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A Model for Determining the Width of Airport Pedestrian Corridors

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ABSTRACT

A mathematical model for designing pedestrian corridors in airport terminals is presented. The model is based on a concept of minimizing the sum of construction costs, operating costs, and passenger walking time. The development of the model is explained. The model has been written for use with a hand-held programmable calculator and tested to check the validity of the model results against other design procedures. A sensitivity analysis was performed to determine the effects of different values for independent variables. Finally, the model results are compared with an actual terminal building design. The design procedure selected a width very close to the actual design. The results indicate that the model may be a useful tool in selecting the width of passenger corridors.

Many models have been developed for designing airport passenger terminals. Service facilities such as ticket counters, security checkpoints, and gate check-in lend themselves to modeling as queuing processes. The overall design philosophy has been modeled by both de Neufville (1) and Braaksma (2). The size of waiting areas at boarding gates is based on queue size for passengers arriving at the gate (3). The size of walking areas is based primarily on the work of Fruin (4). Design is based on the desired level of service and the facility size is chosen to meet that level of service for the pedestrian flow. This concept is illustrated in Figure 1.

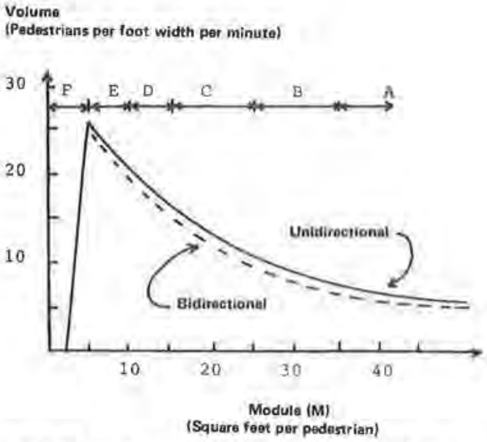

FIGURE 1 Volume of pedestrian flow and area occupied on walkways *(4)*.

The levels of service normally associated with terminal design are B and C. At level B the pedestrian is free to select a walking speed, but may experience crossing and reverse direction conflicts. This level would be an appropriate design for terminals without severe peaking. At level C the pedestrian's freedom of speed becomes restricted and is appropriate for terminals that have severe peaking. Levels of service D, E, and F are not considered to be appropriate for design, although D and E might be acceptable during very short peak flow periods.

As can be seen, this design procedure relies heavily on the judgment of the designer for determining an appropriate level of service and then selecting a point within the range of the level of service. No specific consideration is given to the trade-off between costs of congestion and costs to construct, operate, and maintain wider corridors. de Neufville and Grillot (5) note that the selection of level of service represents a compromise between construction costs and inconvenience. Economic efficiency requires that a system operate at the point of minimum cost. In this case that point is the minimum of the sum of delay, construction, and operating costs. A rational design procedure would be to minimize some function of costs. This model formulation develops such a design procedure.

MODEL FORMULATION

To minimize the sum of pedestrian delay, construction costs, and operating costs, it is necessary to select measures of each that are compatible. The measure selected is monetary cost. Construction cost is initially a monetary cost and, for comparability, the capital cost need only be discounted to an appropriate time period. Similarly, operating cost may be estimated in monetary terms. Measurement of pedestrian delay in terms of money is more difficult. Instead of measuring delay, it is equivalent to measure walking time over a set distance and use this walking time multiplied by the value of that time to the traveler. The time to traverse a corridor is a cost to the pedestrian and any change above the minimum is the actual delay.

To determine walking time, it is necessary to know the walking speed. The best study of walking speeds with congestion effects is that done by Fruin (4). Relying on Fruin's work, it is possible to develop several relationships that lead to the formulation of an unconstrained minimization problem. For the purpose of developing a design tool, the analysis has been limited to corridors such as those found in pier finger type terminals. A further simplifying assumption is that no gates are located in the area to be designed. These assumptions restrict pedestrian flow to be along the corridor without interference from crossing flow or queues. The design procedure may then be modified to consider more complex situations. The case where a gate area is adjacent to the corridor will be analyzed specifically in a later section.

