Dwell Time Relationships for Light Rail Systems

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Vehicle dwell time is an important determinant in the capacity and performance characteristics of high-frequency, high-ridership light rail lines that are common in Europe. In the United States these systems are best exemplified by the Green Line of the Massachusetts Bay Transportation Authority (MBTA). In such systems cumulative dwell time can represent a significant proportion of total train running time and can contribute greatly to headway variability, which in turn affects passenger service quality. Models are estimated for both one- and two-car trains based on data gathered for the MBTA Green Line. These models explain about 70 percent of the observed variation in dwell times using three explanatory variables: passengers boarding, passengers alighting, and passengers on board. The effect of passenger crowding is statistically significant in most models, and adding crowding variables to reflect congestion on board the vehicle significantly improves the explanatory power of most models. Nonlinear forms of the crowding effect were also estimated, and generally these forms performed better than the corresponding linear forms.

Vehicle dwell time is an important determinant of system performance and passenger service quality in many forms of urban public transportation. Dwell time directly affects vehicle trip time and hence number of vehicles required to operate a given timetable and most measures of productivity. Beyond this obvious effect, dwell time may govern line capacity in systems that have on-line stations with no overtaking permitted such as most urban rail systems. Furthermore dwell time is generally accepted to be the major factor causing vehicle pairing (bunching), which results in variability in headways. Headway variability itself results in higher than necessary passenger waiting times and uneven vehicle passenger loads, both of which are sources of user dissatisfaction with transit service.

Although dwell time will have some effect on transit operations, the extent of this effect varies across mode and service type. At one extreme is commuter rail operation in which headways are typically relatively long and cumulative dwell time represents only a small fraction of total trip time. At the other extreme is a long, high-frequency, high-ridership bus line. In this case dwell time may be a substantial fraction of running time, dwell time for a particular bus is quite sensitive to passenger movements, and difference in cumulative dwell time over the route can readily exceed initial headway between successive buses. In most North American bus systems, fare payment is on board, resulting in boarding through a single door in a single stream, which contributes to the longer dwell time.

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Rail rapid transit and light rail transit lie between these two extremes in terms of the impact of dwell time on operations. Rail rapid transit systems are designed for high-volume operations, with fare payment off the vehicle, and use vehicles designed for rapid passenger boarding and alighting. At the same time, because headways are usually short, differential dwell times have the potential to induce variable headways. Light rail transit operates under quite a wide range of circumstances so that dwell time may, or may not, be an important determinant of overall operational performance. For example, some newer light rail systems operate with relatively high headways, low passenger loadings, and off-vehicle fare payment; in these systems dwell time should not be a critical factor. On the other hand, in light rail systems that operate at high frequency and with high passenger volumes, dwell time is likely to be important even with off-vehicle fare payment.

Dwell time models for light rail systems that use off-vehicle fare payment have been estimated and can be used to address for the first time the relationship between dwell time and train length. After a review of prior work on dwell times, the theoretical aspects of dwell time modeling are discussed. This is followed by a description of the MBTA Green Line system on which data for model estimation were gathered, and finally the models themselves are presented.

PRIOR WORK

Prior work on vehicle dwell times (or the related measure, passenger service times) has been focused on bus systems, not surprisingly given its critical importance to bus operations, with relatively little attention paid to light rail dwell time relationships. Typically these studies have used ordinary least squares regression to relate vehicle dwell time to the numbers of passengers boarding and alighting, with separate models estimated for different operating characteristics likely to affect dwell time, such as restrictions on door usage for boarding and alighting, fare payment method, one- versus two-person operation and vehicle design. In at least one study (*1*) the passenger service time was also found to increase when the passenger load exceeded the seating capacity of the bus. More about prior bus dwell time research can be found in the *Highway Capacity Manual* (*2*), as well as papers by Levinson (*3*), Guenther and Sinha (*4*), Boardman and Kraft (*5*), Kraft and Bergen (*6*), Kraft (*7,8*), and Cundill and Watts (*9*).

