Dynamic Capacity of Airport Enplaning Curbside Areas

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An analytical model based on the theory of time-space was developed to calculate the dynamic vehicular capacity of the enplaning curbside area at airport passenger terminal buildings. The enplaning curbside area was considered as a system, and most of the variables that affect the capacity of this system were taken into account. To calculate the practical capacity, two distribution functions were developed. First, the traffic distribution around the doors of the terminal building was analyzed, on the basis of drivers' parking space preference, in the form of a binomial function. Second, weighting functions were developed and calibrated on the basis of users' door preference for unloading, in the case of more than one door, in the form of a modified binomial distribution. Using these functions, the percentage of distribution of traffic as well as the practical dynamic capacity of the enplaning curbs were found.

One of the most significant traffic bottlenecks at airports is the curbside area at which people and their baggage enter or leave the terminal. The curbside area is defined as the "temporary" loading or unloading facility on the roadway next to the passenger terminal building. The enplaning curbside exists primarily for people arriving at the airport from the community.

The objective of the dynamic capacity analysis for the curbside area is to determine the maximum vehicle flow rate for the design period, for example, 1 hr. In other words, the dynamic capacity of the curbside area is defined as the maximum number of vehicles that can pass through a certain point of a terminal frontage road in a specified period of time.

From the literature review it was found that curb capacity is usually defined as the maximum length of curb or maximum number of stalls available at any period of time, that is, a static capacity. Transport Canada developed a model for static curb capacity calculations, and a coefficient (m = 0.35) was used to convert static capacity to dynamic capacity (*1*). Cherwony and Zabawski defined theoretical and practical capacity (*2*); according to their definition, practical capacity is 70 percent of theoretical capacity. Mandle and Whitlock stated that door location is one of the most important factors in curbside capacity, but they did not consider door locations in their analysis (*3*). Moreover, most of the studies have focused on how much space there is rather than on how it is used. A rule-of-thumb method suggested by DeNeufville for use in the United States is 4 in. of curb length for every 1,000 annual passengers (*4*). The method developed by Whitlock for Eastern Airlines at Kennedy International Airport stipulates that 1 ft of curb space per hour is required for 2.42 enplaning persons and that the same amount is required for 2.28 deplaning persons (*5*). Transport Canada relates the curb length requirements to the passenger peak-hour planning period (*6*). To consider users' characteristics, stochastic approaches based on queueing theory were developed (*7,8*). Some basic assumptions of these approaches are not supported by real-life curb traffic operations: for example, no preference for vacant spaces is given in the assumption, which is violated in practical cases. By taking the user characteristics into account, it was found that the curb users are sometimes inclined to wait or double park for a vacant space near the terminal doors rather than park in a space farther away. Therefore, increasing the length of curb without changing the terminal layout is not necessarily a solution to the congestion problem. Even though some airports provide enough curb length, they still suffer from congestion and double parking and also need a very strict enforcement policy.

However, it was thought than an analysis of how people use the curbside with respect to the terminal layout—in particular, door locations—is of utmost importance. Therefore, some analytical tools should be developed to consider the users' behavior in curbside area capacity and design.

MODEL DEVELOPMENT

The theory of time-space is applied to the curb system operation to develop an analytical model for dynamic capacity calculation. In this study the maximum vehicle flow rate that can be processed by the system over a 1-hr period is defined as the dynamic capacity (*9*). Simple assumptions are considered during the analysis, such as what would occur under ideal conditions. After finding the maximum flow rate under these conditions, adjustments based on field observations were made to calculate the capacity under prevailing conditions. Assumptions that are expected to hold during calculations are as follows:

- Average influence length and a deterministic average service time of vehicles are considered.
- Average speed is considered for the system, which cannot exceed the allowable speed limit.
- Double and triple parking is not allowed, and vehicles can stop only in parking spaces directly in front of the doors.

In considering the foregoing assumptions, formulas for calculating the maximum and minimum service flow rates were found.

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Minimum Flow Rate

The minimum flow rate occurs where there is only one service station (one parking space in front of the entrance door), and it is assumed that vehicles unload only in this space. The objective is to calculate the maximum number of vehicles that can pass through the curb length, assuming that there is a continuous flow of demand, or no gaps.

