Analyses of Passenger and Baggage Flows in Airport Terminal Buildings

Robert Horonjeff*
Institute of Transportation and Traffic Engineering, University of California, Berkeley, Calif.

Passenger flows into departure lounges can be expressed by an S-shaped quartic curve. The flow of passengers from the departure lounge into an airplane and from the airplane into the lounge is nearly linear. Scheduling of arrivals of large aircraft at about the same time will result in very high passenger flow rates in pier finger corridors during very short intervals of time. Deterministic theory can be applied to passenger and baggage arrival characteristics which in turn can be used to estimate space requirements for passengers in baggage claim area.

Introduction

The air transport system is essentially made up of three major subsystems: 1) access to the airport, 2) processing at airports, and 3) flight. This paper deals with processing at the airport, with emphasis on passengers and baggage.

In terms of research, the effort devoted to the flight and access subsystems has been much greater than that devoted to processing at the airport. The reasons for this are understandable. All of the activities related to flight are under the jurisdiction of or are of direct interest to the Federal Government; hence, there has been substantial Federal support in this area. Likewise, a good share of the access to airports has been by automobile, and the entire street and highway program has received substantial support for research from the Federal and State Governments. But between those two areas lies the relatively unexplored area of passenger and baggage flows through the terminal building. The prime responsibility for the design of the terminal building rests with the airport owner, who does not have the resources to invest in research. In recent years, the airlines have undertaken to develop passenger processing techniques to deal with growing volumes of traffic, but the body of knowledge available to date is far less than for the other major subsystems.

The introduction in the 1970's of large jet aircraft capable of carrying several hundreds of passengers will create new space requirements in airport terminal buildings. A better understanding of the flow processes in these buildings will ultimately be useful in making decisions concerning their design. With this in mind, we have been applying some research effort in this direction.

Passenger Flow to Departure Lounges

Space for departure lounges will be a problem with the introduction of large jets. It was decided to study the characteristics of passenger flows to departure lounges and from the departure lounge into the aircraft. From this analysis some clues to the interrelationship between the size of the lounge, the number of aircraft doors available for loading, and the time allotted to loading the aircraft were developed.

Two analytical models were developed; one model describes the flow process of passengers into the departure lounge and the other the flow from the lounge into the aircraft. The models were developed from observations at San Francisco International Airport; therefore, no claim is made for their validity elsewhere. They merely indicate a type of approach that can be made for making design decisions concerning the sizing of departure lounges.

The common procedure followed by a number of airlines is to commence checking passengers into the lounge approximately 60 min prior to scheduled departure time and to open the door to the jetway 10–20 min prior to departure time. This procedure was used at San Francisco International Airport during the time this study was made; therefore, the study results are only applicable if similar procedures will be used in the future.

The flights sampled were all long-range—to New York, Honolulu, Washington, St. Louis, and Philadelphia—so the characteristics of commuter flights are not included. The flow of passengers to the departure lounge is time-dependent, and also dependent upon the activities of the passengers elsewhere in the terminal. The total number which arrive at the lounge at any given time before departure can be called the cumulative flow. This is illustrated in Fig. 1. The cumulative flow is $F(t)$, where t is minutes before departure. The total number of passengers waiting in the lounge at any time t is $Q(t)$. The time that the entrance doors into the aircraft are opened is designated as t_b and the flow into the aircraft is $G(t)$. Before t_b, the number of passengers waiting in the lounge $Q(t)$ is equal to the cumulative flow to the lounge. Between t_b and t_2, $Q(t)$ is equal to the difference between $F(t)$ and $G(t)$. At time t_2, the queue dissipates and the flow rate into the aircraft thereafter is equal to $[dF(t)]/(dt)$. If the capacity flow rate into the aircraft is always equal to or greater than the flow rate into

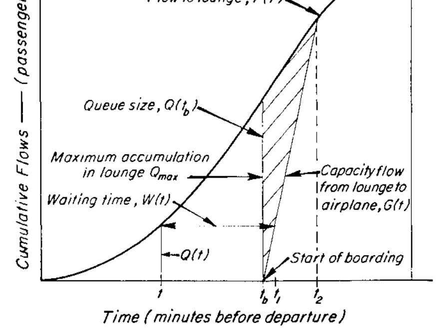

Fig. 1 Typical boarding sequence.