In terms of light rail studies, Fritz (*10,11*) estimated models for the MBTA Green Line with the President's Conference

Committee (PCC) cars in use. Linear relations were estimated between the number of passengers boarding per unit time and concurrent passenger counts (or density) both on board the car and on the platform. These models showed that boarding rates declined markedly with increasing passenger crowding, especially as the space per standee fell below the often used nominal standee space allocation of 2.7 ft^2 and approached crush capacity density of 1.5 ft^2. At lower levels of congestion these models produced results quite similar to predictions from constant service time models. These results cannot be applied to a modern, articulated light rail vehicle (LRV) because of the radically different vehicle design, including number and size of doors. Fritz's models were estimated only for single-car trains and did not consider the general case of boardings and alightings occurring simultaneously.

In the most closely related prior work to this, Koffman et al. (*12*) collected two data sets on the MBTA Green Line and another on the San Diego Trolley to estimate the effects of the self-service fare collection system being used in San Diego. One MBTA data set referred to outbound operation in which no fares were collected, whereas the other referred to inbound operation with on-vehicle fare collection. All models estimated used independent variables, passengers boarding, passengers alighting, and passengers on board to estimate the dependent variable dwell time. All three variables were found to be statistically significant in all data sets with the model explaining between 43 percent and 84 percent of the variation in the observed dwell times. Although these results are suggestive, they cannot be directly applied to a high-ridership, high-frequency operation because of the low level of passenger movements and low passenger loads (the MBTA observations were made on the surface portion of the line, not the high-density central subway portion). The MBTA Green Line observations were also made only for one-car trains. However Koffman's MBTA model results will be compared with those developed here later in this paper.

THEORY

Dwell time of a train at a station may be affected by many factors, grouped by Kraft (*7*) into seven categories: human, modal, operating policies, operating practices, mobility, climate/weather, and other system elements. However, for a given property and system, most of these factors are constant, and the principal determinants of dwell time are likely to be various aspects of passenger demand and human behavior as it affects both operators and passengers.

Differences in operator characteristics, such as how long the operator might wait with the doors open for someone who may want to alight from a crowded car, will clearly lead to dwell time differences, but even if such characteristics could be captured in a mathematical model, they could not be used to forecast future system performance because the future composition and assignment of the operating work force is unpredictable. Similarly although passenger characteristics, such as the number of mobility-impaired passengers, is likely to affect dwell time, they cannot be used to predict dwell time for a specific train in the future. For these reasons no attempt will be made to incorporate human factors into the models to be estimated, and the influence of these factors will simply be included in the error term: the larger the error term, the more significant are those factors that are not included explicitly among the independent variables.

Thus the somewhat predictable factors likely to affect dwell time are simply the numbers of passengers boarding and alighting from a train and the number of passengers on board the train, as well as the number of cars in the train. These are referred to as being "somewhat predictable" because their mean values may be known from passenger counts per unit time, although their specific values will vary on a train-to-train and day-to-day basis. If mean passenger boarding and alighting rates are known from observation of the system, then mean numbers of passengers boarding and alighting at a station can be estimated given the train headway. Mean number of passengers on board can be estimated in a similar fashion given passenger boarding and alighting rates at all stations on the line.

In developing the theory underpinning dwell time one can think first about the way each independent variable would be expected to affect the time required to move passengers through a single door and then about the relationship between door open times and the total dwell time for the train. Consider first the time required for a given number of passengers to move through a single door in both directions. First assuming constant boarding and alighting rates without interference between boarding and alighting, and without interference with passengers standing on either side of the door, the following simple linear model might apply:

$$DOT = a + b(DONS) + c(DOFFS) \qquad (1)$$

where

DOT = door open time,
$DONS$ = number of passengers boarding through door,
$DOFFS$ = number of passengers alighting through door, and
a,b,c = estimated parameters.

