REFERENCE

1. Automatic Fare Collection Property Evaluation Plan. Input Output Computer Services, Inc., Waltham, MA, Draft Rept., Sept. 1980.

Publication of this paper sponsored by Committee on Rail Transit Systems.

Effect of Crowding on Light Rail Passenger Boarding Times

MARSHALL S. FRITZ

Passenger congestion may have important effects on passenger level of service and station stop or dwell times. In order to examine this concept, research on boarding and alighting times of passengers on light rail vehicles was conducted by sampling rush-hour operations on the Presidents' Conference Committee vehicles of the Massachusetts Bay Transportation Authority's (MBTA) Green Line, a high-volume, light rail subway-surface line. The boarding process is emphasized here, but similar treatment has been undertaken for alighting. Linear regression relations were calibrated between the number of passengers boarding per unit time and concurrent passenger counts (or densities) on board the vehicle and on the platform. These alternatively formulated models reflect the trends in the raw data that the boarding rates decline markedly under increasing congestion, especially as the space per standee falls below the often used nominal standee space level of 2.7 ft^2/standee and approaches crush-capacity density of 1.5 ft^2/standee. On the other hand, at freer circulation levels, these models provide predictions quite similar to predictions from constant-service-time models frequently formulated in earlier research. The modeling approach and subsequent results can be absorbed in future research and operational endeavors for MBTA, for other operating authorities, and for vehicle manufacturers in (a) quantifying the effects of passenger congestion on travel time and reliability, (b) permitting more refined simulation models of travel time, (c) providing a practical approach toward evaluation of realistic vehicle capacity through knowledge of circulation difficulties manifested in low boarding rates, (d) supporting short-term and low-cost operational measures to alleviate frequent problems of rush-hour service, and (e) planning new system or rolling stock requirements.

This paper is based on earlier research (1) and consists of an abridgment of coverage of that work. In particular, the emphasis given here is on the boarding process where only one of the vehicle doors is in use to process passengers who are queued to enter or exit the vehicle. The original work also covered the alighting process, as well as further treatment of multiple doors in processing passengers.

Congestion may have an important impact on station stop or dwell times. As passengers board, they must circulate on board to their respective resting positions to sit or stand. Passenger congestion may prevent passengers from circulating within the vehicle as freely as they would desire without interactions. One can term this relative freedom, or ability to circulate, as the circulation potential. Several authors (2-4) have found a reduction in flow rate, or the number passing through the doors in unit time, when standees are present; however, fluctuations in flow rate parametrically related to varying passenger densities (passengers per unit area of floor space) have not been established. Moreover, only limited attention has been given to studies of light or heavy rail systems or of bus transit corridors where high passenger densities are the rule rather than the exception. The focus of this study extends models of passenger service time--the dwell-time components related to boarding and alighting--to include high-density situations; subsequently, passenger service times in both high- and low-density situations are compared.

Indeed, actual circulation patterns on board the vehicle are difficult to quantify. Kraft (3), in his development of passenger vehicle interface (PVI), hypothesized that the manifestations of passenger-passenger and passenger-vehicle interface might be reflected in the rate at which groups of passengers enter or exit the vehicle. Possibly, low-circulation potential might be reflected in slower passenger service times--quantities that are relatively more amenable to measurement than circulation patterns themselves.

Experimental designs must be carefully chosen if results and conclusions are to be generic in nature. For example, boarding observations of vehicles with fare payment, which are typical of most of the previous studies, involve access to the vehicle, the fare payment itself, and access to the vehicle interior. However, time-consuming fare payments may confound any congestion effect due to access times.

In order to fill this research gap, and at the same time select an appropriate sampling frame, the Massachusetts Bay Transportation Authority's (MBTA) Green Line, a network of high-volume light rail routes that merge in the Central Subway, was selected as the site at which to investigate possible impacts of passenger-vehicle interaction on passenger service times under congested conditions. Several pertinent reasons accompanied the choice of the Green Line:

1. Long dwell times that constitute a high percentage of travel time (2);
2. High daily rush-hour passenger volumes (2);
3. Prepaid fares that eliminate the need to stop and pay on board;
4. MBTA's President's Conference Committee (PCC) fleet (the Boeing Standard Light Rail Vehicle fleet was not yet in operation at the time this study was initiated), which is an historical and well-used vehicle that is still in use there and elsewhere; and
5. Unique platform berth variations for comparative analysis when one, two, or three doors per vehicle are in use at a given station.

By expanding on Kraft's PVI dwell-time studies concept, this focused sampling frame, with several variables controlled, was used in producing a generic modeling approach for better understanding the effects of passenger congestion. Two proxy variables, observable or estimable from the platform, were selected to reflect circulation potential and level of service: passenger flow rates at the vehicle door, and the estimated passenger load volumes on board the vehicle, respectively. The latter are inversely proportional to standee densities.

After the data-collection phase of the study was completed, two modeling approaches were examined (each calibrated through linear regression) to predict the passenger service time on light rail vehicles: (a) the total dwell time required to board and/or alight all waiting passengers (the traditional model, which assumes constant boarding rates for each additional, or marginal, passenger), and (b) the time required for each passenger to board and/or alight given concurrent environmental conditions (the alternative set of models where, for example, high and low congestion levels are taken into account). The second approach is an extension of the first approach into more widely ranging passenger processing situations than previously undertaken. Even though derived from an alternative point of view, dwell-time predictions will be similar when passenger density is low. The conceptual framework developed here with the alternate models may prove potentially useful as an aid to researchers and transit operators in evaluating impacts of high-density patronage and interacting system components on level of service.