Presented as Paper 68-111 at the AIAA 5th Annual Meeting and Technical Display, Philadelphia, Pa., October 21–24, 1968; submitted October 21, 1968; revision received February 7, 1969.

* Professor of Transportation Engineering. Member AIAA.

the lounge, the maximum will occur at some time after t_b, i.e., nearer to departure time. Models were developed for $F(t)$ and $G(t)$.

The model for $F(t)$ was determined by observing the flow to the lounge. Passengers were counted as they arrived and their arrival time was recorded. This procedure was continued until departure time. Prior to developing the model, the number of passengers on each flight was normalized in terms of percent. This step served as the basis for using the model to predict the number of passengers arriving at any time t, if the total number of passengers to be boarding a given flight was known.

The data obtained were used in a least-squares regression analysis. It was found that the best fit, i.e., the curve having a minimum value of the sum of the squares of the deviations of the theoretical points from the observed points, was a quartic curve of the form

$$F(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4$$

where $F(t)$ = percent of passengers boarding a flight, t = minutes before departure, $a_0 = -1.78$, $a_1 = 0.72$, $a_2 = -0.02$, $a_3 = 0.0025$, and $a_4 = -0.00003$.

The standard error of estimate of $F(t)$ on t was found to be $\dot{\sigma} = 1.6$. A chi-square test for goodness of fit of the curve to the data revealed that the fit was good with a probability of 0.55. Detailed calculations are contained in a study by Paullin.[1] (60-t) is used as abscissa in Figs. 2, 3, and 4.

The model for $G(t)$, the flow into the airplane, was developed by observing passenger flow through the jetway and aircraft door. A regular pattern was evident, in that all or most of the waiting passengers began queueing in the jetway as soon as the boarding announcement was made. The queue lasted until waiting passengers were boarded, at which time the flow into the aircraft reduced to equal the flow of passengers arriving at the lounge or $G(t) = F(t)$.

During the period of queueing in the jetway, flow rate into the aircraft was maximum. The period of queueing varied from 3 to 5 min, during which the flow rate was nearly constant. The model for the flow into the aircraft was, therefore, selected as

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

where $G(t)$ = number of passengers having boarded at time t, b = capacity flow rate, passengers/min, t = minutes before departure, t_b = initial boarding time, and t_2 = time at which queue dissipates (see Fig. 1).

It should be noted that $G(t)$ is absolute, in terms of number of passengers and not in percent of passengers as is $F(t)$. The term $G(t)$ is a function of the size and number of aircraft doors available for loading and the interior configuration of the cabin.

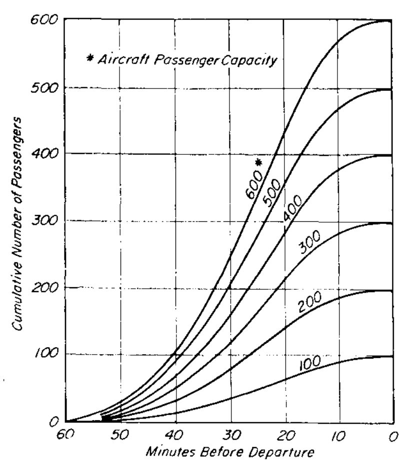

Fig. 2 Passenger arrivals at departure lounge.

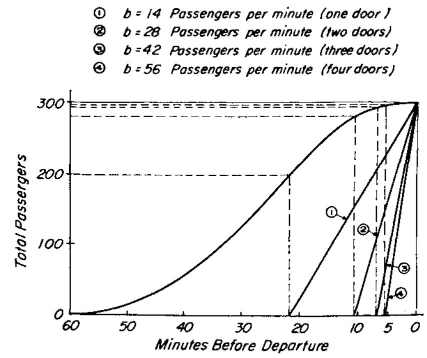

Fig. 3 Departure lounge sizes for 300 passenger airplanes.