The first relationship defines P, the volume per unit width, to be equal to the total volume divided by the width of the corridor. The relationship used is then $P = D/x$, where P = flow in pedestrians per foot width per minute (PFM), D = flow in pedestrians per minute, and x = corridor width in feet.

The next relationship in determining walking speed is based on observations made by Fruin. Figure 1 shows the relationship between volume and the inverse of density, or module. Observe that the effects of bidirectional versus unidirectional flow are very small. Because terminals that experience peaking (typical of airport terminals) are normally designed for level of service C, it is possible to assume a linear relationship in the range of level C through level E or values of the module from 5 to 25. The approximation of the inverse relationship in Figure 1 is $M = -1.2P + 35$ for $10 \leq P \leq 25$, where M = module in square feet per pedestrian.

The final relationship results in walking speed as a function of the module. Values observed by Fruin are shown in Figure 2. The curve shown in Figure 2 may be approximated by the function $S = 50 + 60 \ln(M - 2)$, where S = walking speed in feet per minute. Walking time is simply the distance traversed divided by the speed. By selecting the distance to be 1 ft, the total length of the corridor need not be known. Construction cost per square foot is approximately equal to the cost per foot of width over the range being considered. If the cost increases dramatically by widening the corridor, the designer must consider that in determining a design width after using this procedure to establish the desired effective width. Operating costs are treated similarly. If the time period is selected as one year, the problem becomes

$$\min TC = T\theta D/[50 + 60 \ln(-1.2 D/x + 33)] + cx + Ox$$

where

TC = total annual cost,
T = total time of peak flow in hours per year,
θ = value of time in dollars per hour,
D = peak flow in pedestrians per minute,
x = corridor width in feet,

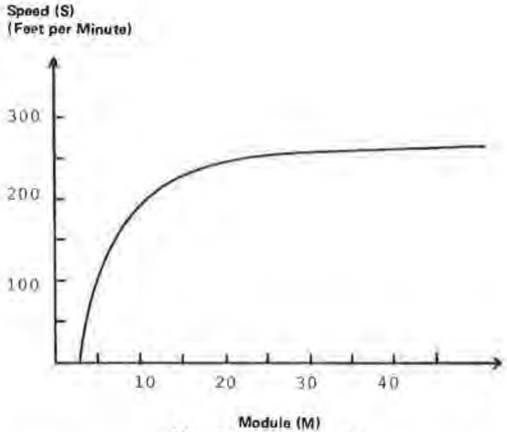

FIGURE 2 Pedestrian speed on walkways: traffic impeded, one-way flow *(4)*.

c = annualized capital cost per square foot, and
O = annual operation and maintenance cost per square foot.

Because the problem is nonlinear, the solution technique chosen was a Golden Section Search over the range of x for $10 \leq P \leq 25$ (6). Termination was set for a solution within a range of 0.5 ft of the minimum. This range is satisfactory for design because other factors in construction influence the optimal width and a value to the nearest foot for pedestrian flow is acceptable. A program to solve the problem was written for a hand-held programmable calculator. The program required approximately 300 steps and goes through eight iterations of the search to reach the closure criterion. The time required for solution is approximately 1 min. The program could be written for other hand-held calculators with sufficient program memory.

MODEL RESULTS

The model was tested (a) to analyze the sensitivity of the solution to different input values and (b) to determine the validity of results of this procedure compared with results from other design procedures. The average value of time for air travelers was based on Yu and Kerr who found that in 1971 the values ranged from $5.78 to $14 per hour with a most likely value just under $10 (7). These values were increased at a rate of 5 percent per year so that a range of $10 to $20 per hour with a most likely value of $16 was used in the model. The designer should be aware of the problems associated with both estimating and using an average value of time. An in-depth discussion of the question of value of time is beyond the scope of this paper; however, a sensitivity analysis was performed to show the effects of using different values of time.