BACKGROUND

Research studies from the available literature were found to deal with two quantities relevant to passenger congestion and dwell-time delays: passenger density and passenger service times. These quantities relate to both pedestrian and transit network levels of service. However, no definitive studies were found that analyze passenger congestion effects when congestion is high.

Level-of-Service Concept

The transit system level-of-service (LOS) concept includes three criteria relevant here: travel time, reliability, and passenger density. Although MBTA, for example, uses a standard standee space allowance of 1.5 ft^2 in assessing vehicle capacity, Alter (5, p. 38) maintains that even 2.1 ft^2/standee should be avoided in actual operations due to the high level of physical interactions between passengers on board at these high densities.

Going beyond these authors, Fruin (6) concentrated on pedestrian LOS. A number of his approaches and findings are of great use in planning and evaluating transit system components such as passageways, stairways, bus and light rail vehicle stairwells, queuing at vehicle berths, and on board standing conditions. Furthermore, his descriptions of movement potential at various densities provide an alternate check on evaluating dwell-time model results under various operating conditions. By using Fruin's terminology, the type of queues found on the subway platform are "bulk" queues, which are unordered and without queue discipline, whereas "lineal ordered" queues are first-in, first-out type queues typically found at ticket counters. Fruin segmented pedestrian standee spacing into six zones (6, pp. 85-87), depending on the degree of bodily contact and possible circulation. The zone names are free circulation, restricted circulation, personal comfort, no-touch, touch, and body ellipse; the latter corresponds to an area of less than 2 ft^2, with ensuing physical and psychological discomfort. The two measures used most often to rate vehicle capacity--design capacity and crush capacity--fall into the touch and body ellipse zones, respectively. Design capacity has been characterized as a standing load with a minimum freedom of movement, typically 2.7 ft^2/standee (7), when specified. Crush capacity has been defined as the maximum passenger capacity of a vehicle such that a passenger can still board without causing serious discomfort to other passengers; 1.5 ft^2/standee is MBTA's standard.

Passenger Service-Time Studies

Although there have been numerous efforts in the United States and Great Britain (3,4,8) to study the boarding and alighting process characteristics of fare-paying passengers on buses, most of the limited studies available that examine light rail (3,8) capture these latter modes under operations more typical of the bus mode (i.e., fare paying on board, moderate patronage levels) than of high-volume rail lines; hence, opportunities to transfer results to the high-volume Green Line may be limited. Simple regression models, with average service time per passenger to board and alight, were generally calibrated. Among the significant factors found were fare systems, vehicle access, personal effects carried, presence or absence of standees, and vehicle type.

Kraft (3) developed the PVI, which is measured in terms of passenger service time, to denote the interaction between passengers and transit system elements while passengers board or alight. The presence and impact of PVI was tested under several service conditions, such as whether passengers were boarding only, alighting only, or both simultaneously; varying door geometries; the type of passenger; and varying fare-collection systems.

Kraft, in his Newark PCC dwell-time studies, notes that passenger service times may not have been affected if only a few standees were present and they did not hinder movement. In searching for a generalized approach, Kraft (3, p. 163) quotes Radelat (4): "No definite effect can be detected from the presence of standees....It could be possible that the retarding effect of the standees is stronger as their number increases, but this possibility could not be investigated for lack of data." Kraft recommends data collection and models to "relate the density of standees with changes in the passenger service requirements" (3, p. 148). The design selected for this Green Line study has attempted to fulfill this need to extend the research sampling frame into situations with more limited circulation potential.

DATA COLLECTION

PCC vehicles at several high-volume MBTA Green Line stations were surveyed during January 1975 under normal, but not adverse, winter weather. Several important characteristics of the data-collection process are noted here. Most of the detailed passenger transaction observations were made at the Park Street and Government Center stations, the two heaviest volume stations. A significant number of observations were of vehicles berthed with only the left center door open for passenger processing. Time intervals of 10 seconds (s) for recording passenger transactions were chosen as a practical compromise between human recording accuracy and the aforementioned need for collecting data on intervals short enough to discover dynamic effects as congestion builds. In order to capture information on arrival and departure loads, scale values of 1 to 5 were used as indices to represent the range of 0 to 142 passengers possible on the newer PCC vehicles.

MODEL CALIBRATION

Model Approaches

The passenger processing information permitted the establishment of two data set formats for use in the analysis: (a) disaggregated, 10-s passenger counts for each individual door of the vehicle, and (b) aggregation of the above 10-s counts into total time and total passenger counts for each door monitored. The analysis here concentrates on vehicles with a single left rear door operating at the station berth, with some mention of vehicles with two right-side doors open.

One of the objectives of this research was to test hypotheses relating to retarding effects of passenger congestion on dwell time. The aggregate or traditional approaches have assumed, or implied, that boarding and alighting rates are constant throughout the dwell-time period. In order to test the alternative retarding-effect hypothesis, the disaggregated data were used to observe dynamically changing conditions during the dwell-time period. The disaggregate models, as formulated, can accommodate effects such as bulk queues with pressure on those at the head of the queue, changing circulation potential as passenger density increases, and passengers turned away when doors of a fully loaded train close.