An average capacity flow rate was calculated from the observed flights, and the value of b turned out to be 14. The final model for passenger flow into an aircraft was, therefore,

$$G(t) = 14(t - t_b)$$

Ninety-nine percent confidence limits for the expected value and variance of the capacity flow rate were $12 < \xi < 14$ and $1.3 < \sigma^2 < 17.8$, respectively.

The models can be used to investigate the relationship between the number of aircraft doors, the time before departure that these doors are opened, and the size of the departure lounge. Tradeoffs in time and space can be analyzed and decisions formulated regarding future loading procedures.

Applications of the models are shown in Figs. 2, 3, and 4. From these illustrations, it is evident that the size of a departure lounge depends on 1) the size of the aircraft, 2) the number of available entry doors into the aircraft, 3) the arrival pattern of passengers to the lounge, and 4) the time allowed for boarding passengers. Increasing the number of entry doors into the aircraft permits a reduction in boarding time; but if this is the goal, it is achieved at the expense of increasing the size of the departure lounge.

Additional Observations on Inflow and Outflow of Passengers

Since the completion of the study by Paullin,[1] additional observations were made on rates of flow of not only enplaning but also of deplaning passengers.[2] Passenger flow characteristics and estimated flow rates for loading passengers were determined for two passenger handling strategies. The first strategy was to load passengers without seat assignment and the second was to load passengers with seat assignment. In addition, unloading rates were also observed. All passengers were loaded and unloaded through a jetway. A queue of passengers existed for all of the observed flights. The

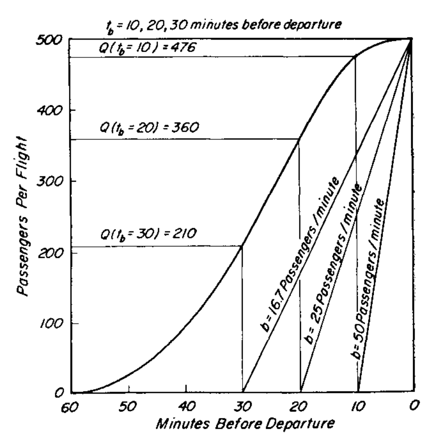

Fig. 4 Departure lounge sizes for B-747, 500 passenger capacity.

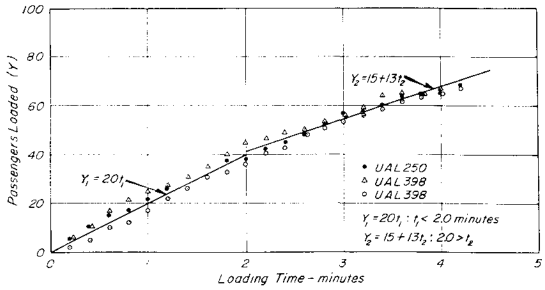

Fig. 5 Cumulative number of enplaned passengers (passengers loading with seat assignment—Boeing 727).

flights sampled were primarily short-haul domestic flights to and from San Francisco International Airport.

Typical results for enplaning passengers are shown in Figs. 5 and 6. It will be noted that 1) enplaning rates do not remain constant throughout the loading time but that an initial surge occurs and 2) the rate is higher for flights with no seat assignment. With seat assignment, the average loading rate at 4 min was about 16 passengers/min, which is not much different than the 14 passengers/min reported by Paullin.[1] With no seat assignment, however, the average rate was about 20 passengers/min.

Of equal importance is the unloading rate, since the number of doors required for large aircraft could well be governed by the time desired to empty rather than load an aircraft. Figure 7 illustrates the typical results from several flights and indicates that the rate is fairly constant at about 36 passengers/min.

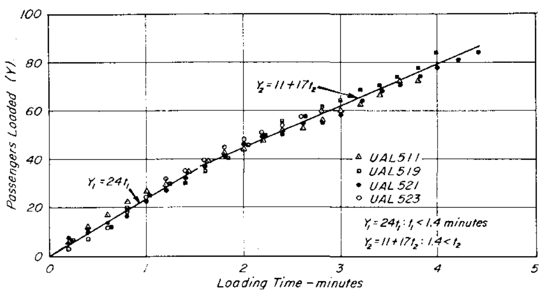

Fig. 6 Cumulative number of enplaned passengers (passengers loading without seat assignment—Boeing 727).