The passenger flow volume used for testing was obtained from Horonjeff (8). The peak flow occurs for 10 min at a rate of 260 pedestrians per minute with other flows less than 120 pedestrians per minute. The value of T is based on the 10 min peak flow and is obtained by converting minutes to hours, assuming the peak occurs 5 days per week, each week of the year. Construction cost was estimated at $50 per square foot. This cost is much lower than commercial airport terminals but is useful in analyzing the sensitivity of the model. Three discount factors were used: 10 percent based on the standard used by the government, 14 percent based on the rate of government bonds, and 18 percent based on the prime rate. The different discount factors also give an indication of what happens to the solution for changes in the estimate of construction cost. The economic life of terminal facilities was selected as 15 years based on the findings of Ashford (9). Operating costs were estimated at $4 per square foot.

Figure 3 shows the results for different values of time and annual capital construction costs. As expected, the corridor is wider for increased values of time and for lower construction costs. Also, the sensitivity to the value of time decreases as construction costs increase. Figure 4 shows the effect of increasing pedestrian flow from 260 to 350 pedestrians per minute. Note that as the flow increases, the solution becomes more sensitive to the value of time as indicated by the slope of a line drawn through the solutions.

The next step in testing the design model was to compare model results with results from other design procedures. Fruin gave two examples that are useful for this test (4). The first is for the design of a pier finger in an airline terminal. The problem statement is: "A Boeing 747 is expected to discharge up to 362 passengers in a 5-minute period. Determine the approximate finger width... Evaluate the impact of the simultaneous arrival of a second such aircraft." Assuming level of service A for the first aircraft, Fruin determined the appropriate width to be 10.2 ft. He then checked the simultaneous arrival of a second aircraft and found that this is level of service C, which is acceptable.

Using the model the approach to the problem is different. The simultaneous arrival is assumed to be a 5-min peak flow of 145 passengers per minute. Using $16 as the value of time, $9.82 as the annual capital cost, and $4 as the annual operating cost, the solution is 8.6 ft. This width is at the upper end of level of service D, which may be acceptable for a 5-min period. Thus, there is only a small difference between the model result and the result using Fruin's procedure.

The second example is a design for a terminal concourse. The problem reads: "Based on forecasts of future passenger demand and traffic patterns, a commuter transportation terminal is estimated to have a 15 minute design peak of 5,000 passengers. During the peak 15 minutes, a short, 5 minute micropeak, or peak-within-the-peak, is expected to occur, which is estimated to be 50 percent higher than the average for the design period. Based on the estimated demand, determine...the dimensions of the main access corridor...." Although the problem is for a commuter terminal, the results provide additional comparison for the model. Fruin designs for level of service C and determines the width to be 22.2 ft. Checking the micropeak he finds level E, which "could be tolerated for short periods." The model result, using $10 as the value of time, $9.82 as the annualized capital cost, and $4 as the annual operating cost, is a width of 22.9 ft. This is very close to Fruin's solution.

Evaluation of the micropeak results in level of service E, which is acceptable. Designing for the micropeak using the model yields a width of 26.8 ft, which is level of service D. As the peak period is lengthened, the level of service increases toward level B. This also is in accord with design practice