Suppose an arriving vehicle enters the curb from the entrance ramp with an average driving speed of v. It will park, unload, and start to leave within the service time τ. The vehicle travel time is obtained by dividing the length of the curbside area by the average speed. The effect of deceleration and acceleration are inherently included in the average speed. The time it takes for the first vehicle to exit the system or pass the curb frontage road from B to A in Figure 1 is as follows:

$$t_1 = \tau + L/v + \alpha/v \tag{1}$$

where

t_1 = exit time of first vehicle,
τ = deterministic service time,
L = total length of enplaning curb,
α = influence length of vehicle, and
v = average speed of vehicles.

Elapsed exit time for the second vehicle would be

$$t_2 = t_1 + \tau + \alpha/v \tag{2}$$

The difference between t_1 and t_2 is the service time of the second vehicle plus the time it takes to travel the influence length of one vehicle. Because the next vehicle must wait until the previous vehicle leaves the door, the value of α/v is defined as delay for the oncoming vehicle. It should be noted that this very short period of time (α/v) is the extra time over and above the service time. Figure 2 illustrates the time-space diagram of vehicles in the case of only one service station. As shown in Figure 2, one vehicle can be serviced in each system operation cycle. Subsequently, by the same procedure, the processing time of the kth cycle or elapsed exit time of the nth vehicle would be as follows:

$$t_k = k(\tau + \alpha/v) + L/v \tag{3}$$

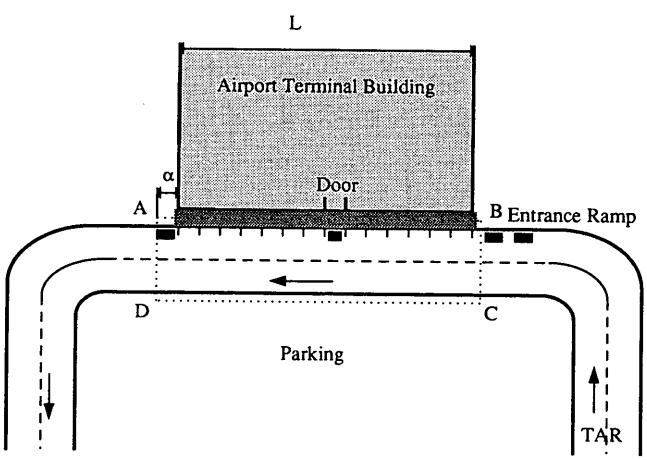
where t_k is the processing time of the kth cycle and k is the total number of system processing cycles.

In this situation, k is the number of system processing cycles, which, because there is one service station, is equal to the number of vehicles. Suppose t_k is equal to the time period T, usually 1 hr; then the number of system processing cycles or maximum number of vehicles that can pass through the system during the time period T is obtained as follows:

$$T = k(\tau + \alpha/v) + L/v \tag{4}$$

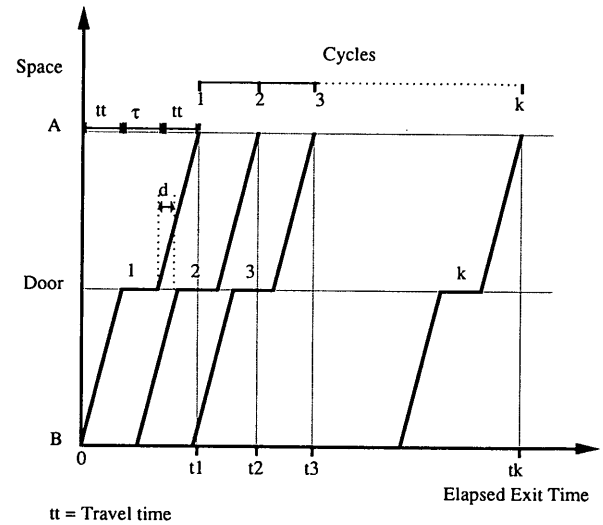
$$k = \frac{T - \dfrac{L}{v}}{\tau + \dfrac{\alpha}{v}} \tag{5}$$

In practical curbside operations, some spaces on either side of the entrance are used as service stations in addition to the spaces in front of the door entrance. This affects traffic distribution along the curb and will be discussed later.



ABCD = Curbside Area (System)
TAR = Terminal Access Road
L = Length of Enplaning Portion of the Terminal Building
α = Influence Length of the Vehicle

FIGURE 1 Schematic layout of enplaning curbside area (system).



tt = Travel time
d = Delay = α/v
τ = Service time
Door = Door location

FIGURE 2 Time-space diagram of vehicles, one door.