Paullin[1] and Kaneko[2] both point out that the rates of flow are for the present size of doors. However, the doors on the 747 and other aircraft will be larger, so that flow rates will probably be greater. At no time during the observations were the jetways a constraint, either for loading or unloading.

There are many factors that can affect passenger flow rates into an aircraft. Unfortunately, there was no opportunity to study all of them, but they are listed below in the event continuing studies are made. These factors are as follows: 1) width of jetway, 2) aircraft entry door width, 3) type of service rendered at aircraft door (collect gate pass, etc.), 4) aisle length and width, 5) seat assignment vs no seat assignment, 6) number of seats/row served by an aisle, 7) seat spacing (longitudinal), and 8) composition of passengers. Only item 5 above was studied in detail by Kaneko.[2] But even from this very preliminary study, it was clearly evident that the constraint in loading was not the size of the aircraft door but the amount of congestion in the aisle.

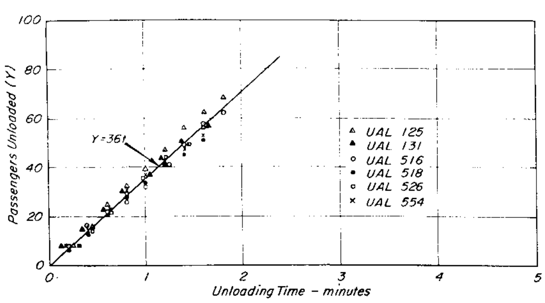

Fig. 7 Cumulative number of deplaned passengers.

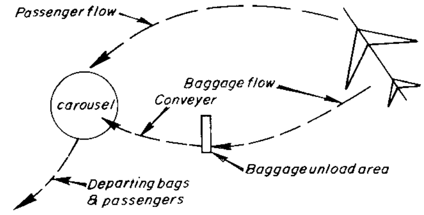

Fig. 8 Baggage claim system.

Passenger and Baggage Flow at Arrival Baggage Claim Area

Space requirements for baggage claim are an important input in the design of airport terminal buildings. Space needs can be greatly influenced by the interrelationship of passenger and baggage arrival patterns at the baggage claim area. A deterministic queueing model was developed to relate the number of bags on a carousel to the arrival distribution of passengers and baggage. The model was based on experimental data taken at San Francisco International Airport.[3] From these data, the following were developed: 1) cumulative passenger arrivals at the baggage claim at time $t = A_p(t)$, 2) cumulative bag arrivals at the carousel at time $t = A_b(t)$, and 3) bags remaining unclaimed at select times after the start of baggage arrival. Time was measured from the instant an arriving flight began to disembark passengers.

The baggage claim system at San Francisco International Airport is schematically illustrated in Fig. 8. When the aircraft reaches its position on the ramp, personnel move a train of baggage trailers into position at the aircraft. For containerized aircraft, containers are lowered onto gondola trailers, which are then towed to the baggage unload area for unloading. For pit loaded aircraft, bags are unloaded, with the help of mechanized loading equipment, to flatbed trailers. Airport policy limits the number of trailers in tow to six, and the airlines frequently tow fewer than this number. Thus, for large baggage loads, several trips may be required between the aircraft and baggage unload area.

At the baggage unload area, ramp crews manually remove bags from the trailers and place them on a conveyor belt leading to a carousel. Maximum flow rate for the belt, based on the capacity of the carousel to accept bags without clogging, is approximately 40 bags/min. The unloading rate for one man varies from 10–15 bags/min. Thus, the delivery rate can be very dependent on the size of the crew offloading baggage.

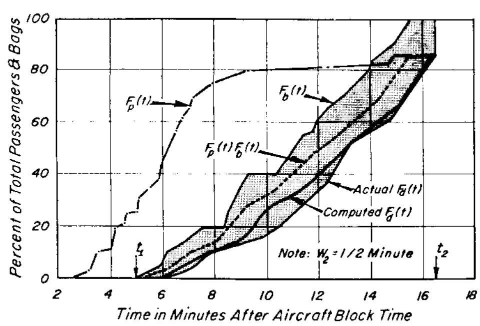

Fig. 9 Application of analysis to data of flight AA 225, July 28, 1967.