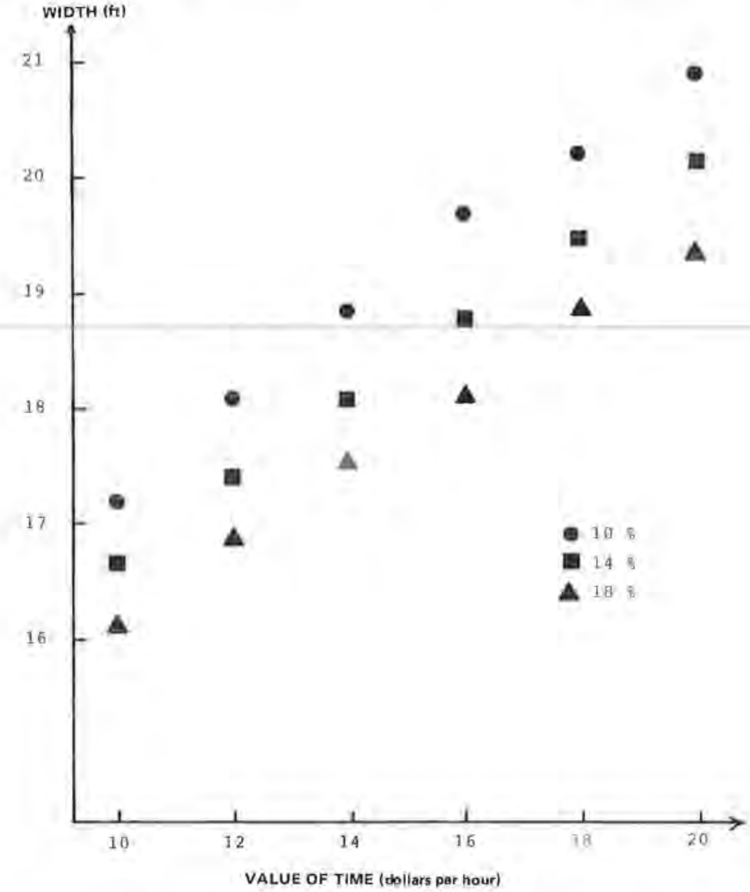

FIGURE 3 Results for different values of time and annual capital construction costs.

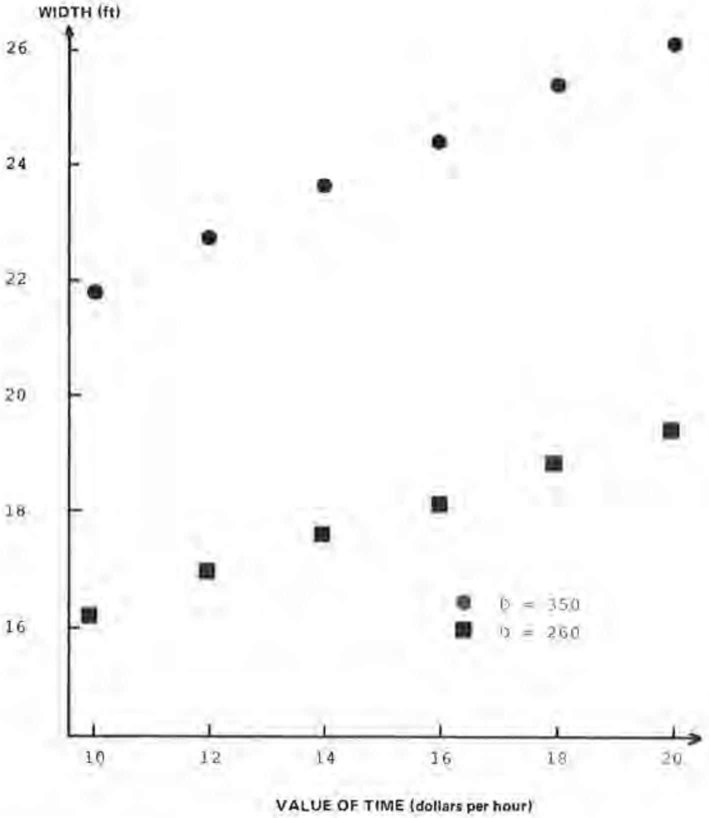

FIGURE 4 Effect of increasing the pedestrian flow.

for terminals that do not have severe peaks. Shorter peak periods move the design width toward level D, which can be tolerated for very short periods. The model results compare favorably in both cases with results using other design procedures.

These two design examples are clearly simplifications and do not consider all possible pedestrian flows. In the case of the arrival of two 747 aircraft, it is likely that additional aircraft would be arriving or departing and that nontraveling pedestrians would add to the flow. An accurate design would require a full analysis to determine the peak pedestrian flow.

APPLICATION

The model results are now compared to an actual terminal building. The D concourse at Stapleton International Airport in Denver, Colorado, was designed for a capacity of 16 PFM. The effective width of the corridor as it leaves the main terminal is 53 ft. The flow is 850 pedestrians per minute. The estimated cost of construction for terminal concourses in Denver is $110 per square foot. Assuming that the peak is a 10-min period, Figure 5 shows the model results for different values of time and discount factors. The implication is that the value of time is at the middle of the range used for analysis. The most likely values for model parameters yield an effective width of 53 ft for the peak flow period. The results are in the appropriate range and provide service near the transition from level C to level D.

