in the Erlang distribution is given by Equation 8.

$$v = \frac{S^2}{x} \tag{8}$$

Therefore, if a component in a system is observed and both the average service rate and the variance of the service rate are computed, the integer x may be found from Equation 8 and this value substituted into Equation 7 to find the Erlang constant, C_x, in Equation 6. Once this x is known, the specific service distribution for the component is defined. For example, in a single server system with a Poisson arrival distribution and Erlang service distribution, the average waiting time at the processor, W_{ERL}, is

given by Equation 9.

$$W_{\mathrm{ERL}} = \frac{1 + x}{2x} \frac{DS^2}{(1 - DS)} \tag{9}$$

This equation can be reduced to Equation 2 by substituting the relationship for the variance of the mean service time, Equation 8, into Equation 9 for the quantity x.

The characteristics of airline passengers at different airports vary to a great extent, and the model does not adequately address this fact. Airports with a large proportion of business passengers perform differently than airports with a large proportion of tourist passengers. The facilities used by various types of passengers can differ, or at least the manner in which the facilities are used are often different. At tourist airports, most passengers are preticketed and have a considerable amount of baggage. Their knowledge of the airport is usually very limited; therefore, these passengers often spend more time within the terminal building moving between passenger processors than does a typical business traveler.

The original model does not consider visitors who may accompany passengers through certain areas of the terminal complex. These visitors add congestion to queuing areas around processors, waiting areas, and concourses; and they use certain processors, such as the security checkpoint. Consideration of the impact of visitors on processors has been included in an updated version of the model (*8*), but explicit measures of congestion that are of considerable importance in evaluating a facility design and service quality afforded by a facility should also be incorporated into the model.

Although not discussed in detail in this paper, the manner in which the model treats ground access traffic and its effects on terminal area performance requires additional research. In its analysis of the ground access system, the network and the vehicular splits between processors are fixed within the model, and it is not possible to configure a particular network representation of a specific airport ground access system. Attention should also be directed to the models used to represent the performance of ground access system components. Considerable research has been performed on the ground access system that may be utilized to structure the model to conform to specific airport requirements (*15–20*). Provisions do not exist within the model to distinguish between the location or nature of short-term, long-term, and remote parking facilities. Similarly, the provision and performance features for queuing areas for taxis and public transit vehicles should be addressed. These features can readily be incorporated in the model through use of a transition matrix for the ground access system and the development and testing of the relevant component models.

SUMMARY

The model discussed and assessed in this paper offers considerable merit in terms of its structure, computational technique, and network representation in addressing the need for a reliable and universally adaptable analytic procedure for evaluating airport terminal systems for capacity, delay, and service quality. Considerable refinement is necessary in the formulation of several of the processor modeling formulations to improve the model's ability to predict terminal system performance. Additional measures of performance must be incorporated in the model to enable consideration of other factors that are important in assessing service quality. The overall framework used by the model is adaptable to such changes, however. In general, the model in its present form offers an alternative to the application of discrete event simulation models (*5*) to the analysis of queuing in terminal building processing components. It also improves upon the information obtained through the application of simple space approximation techniques (*12–14*) in sizing terminal building components for aggregate measures of terminal building demand. The model is adaptable to meeting the analytic needs of specific airport projects and is unique in its ability to be integrated into the terminal design process. The accuracy of the results predicted by the existing model appears to be reasonable, based on its limited application in terminal design processes and the degree to which accurate passenger demand forecasts can be made. It is apparent that considerably more use is required before sufficiently definitive statements can be made about the level of overall accuracy obtainable through its use.

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