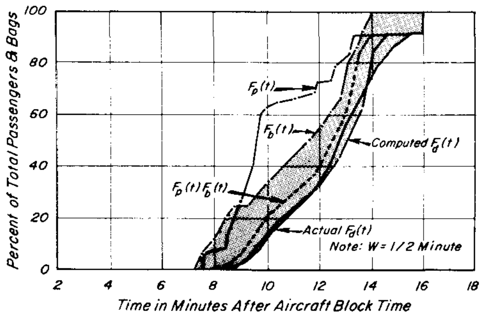

Fig. 10 Application of analysis to data of flight TWA 41, July 20, 1967.

Flights known to have large passenger and baggage loadings were selected for analysis. The structure of the analysis is shown in Fig. 9. Knowing $A_p(t)$, the probability distribution of a passenger arriving at the baggage claim area $F_p(t) = A_p(t)/N_p \leq 1$, where N_p is the total number of arriving passengers. Knowing $A_b(t)$, the probability distribution of a bag arriving at the carousel is $F_b(t) = A_b(t)/N_b \leq 1$, where N_b = total number of bags. Since the bags remaining on the carousel were counted for select times, the expression for the cumulative number of bags removed from the carousel at time t, $D_b(t)$, equals $A_b(t)$ minus bags on carousel at time t. Then the probability distribution of a bag removed from the carousel is $F_d(t) = D_b(t)/N_b \leq 1$. At any time t, the total number of bags remaining on the carousel $Q_b(t)$ is $N_b[F_b(t) - F_d(t)]$, where N_b = total number of bags on a flight. This total should not be much larger than the capacity of the carousel, which at San Francisco was about 80 bags (one-row deep—25.5 ft in diameter—circumference 80 ft).

The average waiting time W for a bag to remain on a carousel is the area between the two curves $F_b(t)$ and $F_d(t)$, which is equal to

$$\int_{t_1}^{t_2} F_b(t)F_d(t)dt$$

where t_1 = arrival time of the first bag and t_2 is the last bag to be claimed. W is the shaded area shown in Fig. 9 multiplied by the total number of bags N_b. This average waiting time is the sum of two time periods W_1 and W_2. The first period W_1 is the average waiting time when the bag arrives at the carousel first and must wait for the arrival of the passengers and W_2 is the average waiting time for the passenger to remove the bag from the carousel, assuming that both passenger and bag are at the carousel. Clearly, W_1 would be equal to zero if all passengers arrived before the first bag arrived. If the passenger is at a certain position along the circumference of the carousel, waiting for his bag and the bag is at the mouth of the carousel, W_2 would be the average time taken for the bag to travel from the mouth of the carousel to the location of the passenger and W_1 is equal to zero.

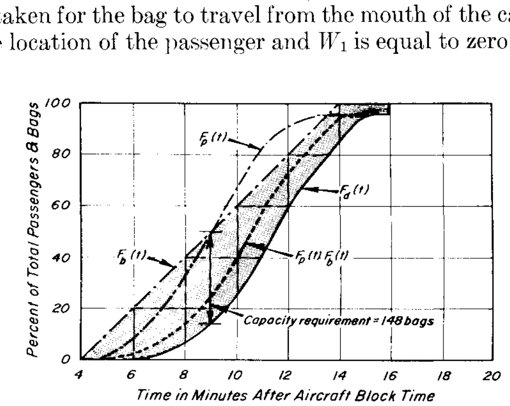

Fig. 11 Analysis of baggage requirements for a flight with 200 passengers and 400 bags at 40 bags/min delivery rate.

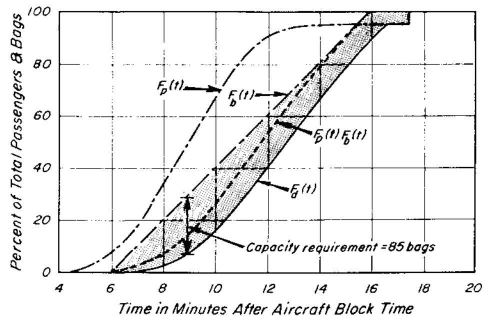

Fig. 12 Analysis of baggage requirements for a flight with 200 passengers and 400 bags at 40 bags/min delivery rate—delayed delivery.