Two approaches were pursued to calibrate regression models of passenger processing: (a) the traditional linear regression model that uses aggregate boarding and alighting counts to predict dwell-time components, and (b) alternative formulations calibrated on the disaggregated data to explain variations in observed rates due to other observable variables that undergo changes during the dwell-time period. Simple algorithms based on these models can be developed to predict dwell time.

Aggregate Model Calibrations

Calibration of the traditional dwell-time modeling approach used aggregate counts of passengers boarding or alighting at each door. These simple models are limited by the implicit assumption that both free circulation passenger processing and passenger processing under congestion can be modeled by using a single constant rate of passenger flow. Scattergram plots (not shown) suggested that the calibrated straight-line curves underestimate passenger processing times at higher boarding counts where congestion is necessarily on the increase, despite R^2 statistics in the range of 0.8-0.9 and tight fits at lower boarding counts. Consequently, there may be other important variables not being considered in these formulations to explain the possible model bias.

Disaggregate Data Subset Handling

The raw data, which consist of the original 10-s observations, were classified according to subclasses such as vehicle vintage, door observed, whether standing room only was present, and number of doors available at the particular platform observed. The significant variables that were used in the disaggregate models are given below to explain the variation in the dependent variable RATE:

1. RATE: RATE(N) is the passenger processing rate, or observed number of passengers being processed during the Nth 10-s interval.
2. PASS: PASS(N) is the current estimated on board passenger count at the end of N time intervals. Subsequent values of PASS depend on net passenger count changes.
3. REM: REM(N) represents the number of passengers still remaining on the platform in front of each operating door at the end of N time intervals waiting to board. REM measures a hypothetical affect of the pressure exerted on those in front of the queue about to board. Such impact could be both physical or psychological in nature.
4. SEQ: SEQ represents the sequence number (e.g., N) of the observed passenger boarding interval and relates any effects that are dynamic in a temporal sense.
5. FRONT: FRONT is a dummy variable that represents differences between the boarding rates at the right front (FRONT = 1) and right center (FRONT = 0) doors of the PCC vehicles. Adams (2) notes that circulation patterns at the front, center, and rear of the cars are different.
6. REMSQ: REMSQ = REM * REM (quadratic REM term).
7. PASSREM: PASSREM = PASS * REM (interactive term).

Disaggregate Model Calibrations

For each of the striated data subsets, the variables on board passenger load (PASS), passengers still waiting on platform (REM), and the 10-s interval sequence number (SEQ) were individually examined for univariate relations with the boarding rate (RATE). RATE, PASS, and REM are variables that continuously change during the dwell-time period and cannot be incorporated in the aggregate model. Subsequently, multivariate relations that use the variables listed above (items 1-7) were also tested. For each data subset, the following generalized hypothesis was tested by using the Statistical Package for the Social Sciences (SPSS) REGRESSION procedure:

> H_0: The variation in the boarding rate (RATE) is not explained by any one of the six variables, either taken individually or in groups. Moreover, there is no statistically significant improvement offered by any linear combination of these variables over the model where RATE remains constant.

All models shown in Table 1 are significant, as are all variables in the multivariate models. Therefore, H_0 can be rejected for each of the data subsets examined, inasmuch as at least one linear combination of variables, and often several, were significant within each data set. The general trends of the decreasing marginal boarding rate--the rate for each successive boarding passenger that decreases as passenger density increases--appear both graphically strong and statistically strong, as evidenced by the sample scattergram in Figure 1 and the F statistics in Table 1. [Note, for Figure 1, the plot, which is based on left-center-door observations of the pre-1951 car, shows the general trend of monotonically decreasing boarding rates (RATE) as the on board passenger load volume (PASS) increases and approaches crush capacity. The calibrated regression line for these points is RATE = 13.51 - 0.0883 * PASS.]

The univariate regressions of Table 1 of the form RATE = $b_0 + b_i * x_i$ were further examined. As may be seen from Table 2, several consistent patterns in the coefficient values were found. These are briefly described below:

1. The univariate relations between RATE and PASS for heavy-load boarding are reasonably uniform within each of the single door data subsets.
2. The generally consistent and positive values of b_{REM} suggest a pressure-induced increase in boarding rates when the bulk queues are larger.
3. Light-load boarding situations appear only to be explained by linear and quadratic functions of REM, except in the case of the pre-1951 car (left center door) light-load situation where PASS, too, was significant. This justifies testing REM for significance in other multivariate heavy-load hypotheses.

Table 1. Regression calibrations: variables and model statistics.