Two more comparisons were made using the model. Looking at the pedestrian flow in the first example and the widths computed in Figure 3, the level of service is C for the peak flow period and level A for all the other flows. This is clearly an acceptable design. Figure 6 shows the results of a queuing model for passengers arriving at a departure lounge. Making several assumptions about the characteristics of the queue, an estimate can be made of the effects on pedestrian flow. Assuming for purposes of illustration that the aircraft seats 200 passengers, the maximum queue length is estimated to be 75 passengers and the flow to the gate to be five passengers per minute. Assuming further that passengers in the queue require 7 ft^2 each, that the queue is entirely in the corridor, and that the queue extends along the corridor for 75 ft, the queue occupies 7 ft of the corridor width. Taking a width of 20 ft and the flow passing the gate of 255 pedestrians per minute, the level of service lies between levels D and E. The assumptions used are conservative because many people choose to wait in the lounge area before checking in rather than standing in a queue. The level of service may be acceptable for the period during which it might occur. If the queue is not orderly, the effective corridor width may be further degraded to the point that the corridor itself becomes a queuing situation. The importance of providing space for formation of the queue within the departure lounge is evident in order to reduce the deterioration of level of pedestrian service.

All of the tests of the model have shown the results to be valid for the design of pedestrian corridors in terminals that have peak flow periods. When the length of the peak flow period exceeds 30 min, the model results should be checked closely. If the level of service approaches level B, the designer should consider alternate design procedures as the model is constrained to operate at level C and below. The model results provide for an effective width, and the design must provide added width for any items that may impede flow. In addition,

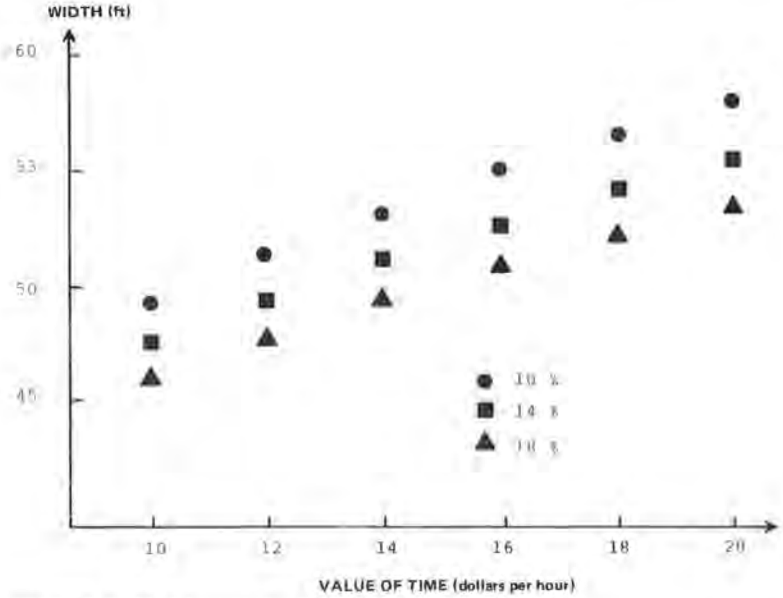

FIGURE 5 Model results for Stapleton D concourse.