Maximum Flow Rate

The maximum flow rate occurs where all parking spaces can be used as service stations with the same degree of utility. In other words, all vehicles can unload at any section of the curbside and all parking spaces have equal preference for the

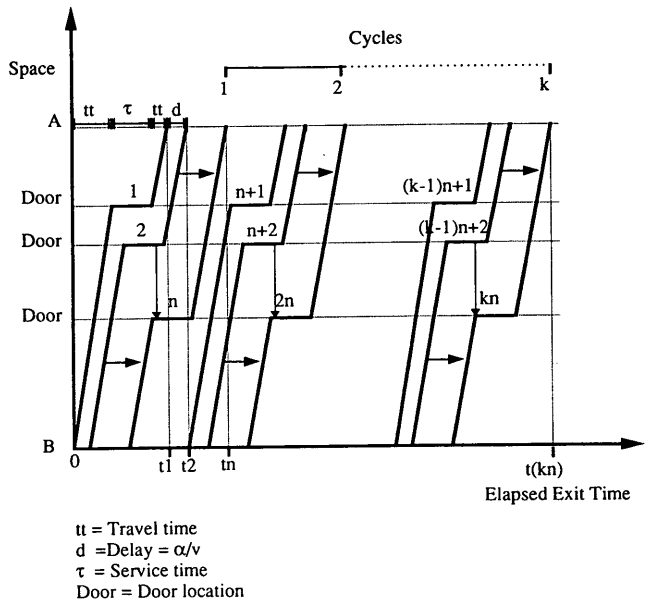


FIGURE 3 Time-space diagram of vehicles, *n* doors.

drivers. Following the same procedure as for the first case, the elapsed exit times of vehicles from the system are as follows:

$$t_1 = \tau + L/v + \alpha/v \tag{6}$$

$$t_2 = \tau + L/v + 2\alpha/v \tag{7}$$

$$t_n = \tau + L/v + n\alpha/v \tag{8}$$

It should be noted that because there are n service stations in the system, n vehicles can be serviced in each cycle. Because of the assumption of equal curb use for the first series of n vehicles, the difference between the exit time of each vehicle is only the vehicle influence length divided by the average speed (α/v). As shown in Figure 3, under the continuous arrival rate for the second series of vehicles and before the third series of arrivals, the elapsed exit times would be as follows:

$$t_{n+1} = t_n + \tau + \alpha/v \tag{9}$$

and

$$t_{n+2} = t_{n+1} + \alpha/v \tag{10}$$

Finally, for the last vehicle in the second cycle of the system, the elapsed exit time is

$$t_{2n} = 2\tau + L/v + 2n\alpha/v \tag{11}$$

The difference between the exit time of vehicles in the first cycle and vehicles in the second cycle is average service time (τ) plus the cumulative value of α/v. If the same process continues until the end of time period T, the processing time for the nth vehicle in the kth cycle would be as follows:

$$t_{kn} = k\tau + L/v + kn\alpha/v \tag{12}$$

where k is the number of cycles that the curbside was occupied and evacuated during the time period T and n is the total number of vehicles that passed the curbside length in each cycle, that is, the total number of service stations.

Therefore, by substituting the specific time period T for t_{kn}, there will be

$$T = k\tau + L/v + kn\alpha/v \tag{13}$$

Hence, the number of cycles during the time period T would be

$$k = \frac{T - \dfrac{L}{v}}{\tau + \dfrac{n\alpha}{v}} \tag{14}$$

It is clear that for only one service station, the capacity is equal to the number of cycles. However, involving n service stations, the total number of vehicles that can be processed during the time period T is

$$C_{\text{ideal}} = \frac{n\left(T - \dfrac{L}{v}\right)}{\tau + \dfrac{n\alpha}{v}} \tag{15}$$

The number calculated in Equation 15 can be referred to as the maximum dynamic capacity of the curb during time period T under specified conditions. It should be noted that this capacity is valid under the assumption that drivers indicated no preference for a particular service station when unloading. Since this assumption is not supported in practical operations, the calculated maximum dynamic capacity is also called the ideal capacity. The ideal capacity, if adjusted for drivers' behavior, will give the practical capacity.