Data Set			Sample	Variables Included		
Car	Door[a]	Load[b]	Size	in Equation	R^2	F
Pre-1951	LC	Light	76	REM	0.554	91.9
				PASS	0.241	23.5
				REM, REMSQ	0.648	67.2
1951 era	LC	Light	17	REM	0.677	31.4
Pre-1951	LC	Heavy	329	SEQ	0.509	338.5
				PASS	0.429	245.8
				REM	0.239	102.4
				PASS, REM, SEQ, PASSREM	0.574	109.3
1951 era	LC	Heavy	125	SEQ	0.412	86.2
				REM	0.336	62.3
				PASS	0.294	51.1
				SEQ, REM, REMSQ, PASS	0.625	50.0
Pre-1951	RC	Heavy	111	PASS	0.466	95.1
				REM	0.391	70.0
Pre-1951	RF	Heavy	100	PASS	0.430	73.8
				REM	0.257	33.9
Pre-1951	RC and RF	Heavy	211	PASS, REM, REMSQ, FRONT	0.625	86.0

Note: The variable sets included here cover both significant univariate equations and significant multivariate equations with at most four variables and the highest R^2 statistics at that depth. The data subsets shown here focus on those vehicles berthed such that only the left door was open for passenger processing. As a guide to the significance testing, $F^{1,60}_{0.05} = 4.0$.
[a]LC = left center, RC = right center, and RF = right front.
[b]Heavy = standees among the newly boarding passengers and light = all newly boarding passengers guaranteed seats.

Figure 1. Scattergram plot for boarding rate versus PASS, the on board passenger load.

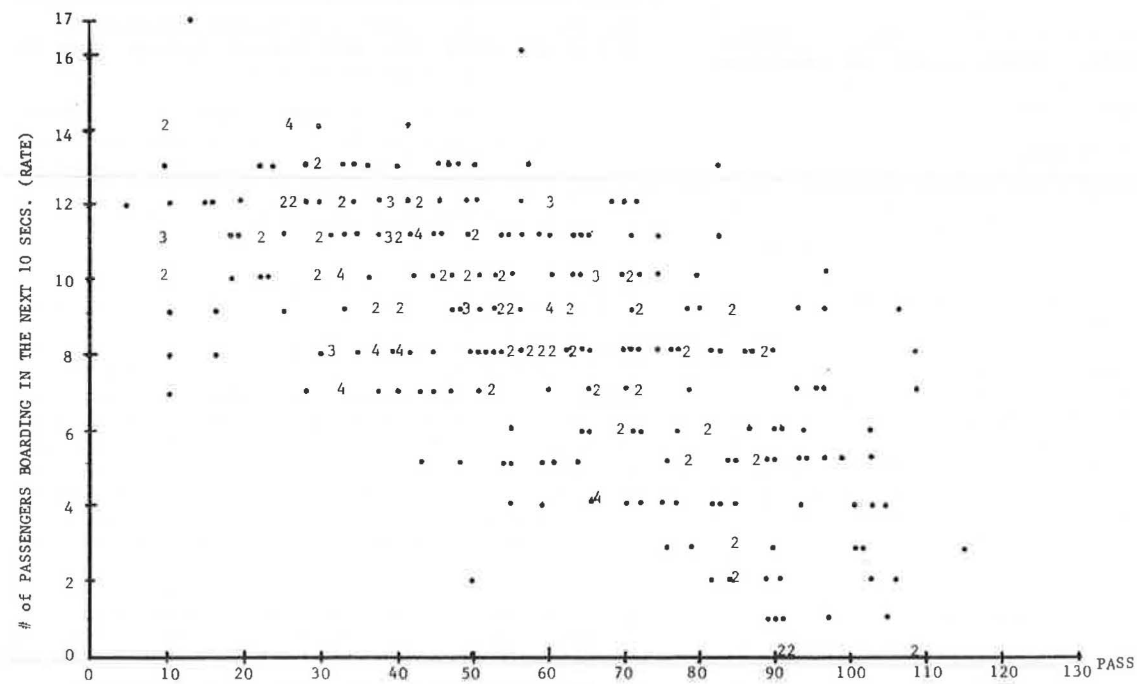


Table 2. Univariate regression coefficients for disaggregate model calibrations.

Data Subset			Independent			Standard
Car	Door[a]	Load[b]	Variable i	b_0	b_i	Error
Pre-1951	LC	Heavy	SEQ	12.15	−0.997	0.054 0
1951 era	LC	Heavy	SEQ	11.81	−1.192	0.128 0
Pre-1951	LC	Light	PASS	11.93	−0.186	0.038 4
Pre-1951	LC	Heavy	PASS	13.51	−0.0883	0.005 63
1951 era	LC	Heavy	PASS	12.25	−0.0608	0.008 50
Pre-1951	RC	Heavy	PASS	12.09	−0.0811	0.008 32
Pre-1951	RF	Heavy	PASS	9.85	−0.0673	0.007 83
Pre-1951	LC	Light	REM	4.40	0.323	0.033 7
1951 era	LC	Light	REM	5.25	0.236	0.042 1
Pre-1951	LC	Heavy	REM	3.90	0.154	0.015 2
1951 era	LC	Heavy	REM	5.04	0.112	0.015 1
Pre-1951	RC	Heavy	REM	4.77	0.148	0.017 7
Pre-1951	RF	Heavy	REM	3.86	0.128	0.022 0

Note: These models are of the form $RATE = b_0 + b_i * x_i$. The standard errors of the independent variable coefficients are also shown. Only RATE models for boarding are shown in this table.
[a]LC = left center, RC = right center, and RF = right front.
[b]Heavy = standees among the newly boarding passengers, and light = all newly boarding passengers guaranteed seats.