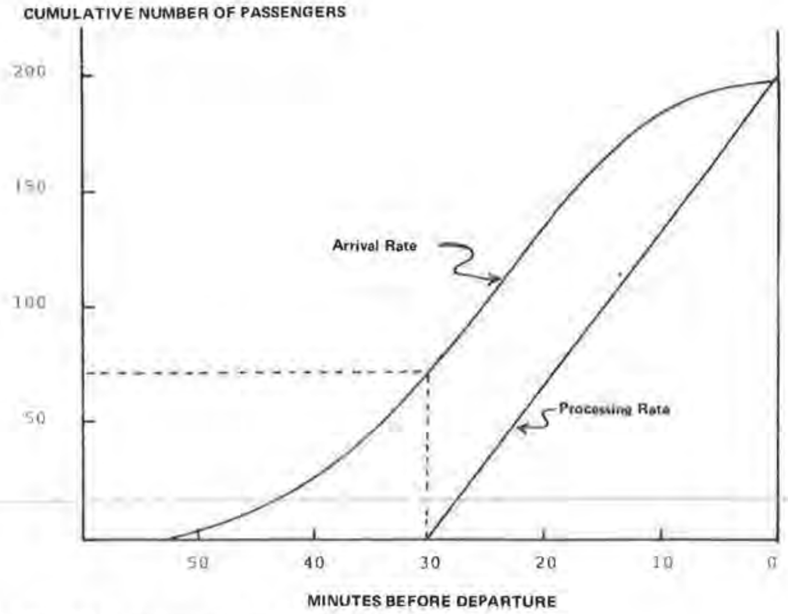

FIGURE 6 Passenger flow to departure lounge.

there is a boundary effect and the designer should allow 1.5 ft additional width along each side of the corridor. The width determined by using this procedure should be used as an input to the total design procedure. The designer must also consider construction costs, procedures, and materials.

CONCLUSION

The model presented provides a rational procedure for selecting the appropriate width of pedestrian corridors. The method is an improvement over selection of width based entirely on the design level of service. For example, consider the Denver concourse. Designing for level of service C would indicate a width from 53 to 85 ft. At $110 per square foot, the construction cost for a corridor 100 ft long would range from $583,000 to $935,000. The designer must select the appropriate point within this range. The model gives the designer a procedure for selecting an initial point which may be modified in consideration of other design requirements. The time to program the calculator and perform the analysis should take less than 1 hour of the designer's time and would be well worth that cost. The alternative is a design that may be too wide and hence too costly or one that may operate at an unacceptable level of service for extended periods.

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Aviation Legislation and Infrastructure: Policy Implications for the 1980s

YUPO CHAN

ABSTRACT

Airport and airway legislation together with technological advances facilitate developments in aviation. Currently aviation is repeating one of its several historical bifurcations as the transition is made from the 1970s to the 1980s. The recently passed airport and airway improvement legislation, for example, authorizes substantially increased expenditures from the Airport and Airway Trust Fund through 1987, the main bulk of which is for modernization of air traffic control facilities and equipment. A collateral legislation, the Airline Deregulation Act of 1978, in addition to rearranging the traffic patterns of the country, may stimulate the growth of the regionals (commuters) and air taxis, thus placing stringent requirements on existing terminal and airway capacity. Exacerbating the terminal capacity problem are certain implications of the Aviation Safety and Noise Abatement Act of 1979, which may result in reducing the time window for flight operations in major hubs, thus further decreasing airport capacity. Fortunately FAA's recent National Airspace System (NAS) plan, together with expanded funding authorized by the Airport and Airway Act of 1982, will address much of the capacity, safety, and productivity issues in the long run--particularly with respect to the enroute environment. In the meantime, however, traffic growth will place serious limitations on terminal capacity--both air and ground operations, with the latter being more intractable. A feasible way to provide both capacity and level of safety in the short run is to redistribute the traffic (particularly connecting traffic) from bottlenecks to the less congested parts of the system; this is clearly allowed by the deregulation act.

In the United States, airport and airway legislation--together with the evolution of the terminal and air traffic control systems--is instrumental in facilitating the development of aviation. The first legislation devoted exclusively to airports, for example, was the Federal Airport Act of 1946, which established a federal-aid program to provide a system of public airports to meet the needs of the rapidly growing civil aeronautics industry. This program was subsidized through the 1950s by the federal government through general revenue appropriations. During this period, the first generation of the Air Traffic Control (ATC) system was put in place.

Traffic growth in the 1960s created a demand for still more airport and airway development, including second generation ATC systems. There was also a requirement for additional financial aid to accommodate growth. By 1968 this, along with the excessive delays at major airports, led to a concerted effort by the federal government and industry that resulted