To compute W_1, the following logic was used. There is valid reason to assume that the arrival time of a bag T_b and the arrival time of the passenger who seeks his bag T_p are independent random variables. The time at which both passenger and his bag have arrived at the carousel is $T_{p,b} = \max(T_p,T_b)$, and the probability distribution function of $T_{p,b}$ is then $F_{p,b}(t) = F_p(t)F_b(t)$ which is the probability that both the passenger and his bag arrive at the carousel at time t. The average waiting time W_1 is the area between the two curves $F_b(t)$ and $F_p(t)F_b(t)$, which is

$$\int_{t_1}^{t_2} [F_b(t) - F_p(t)F_b(t)]dt$$

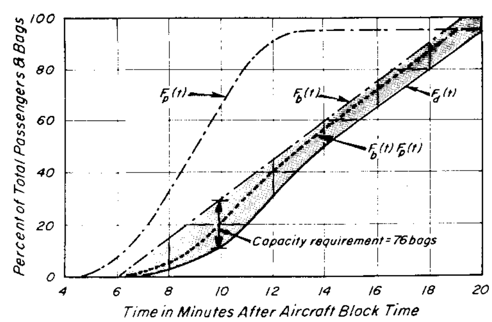

Fig. 13 Analysis of baggage requirements for a flight with 200 passengers and 400 bags at 30 bags/min delivery rate.

The average waiting time W_2 was determined experimentally. A reasonable estimate of W_2 would be one-half the time for the carousel to make one revolution, this being $\frac{1}{2}$ min at San Francisco. This estimate checked closely with experimental data for flights with few passengers and bags, but for heavily loaded flights the value of W_2 was closer to 1 min.

In summary, the mechanics of the analysis are as follows: determine $F_p(t)$ and $F_b(t)$ experimentally. Compute $F_p(t)$-$F_b(t)$ and then displace this line by an average value of $W_1(\frac{1}{2}$-1 min) and obtain $F_d(t)$.

To verify the accuracy of the analysis, compare the computed $F_d(t)$ with the observed $F_d(t)$ as shown in Figs. 9 and 10. Figure 9 illustrates the application to a specific flight, AA225, and Fig. 10 the application to TWA Flight 41.

Figures 11, 12, and 13 show some applications of the analysis in comparing strategies for baggage delivery. In each

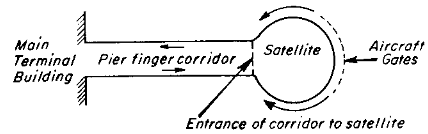

Fig. 14 Satellite arrangement.

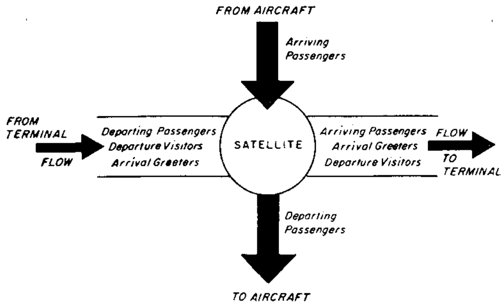

Fig. 15 Passenger flow model.

case, $F_p(t)$ is based on a United Air Lines DC-8-61 with 200 passengers, and W_1 is equal to 1 min.

The comparison of Figs. 14 and 15 shows the effect of the start of delivery time on bag storage requirements. In each case, delivery rate is 40 bags/min, the maximum rate for existing carousels. Note that for a strategy of early bag delivery, storage equipment $Q_b(t)$ is 148 bags compared to 85 bags for a strategy of delivery after passengers start arriving. Note also that there is little savings in total time for early bag delivery.

The strategy for this flight (Fig. 12) was to provide all bags in the shortest possible time. Arrival baggage rates at times exceeded 90 bags per minute. The number of bags waiting to be claimed often exceeded 150 which is what one would predict from the analysis.