4. Compared with the pre-1951 vehicles, the more spacious 1951-era vehicles exhibited less of a drop-off in boarding rates with equal numbers of standees.
5. Although the coefficients of the examined multivariate regressions are not shown here, the signs of b_{PASS}, b_{REM}, and b_{SEQ}, as would be expected from the univariate equations, exhibit reasonable and desirable coefficient "stability" among the regressions.
6. In addition, significant relations for alighting and multidoor boarding were also found and are described in greater detail in Fritz (1).

PREDICTIONS BY USING PASSENGER FLOW-RATE MODELS

Methods for Prediction

The calibrations of the alternative models suggest that the selected variables (PASS, REM, SEQ, FRONT, REMSQ, and PASSREM) explain significant amounts of the variation in RATE. The univariate equations are much simpler than the multivariate equations in both concept and ease of generalizing relations in single equation solutions. Therefore, univariate equations would be useful to the planner who would desire to use easily understood relations to predict dwell times and passenger flow rates (albeit with some loss of accuracy) and to examine whether the statistical significance noted is of practical significance.

Given the calibrations for boarding RATE, as discussed in the previous section, two methods of generating predictions of the number of passengers on board at a future time have been developed by making recursive calculations or by solving difference equations. Although the focus here is on the left center door, and multidoor situations are more complex, statistical techniques were used in Fritz (1) to predict the expected value of dwell time for multidoor vehicles with imbalanced queues among the doors (i.e., the likely case where one door dominates over the others in passenger count and/or passenger service times). Uneven door use can contribute significantly to the existence of greatly protracted dwell times.

Method 1

Simple recursive estimates for either univariate or multivariate regressions, regardless of whether it is a closed-form solution, are possible. For example, the basic equation that relates RATE and PASS as calibrated from the raw disaggregate data is

$$RATE_N = b_{PASS} * PASS_{N-1} + b_0 \quad (1)$$

Adding $PASS_{N-1} + RATE_N$ and collecting terms gives a recursive relation:

$$PASS_N = (b_{PASS} + 1) * PASS_{N-1} + b_0 \quad (2)$$

Method 2

Method 2 is a generalization of method 1 as a difference equation solution for simple cases. The difference equation exemplified by Equation 2 has a unique, closed-form solution:

$$PASS_N = (b_{PASS} + 1)^N * PASS_0 + (b_0/b_{PASS}) * [(b_{PASS} + 1)^N - 1] \quad (3)$$

Solving for N,

$$N = \log [(PASS_N + b_0/b_{PASS})/(PASS_0 + b_0/b_{PASS})] / \log (b_{PASS} + 1) \quad (4)$$

Point-Estimate Predictions

A series of point-estimate predictions were undertaken, which focused on (a) marginal rates (by using Equation 1), and (b) total passenger processing times and average rates given initial conditions of $PASS_0$ and REM_0 (by using Equations 3 and 4). Key load volumes (passengers per vehicle), which cover a wide range of conditions, were selected for use as boundary conditions in the predictions:

0 = vehicle is empty on arrival,
42 = all seats are occupied,
75 = mean passenger count for index scale level 4 (see section on Data Collection),
91 = estimated design capacity for pre-1951 vehicles (2.7 ft²/standee),
95 = mean passenger count for index level 5 (see section on Data Collection), and
130 = pre-1951 vehicle crush capacity based on the MBTA's standard of 1.5 ft²/standee.

Pairs of initial and final load volumes were selected from among these volume levels; total passenger processing times were estimated for the number of passengers indicated in each selected scenario.

Marginal boarding rates under the various conditions are displayed in Figures 2A through E. (Note, the values of RATE shown in Figures 2A through E represent the number of PASS's estimated to board in the next 10 s after reaching the load shown. In A through D, percentages within the bars refer to the relative rates for that load volume and vehicle door combination as compared with its own empty vehicle rate. In E, rates for the left center door of A are compared with the summed rates for the right-side doors of C and D. The estimated combined boarding rate capability for the right front and center doors represents a 31-62 percent greater rate than the left center door alone, as shown in E; however, this is short of the theoretical 100 percent increase of two doors over one.) As loads increase, the trend of decreasing marginal boarding rates, as compared with rates when the vehicle is empty, is evident in Figures 2A through D, both at design and crush capacities, with 49-62 percent and 70-89 percent decreases, respectively. This approach has been used to compare the efficiency of PCC left-side boarding with right-side (right front plus right center) boarding. Figure 2E shows, in a visually comparative way, the relative estimated improvement in boarding-rate productivity that results from the multiple door arrangement; this advantage ranges from 31 to 62 percent here. This is, however, short of the 100 percent increase possible without any PVI present. In reality, queues are likely to be uneven among the open doors, which reduces this advantage further when the boarding time for the more heavily used door is estimated.

Cross validation of any model is highly desirable whenever possible. It is possible to examine the compatibility of the disaggregate model calibrations with Fruin's cited LOS zones. For example, the regression equation for the left door of the pre-1951 vehicle (RATE = 13.51 - 0.0883 * PASS) can be used to predict rates at all passenger densities. Figure 3 relates summary phrases for Fruin's narrative descriptions of crowd conditions with the rates predicted from the examined passenger densities. (Note, the negatively sloped line shown in Figure 3 is RATE = 13.51 - 0.0883 * PASS, as calibrated for the left door subset of pre-1951 vehicle data. The six line segments delineated are based on summary

Figure 2. Predicted marginal boarding rates for several passenger load volumes and vehicle door combinations.