DOOR TRAFFIC DISTRIBUTION MODEL

One of the basic variables in the capacity model was the number of service stations. Under ideal conditions, to get the maximum capacity, it was assumed that drivers showed no preference among service stations when unloading. Since in practice this assumption of equal preference is not borne out, a probability function for curb traffic distribution according to the drivers' behavior should be found. In other words, a probabilistic approach should be considered to find the percentage of traffic distributed along the different sections of the curbside. Because it is assumed that the probability distribution of traffic along the curb can reflect the drivers' preferences or constraints, a comprehensive survey of curbside area was necessary.

Site Inventories

To eliminate the effect of adjacent doors on each other, sites with only one enplaning door had to be considered first. Therefore, a literature survey of all airports in the province

of Ontario was made, and airport terminals with a fair amount of traffic were chosen. Data were collected during two consecutive days at different times for each airport according to the airline schedules at four airports. The surveys were of the observation type so as to avoid passenger interference. Sections 8.0 m long were marked from the entrance ramp along the enplaning curb. A vehicle was assumed to use a particular section if more than half of its length fell in that section.

On the basis of the data analyzed, it was postulated that the curb traffic distribution follows some form of discrete probability distribution. From the analysis it was found that the best function that could fit the data properly was the binomial distribution as a function of the number of spaces and the relative location of the door from the entrance ramp as follows:

$$f_x = \frac{n!}{x!(n-x)!} p^x(1-p)^{n-x}$$

$$x = 0, 1, 2, 3, \ldots n \qquad (16)$$

where

f_x = percentage of curb traffic distribution at xth section from entrance ramp,
n = total number of sections available at enplaning curb,
p = ratio of door location space to total number of spaces (x_D/n), and
x = section number from entrance ramp.

Calibration of Traffic Distribution Model

Although the trend represented by the distribution held for the four specified airports, the extent to which the model can replicate the existing situations is another important aspect to consider. Statistical tests such as the two-tailed F-test and the two-tailed Student t-test were performed. The STATGRAGHICS program using the least-squares method was run between observed and predicted values. At the 5.0 percent level of significance, the Student t- and F-test values were much greater than the critical values obtained from the statistical tables (*10,11*). The coefficient of correlation (r), which shows the degree of linear relationship between the observed and predicted values, was defined as the degree of predictability of the model; it was close to 1 for all four airports.

WEIGHTING DISTRIBUTION MODEL

In a very small airport at which not more than one door is needed, there would be no problem because all traffic must use the same door. But in larger airports with more than one entrance door, the traffic will be split among the doors. Finding the degree of split or the traffic distribution among the doors was an important task. From the field observations it was found that for car drivers, doors close to the entrance ramp have more weight than doors away from the entrance ramp. Drivers tend to stop at the first space they find, for they normally do not know the situation ahead. Because of the foregoing reasons the distribution function among the doors is called the "weighting function."

In this case, since the number of doors is limited, a discrete probability distribution must be considered. Because the model is based on users' behavior, a comprehensive survey must be undertaken to find the distribution. Financial and time constraints prohibited the collection of new data. Therefore, data previously collected by Mo from two large airports, Montreal International Airport (MIA) and Toronto International Airport (TIA), were used to calibrate and validate the function (*12*). On the basis of observations from the field, it was postulated that for an airport with more than one door, the drivers' preference function can be expressed as some form of modified binomial distribution as follows:

$$w_y = \frac{k!}{y!(k-y)!} q^y(1-q)^{k-y} + \frac{(1-q)^k}{k}$$

$$y = 1, 2, 3, \ldots k \qquad (17)$$

where

w_y = percentage of total traffic distribution around yth door,
y = sequential door number starting from entrance ramp,
k = total number of doors at curb, and
q = relative location of first door over total number of doors ($q = 1.0/k$).

In contrast to the binomial distribution, the weighting function is always decreasing and shows the descending weights of the doors away from the entrance ramp. It starts from a value and tends to zero, and its maximum value always occurs at the first door.

For the calibration and validation process, the theoretical data must be compared with the observed data from the field. First, the predicted values are obtained from the two models that have been developed as follows:

1. From Equation 16, find the traffic distribution for each door without considering the effect of adjacent doors.
2. Calculate the weight of each door from Equation 17 (weighting function).
3. Multiply the traffic distribution numbers for each door by their own weight.
4. For each parking space, sum up the numbers obtained from Step 3; finally, these values would be the predicted values of traffic distributed along the curb.