Comparison of Figs. 11 and 13 provides information on the effect of reducing baggage delivery rate. Figure 13 illustrates a delivery rate of 30 bags/min compared to 40 bags/min in Fig. 11. The starting time of delivery is the same for each case. The lower flow rate does reduce storage requirements slightly; however, the tradeoff is an increase in total carousel occupancy time.

Passenger Flow in Pier Fingers of Airport Terminals

The movement of people in corridors of airport terminals is a vital element in their design. Particular questions that need to be answered are 1) what are the combined passenger and visitor flows in corridors of pier fingers that will be generated in the future and 2) what should the width of the corridors be to accommodate these flows?

The objectives of the study described by Smith[4] were 1) to develop a simulation model which could identify the important parameters influencing the flow rates in a corridor generated by arriving and departing aircraft clustered around a satellite and 2) hopefully, to predict within reason what these total flows would be. The term "satellite" refers to a circular area in which the departure lounges are housed, as shown in Fig. 14. The satellite is connected to the main terminal building by a corridor. In this study, no aircraft is assumed to be parked along the side of the corridor. The model develops the flow of people at the entrance of the corridor to the satellite. The characteristics of flow within the corridor are the subject of another study.

The types of people using the corridors are 1) departing passengers, 2) visitors accompanying departing passengers, 3) arriving passengers, 4) greeters accompanying arriving passengers, 5) sightseers, and 6) employees. Sightseers and employees were excluded in the initial model application because of lack of data on their number; however, the model permits their inclusion whenever the data are available.

For the purpose of modeling the passenger flow process, the configuration shown in Fig. 15 was assumed. The process is divided into two separate and distinct operations, arrivals and departures.

In developing any model, simplifying assumptions must be made at the start. After the initial effort, the model must be tested in a real life situation. At this point in time, one can decide to what extent the initial model should be modified. The assumptions that have been made for the initial model are summarized as follows: 1) the aircraft arrival and

Table 1 Forecast of aircraft schedules

Aircraft type	No. of entrance and exit doors	No. of passengers for each flight	Arrival	Departure
DC-8	1	100	1645	1800
DC-8	1	100	1705	1830
B-727	1	76	1730(O)[b]	1800
B-727	1	76	1745	1900
B-727	1	76	1745	1830
DC-8	1	100	1755	1855
DC-8	1	100	1755	1855
B-727	1	76	1800	1820(T)[a]
DC-8	1	100	1800	1900
DC-8	1	100	1805	1855
B-727	1	76	1810	1900
DC-8	1	100	1815	1930
B-747	4	312	1815	1900
B-727	1	76	1830	1915
B-727	1	76	1840	1935
B-727	1	76	1845	2000
DC-8	1	100	1855	1920(T)[a]
B-727	1	76	1900	2030

[a] T = termination flight.
[b] O = origination flight.

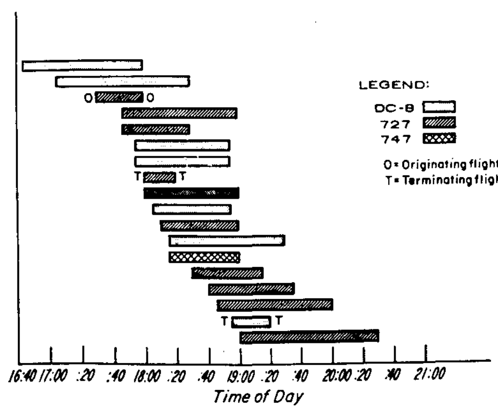

Fig. 16 Scheduled aircraft gate occupancy.