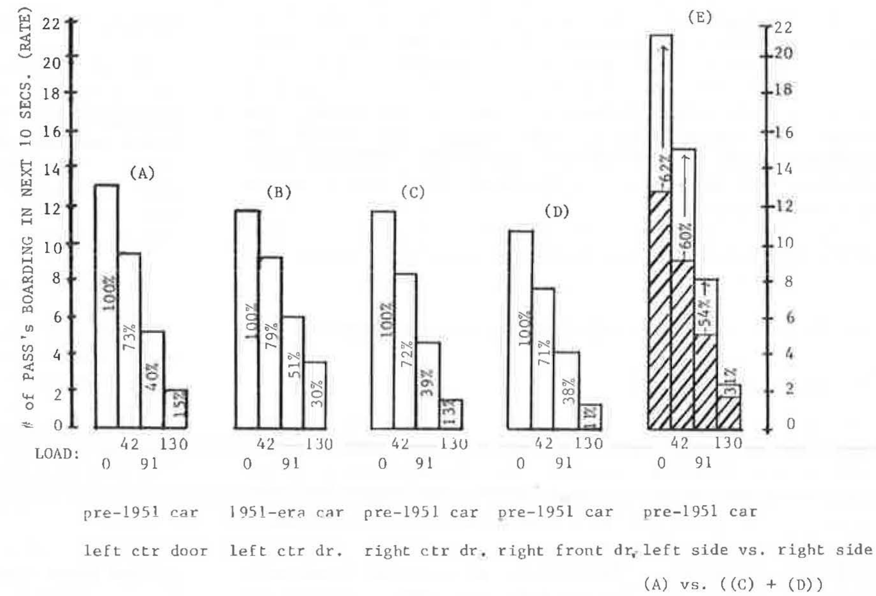
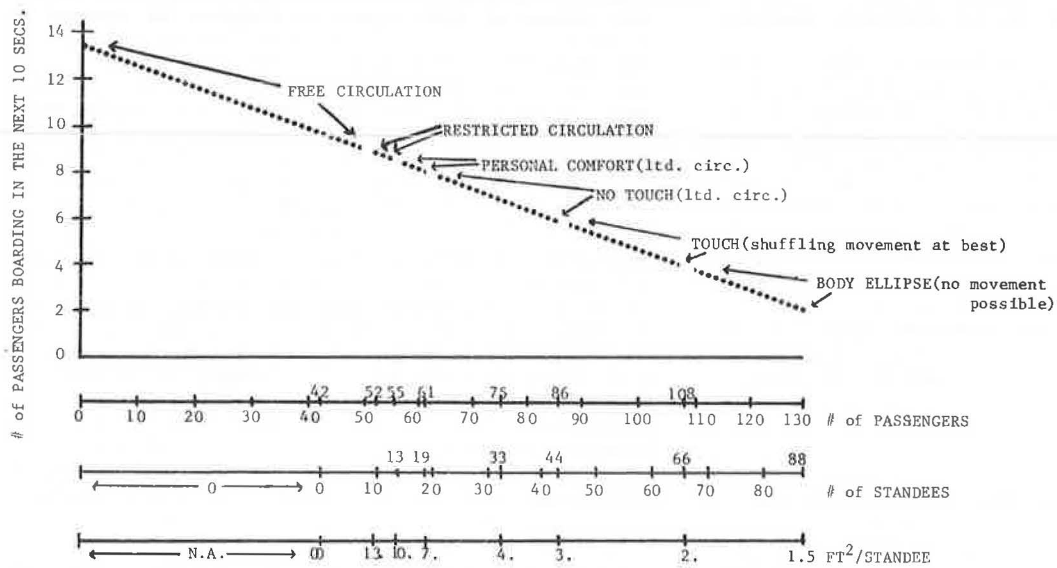


Figure 3. Comparison of Fruin's pedestrian LOS zones with predicted boarding rates.



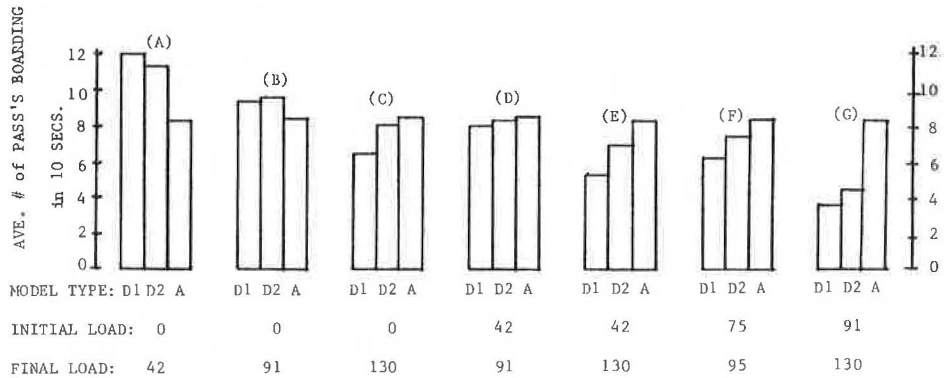
descriptions of Fruin's pedestrian zones.) The disaggregate model predicts boarding rates that range from 13.5 for an empty vehicle to 2.0 at crush capacity--both are relative to 10-s periods. Even at crush capacity, such a relatively low rate of 2 passengers/10 s reasonably coincides with Fruin's expectation that no movement can occur at crush-capacity densities. Therefore the data-collection and model calibration procedures do indeed show desirable consistency with research conducted previously. Furthermore, the existence of numerous cases where passengers were physically unable to board the vehicle due to congestion (RATE = 0) demonstrates that movement inside the vehicle is quite difficult to achieve as crush capacity is approached.