Figures 4 and 5 illustrate the comparison of predicted values against the observed data in the case of transborder and domestic section of enplaning curbside at MIA.

It should be noted that in any case the cumulative value of the composite function obtained from Step 4 should be 1. This is because the area under the curve consists of the total amount of traffic (100 percent) during a specified period of time. A simple regression analysis using the least-squares method was run between the observed and predicted values and the results were satisfactory. Therefore, the trend represented by the model held for two different airports with single curbs at domestic, international, and transborder sections.

PRACTICAL CAPACITY MODEL

By applying the two distributions and using the characteristics of a curbside area such as the length of the enplaning curb

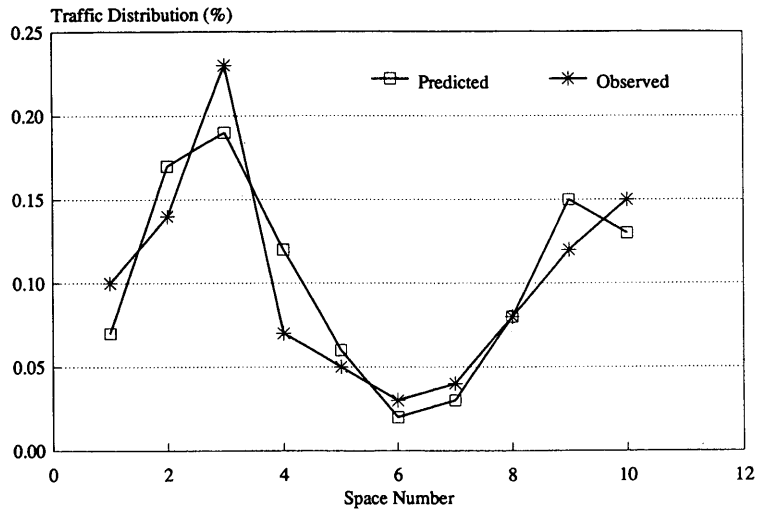


FIGURE 4 Comparison of observed and predicted values of curbside traffic distribution, transborder section, MIA.

or the location of doors, the practical capacity can be found as follows:

1. Find the values of f_x for each door according to the relative location of doors (i.e., p-values).
2. Find the values of w_y for the enplaning curb according to the number of doors (i.e., $q = 1.0/k$).
3. Multiply the values of f_x by w_y to find the traffic distribution for the whole curb (e.g., G_x).
4. Assume a minimum value for the percentage of traffic that is expected to be distributed along the curb [e.g., ($G_x = 0.0$)] and count the number of spaces above the minimum value, that is, effective number (N_{eff}). The term "effective" depends on the minimum percentage of traffic that one expects to be parked at any section of the enplaning curb. Therefore, the criterion for the effective number of spaces is the desired minimum percentage of total traffic at any section.
5. Estimate an average speed and service time according to the historical data, experience, or the airport's policies.
6. Substitute all those numbers in the capacity model (Equation 15) and find the upper volume of traffic that can be handled practically at the curbside area.
7. Calculate the maximum dynamic capacity of the curbside area during time period T from the following equation:

$$C_{\text{practical}} = \frac{N_{\text{eff}}\left(T - \dfrac{L}{v}\right)}{\tau + \dfrac{N_{\text{eff}}(\alpha)}{v}} \tag{18}$$

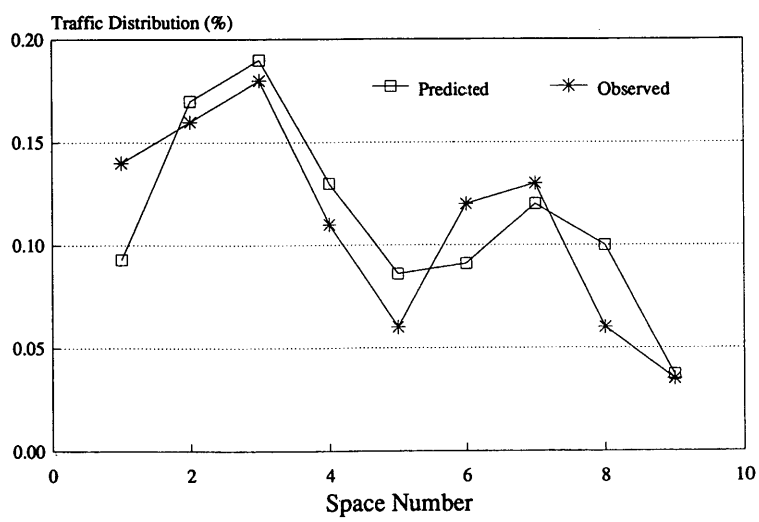


FIGURE 5 Comparison of observed and predicted values of curbside traffic distribution, domestic section, MIA.