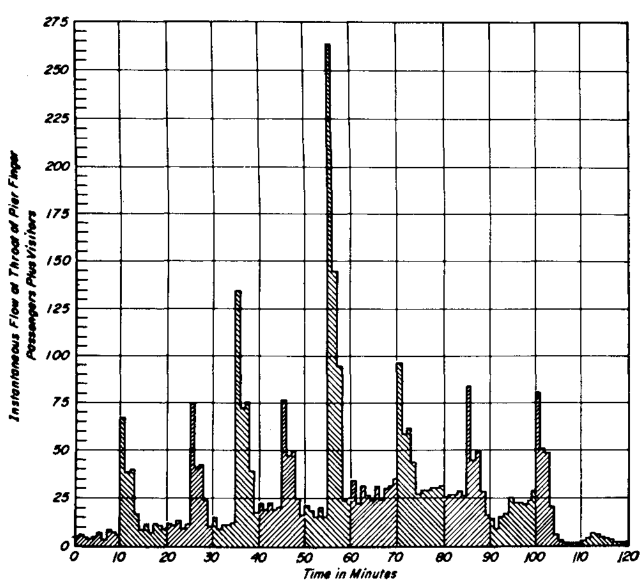

Fig. 17 Flow of people in pier finger corridor.

departure times from the gates are the same as opening the doors to arrivals and closing doors for departures, 2) the flows of people in opposite directions do not interact significantly, i.e., the corridor and the satellite area are wide enough so that free flow can occur in each direction, and 3) the time to walk from any jetway or departure lounge to the entrance of the corridor is the same for all gates.

In developing the simulation model, the generation of flow in the pier finger was assumed as follows.

Generation of Departing Passengers and Departure

Visitors (DEPGEN)

1) Departing passengers are assumed to arrive at the departure lounge in accordance with the investigation made by R. Paullin described earlier in this paper[1] and by Paullin and Horonjeff.[5]

2) Departure visitors are assumed to accompany departing passengers.

3) Departure visitors are assumed to leave the departure area in accordance with the S-shaped cumulative curve developed by R. Paullin[1] but compressed in time to a total of 10 min. It was also assumed that the first visitor leaves the satellite 5 min before the departure of the aircraft.

Generation of arriving passengers and arrival greeters (ARGEN)

1) Arriving passengers are assumed to exit from the airport at a constant rate for each jetway (aircraft flow) based on a study by Kaneko and others[2] and leave the satellite at this rate.

2) Arrival greeters are assumed to accompany arriving passengers when leaving the satellite.

3) Arrival greeters are assumed to arrive at the satellite with a distribution similar to the departure passengers but compressed in time to a maximum of 15 min.

It was also assumed that the last greeter arrived at the same time as the aircraft.

The model has been made sufficiently flexible to accept early or late aircraft arrivals and late departures (from scheduled). In this way, one is able to examine the consequences of not being on schedule on 1) passenger flows and 2) delay to passengers due to lack of available gate positions. It was assumed that arrivals could be as early as 10 min and as late as 20 min, and that between these two extremes the probability of such an occurrence was uniformly distributed (equal probability). Minimum service times were obtained for several types of aircraft, and these were applied to the late arrivals whenever the lateness was sufficient to delay the scheduled departure time.

To illustrate the application of the model, a hypothetical case was investigated. Given the following schedules (Fig. 16 and Table 1), aircraft load factors, number of jetways, and number of visitors, and assuming that the aircraft are all on time, what would the people flow be at the entrance of the corridor to the satellite?

It was assumed that for this particular application there were $\frac{3}{4}$ visitors for each passenger. The results of the simulation are shown on Fig. 17.

References

[1] Paullin, R. L., "Passenger Flow at Departure Lounges," Graduate Report, Institute of Transportation and Traffic Engineering, Univ. of California, Berkeley, July 1966.

[2] Kaneko, E. T., "Passenger Enplaning and Deplaning Characteristics," Graduate Report, Institute of Transportation and Traffic Engineering, Univ. of California, Berkeley, Aug. 1967.

[3] Barbo, W. A., "The Use of Queueing Models in Design of Baggage Claim Areas at Airports," Graduate Report, Institute of Transportation and Traffic Engineering, Univ. of California, Berkeley, Sept. 1967.

[4] Smith, E. E., "Simulation of Passenger Flows in Pier Fingers," Graduate Report, Institute of Transportation and Traffic Engineering, Univ. of California, Berkeley, Aug. 1968.

[5] Paullin, R. L. and Horonjeff, R., "Sizing of Departure Lounges in Airport Terminal Buildings," Proceedings ASCE-AOCI Specialty Conference, Houston, Texas, April 10–14, 1967.