Whereas the previous figures and tables have dealt with marginal processing rates at specified loads, Figures 4A through F show predictions of average rates for one-door situations under selected, prespecified boundary conditions. [Note, the disaggregate model used the calibration solutions of RATE = f(PASS) shown in Table 2, while the aggregate model used total time = 1.86 + 1.16 * number of boarding passes. (Note the dramatic difference between Figures 4A and G.)] These scenarios begin from the initial load as the first passenger boards and end with the final load as the last passenger succeeds in boarding. Calculations were performed by using Equation 4 to obtain total boarding times. The 1951-era vehicles have more total space and can probably accommodate a given number of passengers more easily than the pre-1951 vehicles.

Figures 5A through D compare total predicted boarding times for center doors of the pre-1951 vehicle among the three models: the disaggregate model, the aggregate model based on MBTA data, and the aggregate model that uses Kraft's data from the Newark system. The latter two aggregate models exhibit marginal reciprocal boarding rates of 1.16 and 0.9 s/passenger, respectively.

These histograms are very important. As crush capacity is approached and the boarding rate drops, the growing differences between the disaggregate and the aggregate models can be clearly seen. As might

Figure 4. Comparison of average boarding rates for three models under specific passenger load conditions.

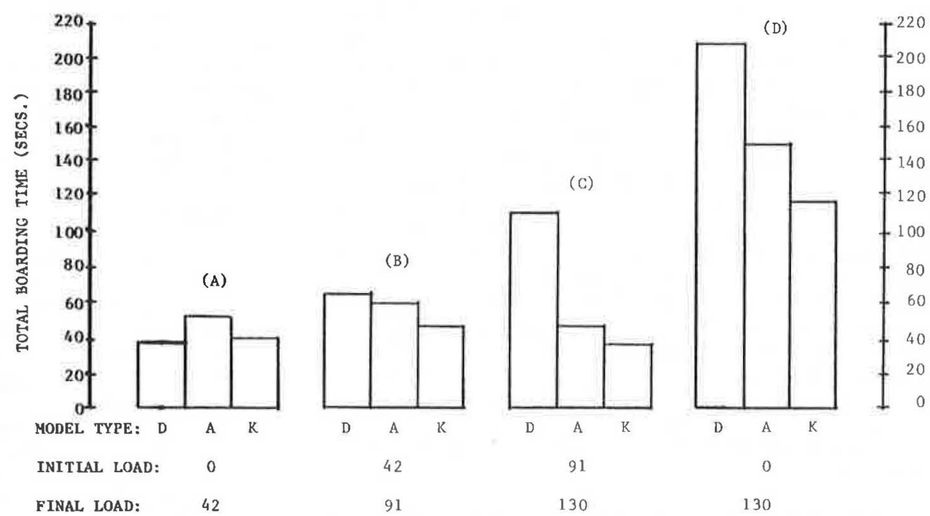


MODEL TYPE D1: Disaggregate Model pre-1951 Vehicle Left Center Door MBTA Data

MODEL TYPE D2: Disaggregate Model 1951-era Vehicle Left Center Door MBTA Data

MODEL TYPE A: Aggregate Model Either Vehicle Left Center Door MBTA Data

Figure 5. Comparison of total boarding time by using three models under specific passenger load conditions.



MODEL TYPE D: Disaggregate Model MBTA data Left Center Door pre-1951 Vehicle

MODEL TYPE A: Aggregate Model MBTA data Left Center Door pre-1951 Vehicle

MODEL TYPE K: Aggregate Model Kraft data Right Center Door pre-1951 Vehicle

be expected, the disaggregate model is similar to Kraft's model only at low passenger loads, and diverges sharply from both aggregate models above moderate loads as congestion effects build. Also, the aggregate model based on MBTA data was calibrated with higher average loads and lower rates than was true of Kraft's model, hence the probable cause of the 25-30 percent differences in rates between these two model calibrations.

CONCLUSIONS

A framework for quantifying dwell-time effects of passenger congestion has been developed. The models presented investigate whether increasing congestion exhibits a continuously retarding effect on passenger processing. It was found that there are important differences between passenger processing under light and heavy passenger loads. The most significant variables that explain the change in observed marginal passenger processing rates were passenger load volume and queue size on the platform. The univariate regression relations shown in this paper were generalized to closed-form solutions of difference equations to permit predictions of total time in which to process given numbers of passengers. From the point-estimate predictions undertaken for varying loads, several important observations can be made:

1. As passenger load volumes exceed design capacity, the passenger processing rates are considerably lower than rates at intermediate volumes. The predictions imply that, as crush capacity approaches, passengers still waiting to board may still be able to board, but extremely slowly.
2. This study independently confirms that the boarding rates Kraft found in his Newark PCC study are likely to be highly accurate for noncongested conditions in those cases where fares were prepaid.
3. Models can be calibrated by using the disaggregate data that reflect the expectation of substantially higher dwell times under congestion than previously assumed.
4. Bulk queues have effects on passenger processing by probably somewhat hastening boarding and thus possibly reducing dwell time despite the passenger discomfort produced.