where

$C_{practical}$ = practical dynamic capacity of curbside area (veh/hr),
N_{eff} = effective number of spaces,
T = specified period of time (min),
L = length of enplaning curbside area (m),
v = average speed of vehicles in area (m/min),
τ = average service time (min), and
α = average influence length of vehicles (m).

A computer program was written to calculate the capacity of the curbside area under different conditions.

The development of the model includes a validation procedure to assess its ability to calculate the dynamic capacity of the enplaning curbside area at different airports. As mentioned earlier, the model for ideal capacity was based on the theory of time-space and there was nothing to validate. The model for calculating practical capacity was based on the theory of traffic operations at the curbs. Therefore, the theoretical results of the model should be compared with the observed data from different fields.

Since the system under consideration was taken to be a two-lane linear curbside area, MIA and TIA were used for the validation process. Because of financial and time constraints, it was decided to use the data that had already been collected for different airports at their request. For TIA a 24-hr survey was done at the enplaning curbside of Terminal 2 on February 19 and 20, 1991, to get the percentage of through traffic. In addition to the percentage of vehicles that did not unload at the curb or that used the 23 short-term parking meters, the total volume of inbound traffic for each 15 min was counted. The validation procedure is summarized as follows:

1. The characteristics of the curbside area such as the total number of spaces and number and the location of doors for each section were obtained from the site. The minimum percentage of traffic that one expects to be parked at any space depends on engineering judgment. To generalize the concept of minimum value, it is suggested that a tenth of the maximum percentage of traffic distribution be considered. Using these numbers the traffic distribution of the whole curb and the effective number of spaces were found.
2. The average service time and the average influence length for the system were computed by means of the modal split model. The 30 km/hr was considered to be the average driving speed of vehicles. Applying these numbers to the capacity model (Equation 18), the practical capacity of the system was obtained.
3. Finally, the value obtained from the model was compared with the maximum volumes of traffic counted during a continuous period of time (e.g., 1 day, week, month, etc.). If the maximum observed value from the field is less than the value obtained from the capacity model, the validation process is complete. This procedure is applied to the two busiest airports in Canada, which meet the assumptions of the model.

Montreal International Airport (Dorval)

The transborder and domestic sections of the enplaning curbside area were considered for validation. The required data for validation were extracted elsewhere (*13*). The part of the curb length that can be used freely by drivers is 168 m. Using the distributions and the modal split model, the following variables were obtained:

- Effective number of spaces, N_{eff} = 19;
- Weighted average service time, τ = 1.4 min;
- Weighted average influence length of vehicles, α = 8.69 m;
- Average driving speed, v = 500 m/min; and
- Specific period of time, T = 60 min.

Substituting these values into Equation 18, the practical dynamic capacity of the system was found as follows:

$$C_{practical} = \frac{19\left(60 - \frac{168}{500}\right)}{1.4 + \frac{19(8.69)}{500}} = 655 \text{ vehicles per hour} \quad (19)$$

Compare this to the maximum observed value of 584 vehicles per hour (vph). This number can be referred to as the maximum number of vehicles that can be handled by the system during 1 hr.

Standard counts of vehicle volumes made by the planning division of MIA using a loop or pneumatic tube detector were used as the observed data. The maximum daily traffic during 1 week was plotted against the practical capacity value and is shown in Figure 6. Although the traffic counts consist of the number of vehicles that stopped at the spaces allocated for official use and through traffic, they are still lower than the capacity value.

Toronto International Airport, Terminal 2

The enplaning curbside area of Terminal 2 was considered for validation. The required data for validation were extracted elsewhere (*14*). Using the distributions and the modal split model the following values were obtained:

- Effective number of spaces, N_{eff} = 52;
- Length of curbside area, L = 440 m;
- Weighted average service time, τ = 1.69 min;
- Weighted average influence length of vehicles, α = 8.07 m;
- Average driving speed of vehicles, v = 500 m/min; and
- Specific period of time, T = 60 min.

Substituting these values into Equation 18, the practical dynamic capacity of the system was obtained as follows:

$$C_{practical} = \frac{52\left(60 - \frac{440}{500}\right)}{1.69 + \frac{52(8.07)}{500}} = 1{,}215 \text{ vph} \quad (20)$$

Compare this to the maximum observed value of 715 vph. This number can be referred to as the practical dynamic capacity of the enplaning curbside area during 1 hr.

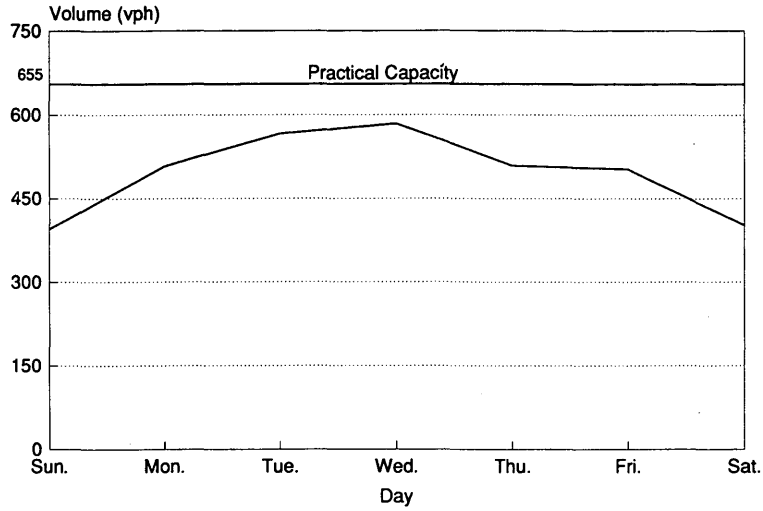


FIGURE 6 Comparison of daily peak-hour traffic and capacity at enplaning curbside of MIA.

Two sources of data were used for validation: first, automatic traffic recorder (ATR) counts conducted by the planning division of TIA during 7 continuous days (*14*); and second, a 24-hr survey in February 1991 just before the opening of Terminal 3. The maximum peak-hour traffic of each day was extracted from the data, and it is shown against the capacity in Figure 7. During the recent survey the total number of vehicles for each 15-min period was counted manually on the approach to the departure curb at Terminal 2. Data were cumulated for each hour, and the results are shown in Figure 8. As shown in both figures, the maximum values are much less than the value obtained from the capacity model. As a result, the model is valid for any airport that meets the assumptions of the model. These results do not necessarily mean that there should not be any congestion problem at these airports. For instance, at TIA, drivers experience congestion during peak hours at enplaning curbside of Terminal 2 despite excess capacity. This is because of the usage of the third lane as a short-term parking, existence of pedestrian crossing, unequal distribution of airlines inside the terminal building, and curbside mixed operation (i.e., bus, car, taxi, and limousine).

MODEL APPLICATIONS IN DESIGN PROCESS

The findings of the study can also be used to consider the interaction between curb use and terminal layout so as to design a curbside area that achieves a more efficient operation: the terminal design can be optimized by applying the drivers' behavior to the design process. Optimization refers to the process of finding the minimum number of doors and their locations to maximize the efficiency of the curbside area

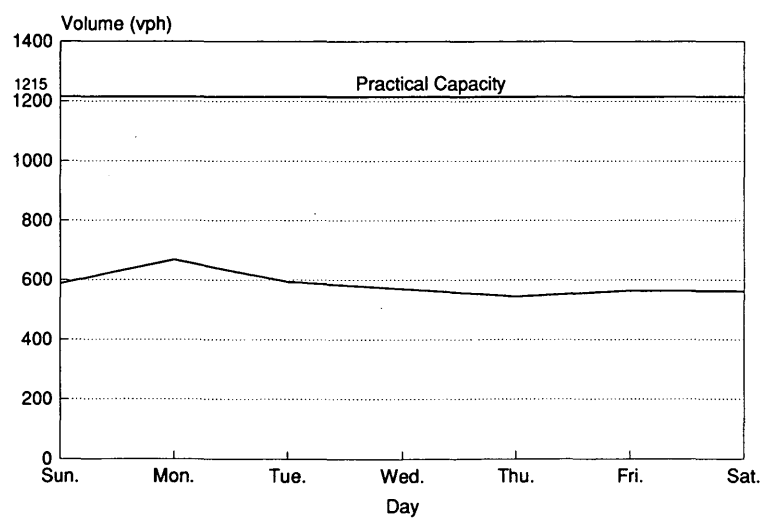


FIGURE 7 Comparison of daily peak-hour traffic and capacity at enplaning curbside of Terminal 2, TIA.