5. The location and number of doors have effects on dwell time, but not quite in proportion to their number.

6. Not only is delay time built up at the major stations, but significant additional delays downstream also can occur as people wait there to board already crowded incoming vehicles. The calibrated curves suggest that these delay-time components are major components of total travel time delays incurred.

The nature of this research would be of value to the operations planner in evaluating vehicle capacity. Such evaluation could be done prior to capital acquisition or for reevaluation of existing fleet equipment. MBTA and other operating authorities may have institutional requirements or constraints (i.e., vehicle shortages or budget cutbacks) that can unintentionally conflict with the goals of reliable, comfortable, attractive, and minimally congested service. However, an alternate crowding level recommended other than crush capacity can be judiciously chosen based on such calibrated models. Indeed, it may be worthwhile for planning purposes to set up live simulations to test whether the 1.5 ft^2/standee crowding level can be achieved year round for each vehicle type in the fleet; this would show whether such a reserve capacity is truly available at those, it is hoped, infrequent times when it needs to be called on. Based on this research, and for reasons other than for passenger comfort, a strong argument can be presented that a reasonable upper limit of capacity, for use in daily operations, occurs in the vicinity of the so-called design capacity of 2.7 ft^2/passenger standee (or 91 passengers on board the pre-1951 vehicle). Vehicles with daily loads that approach crush capacity are unlikely to provide the desired passenger throughput and vehicle turnaround times necessary for service reliability. Other reasons behind support of the design capacity recommendation, in at least the PCC vehicle case, are drawn from the figures and tables:

1. The scattergrams of the raw data (Figure 1) show a distinct drop in the boarding rate above the 70-80 passenger load mark.

2. The Fruin pedestrian approach suggests that limited circulation is still possible at 3 ft^2/standee, which corresponds to 86 passengers on board, but such that circulation deteriorates sharply at higher densities.

3. The calibrated equation for boarding rates suggests that, at design capacity, reasonable boarding rates in the vicinity of about 50 percent of rates where empty seats are available are still possible. Although the particular range of densities most relevant in choosing a desirable and practical vehicle capacity may be different for each distinct vehicle design and required system reliability, this approach is relevant to each vehicle design for both interior layout and door access geometries.

This research provides a small but valuable contribution in the understanding of PVI as it relates to transit and passenger service times and provides a foundation for further research in the high-congestion human factors area. Insights gained from the dynamics of PVI and the potential integration of this modeling approach into simulations of service and reliability could allow for models of significantly greater realism in travel-time prediction and vehicle bunching analysis, as well as for vehicle acquisition planning for systems where passenger congestion is anticipated. Furthermore, greater awareness on the part of operations personnel of the magnitude of problems caused by congestion may, in the short term, lead to more reliable service at no additional cost to the public. Models such as those developed here in the alternative models may, by comparing relative boarding rates, provide a means for evaluating vehicle accommodation of passengers within the upper ranges of their prespecified capacity. Variables in vehicle design such as door size, door number, stairwell geometry, or interior layouts could be observed in real-time mock-up simulations and compared on a cost-benefit basis prior to fleet acquisition.

ACKNOWLEDGMENT

This study was done as independent research initiated while I was a graduate student at the Transportation Center at Northwestern University. I note here my deep appreciation to those who provided invaluable assistance along the way, including the MBTA, Mark S. Daskin and other faculty members on my thesis committee, and the data-collection assistants.

REFERENCES

1. M.S. Fritz. Effect of Crowding on Light Rail Passenger Boarding and Alighting Times. Transportation Center, Northwestern Univ., Evanston, IL, M.S. thesis, 1981.
2. W.O. Adams. The Central Subway System of the MBTA. Traffic Quarterly, Vol. 19, July 1965, pp. 443-459.
3. W.H. Kraft. An Analysis of the Passenger Vehicle Interface of Street Transit Systems with Applications to Design Optimization. New Jersey Institute of Technology, Newark, Ph.D. dissertation, 1975.
4. G. Radelat. Simulation of Urban Bus Operation on Signalized Arterials, Final Report. Traffic Systems Division, Office of Research, FHWA, Rept. FHWA-RD-74-6, Dec. 1973.
5. C.H. Alter. Evaluation of Public Transit Services: The Level-of-Service Concept. TRB, Transportation Research Record 606, 1976, pp. 37-40.
6. J.J. Fruin. Pedestrian Planning and Design. Metropolitan Association of Urban Designers and Environmental Planners, Inc., New York, 1971.
7. LEA Transit Compendium. N.D. Lea Transportation Research Corp., Huntsville, AL, Vol. I, Nos. 5, 6, and 9, 1974; Vol. II, No. 5, 1975; and Vol. III, No. 5, 1976-1977.
8. W.H. Kraft and T.F. Bergen. Evaluation of Passenger Service Times for Street Transit Systems. TRB, Transportation Research Record 505, 1974, pp. 13-20.

Publication of this paper sponsored by Committee on Rail Transit Systems.