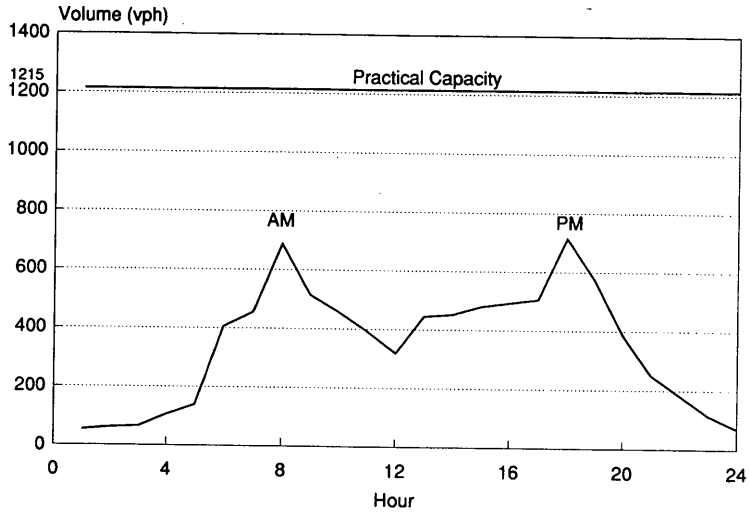


FIGURE 8 Comparison of hourly traffic volume and capacity at enplaning curbside of Terminal 2, TIA.

at a particular airport. This is achieved by assuming a minimum design value (i.e., a minimum percentage of traffic that one expects to be parked at any parking space) and changing the terminal layout so that none of its curb spaces has a traffic value of less than minimum value. The optimization process is very important in large airports at which there is a high volume of traffic. The results of the optimum design procedure can be used to develop a new method for the planning and design of the curbside area.

CONCLUSIONS

The following conclusions are drawn from this research:

- The ideal and practical capacity of the existing enplaning curbside areas can be determined more realistically with the developed model than with other methods.
- A strong relationship was discovered between the terminal layout and the dynamic capacity of the curb. Physical characteristics of the curb such as number and location of the doors, number of lanes, and length of the curbs should be considered in any capacity calculation.
- Probabilistic functions for door traffic distribution and users' preference of doors (i.e., weighting functions) were found to be binomial and modified binomial distributions.
- From the weighting function, it was found that the values of distribution for a large numbers of y (i.e., a sequential number of doors) are zero, meaning that the number of usable doors is limited. (The term usable refers to the doors that can handle a portion of traffic greater than the minimum design value.)
- The distribution models may be used to find the bottlenecks along the curbside area. If the traffic has not been distributed uniformly, the layout may be modified to increase curb use.
- Increasing the length of the terminal building has a negative effect on the dynamic capacity of the curbside area. Therefore, to increase the capacity, instead of lengthening the curbside, the whole curbside area should be duplicated in parallel with the existing curb.
- The number of doors or service facilities along the curbside are no longer of architectural interest only. In reality, they are traffic distributors along the curb and if judiciously placed will enhance the operation of the curb.

RECOMMENDATIONS

- The model was based on a two-lane linear curbside area. More research should be done in airports with more than two lanes and with and without pedestrian refuge islands.
- The effect of pedestrian refuge islands in multilane curbside areas should be studied, and the percentage of increase in capacity should be determined.
- Since the capacity obtained from the model is limited to a single number under any condition, a consistent level of service beyond which delay and congestion are intolerable should be identified by experts for the curbside of different functional categories. This can be achieved by basing judgments on observations and people's perceptions and reactions to delay and congestion. Therefore, instead of a minimum value as a criterion for practical capacity, a level-of-service framework can be found at different levels of demand.

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