If interference with passengers on board is included, then the boarding and alighting rates would be expected to decrease as the crowding level on board increases. Furthermore it might be reasonable to expect that this term would be negligible until there is a standing load on board. Assuming the simplest case in which the passenger service time increases linearly with number of standees and the congestion effect on boarding and alighting service times is identical, the following model results:

$$DOT = a + b(DONS) + c(DOFFS) + d(DONS + DOFFS)(STD) \qquad (2)$$

where STD is the number of standees.

This further assumes that passenger congestion on the station platform is not significant relative to that on board the vehicle (this will typically be true) and that interference effects between boarding and alighting passenger streams either are small or exist in all cases, in which case they will be included in the constant term a.

Although this model may be a reasonable description of the boarding and alighting process through a single door, the question of how this relates to total dwell time for a train remains. Consider a single car that has three doors, such as an articulated LRV. The dwell time for a single LRV would be as follows:

$$DT = \max(DOT_1, DOT_2, DOT_3) \quad (3)$$

where DT is the dwell time and DOT_i is the door open time for the ith door.

Equation 3 simply states that the dwell time for a single car is the longest door open time for any of its doors, where each door open time could be represented by Equation 2.

Clearly the minimum dwell time will occur when both boardings and alightings are evenly divided between all doors (assuming further that any standees are evenly distributed around the doors). In this case dwell time for a single car is as follows:

$$DT = a + b/3(CONS) + c/3(COFFS) + d/3(CONS + COFFS)(STD) \quad (4)$$

where $CONS$ is the number of passengers boarding the car and $COFFS$ is the number of passengers alighting from the car.

At the other extreme, where all boardings and alightings occurred through a single door, Equation 2 would apply at the car level; however, this is very unlikely to be true except for very low levels of boardings and alightings. The true dwell time process for a single car will be bounded by Equations 2 and 4, but is likely to be much closer to Equation 4. Furthermore, because in most LRVs all three doors cannot be operated independently, Equation 2 cannot be estimated directly, whereas Equation 4 can. The structure of these equations is, of course, identical; the only difference would be in the size of the estimated parameters b, c, and d.

Turning finally to the topic of multicar trains, the dwell time model would be analogous to Equation 3, but the maximum would now be taken over the dwell times of individual cars:

$$DT = \max(DT_1, DT_2, \ldots, DT_n) \quad (5)$$

where DT_i is the dwell time for the ith car of an n car train.

In typical North America light rail operations, the maximum train length is two cars, so dwell time for the train is simply the maximum of the individual car dwell times with each car dwell time being represented by Equation 4. Once again the minimum dwell time for the train will occur when boardings, alightings, and standees are evenly split between the two cars, leading to the following train dwell time:

$$DT = a + b/6(TONS) + c/6(TOFFS) + d/6(TONS + TOFFS)(STD) \quad (6)$$

where $TONS$ is the number of passengers boarding the train and $TOFFS$ is the number of passengers alighting from the train.

At the other extreme, with all passengers boarding and alighting from the same car, Equation 4 would hold. Thus Equations 4 and 6 represent bounds on the dwell time for a two-car train with the actual coefficients reflecting the degree of imbalance in passenger movements and loading between the cars.

EMPIRICAL STUDY: MBTA GREEN LINE

In this section dwell time functions are estimated for one- and two-car trains on the MBTA Green line, a light rail line operating with articulated LRVs (*13*). The Green Line operates over a branching network of 28 mi and 70 stations with much of the line fully grade separated, including the central portion that operates in a subway. Trains operate on four routes with separate surface alignments but which converge in one central subway tunnel (from Lechmere Station to Kenmore Station) with trains from all routes operating on the same tracks. Within this subway section, fares are paid upon entering a station rather than on board the train, which is the rule on the surface branches of the line.

In the 1970s, PCC cars were the principal vehicles running on the Green Line; but today they have been replaced with 52-seat (practical capacity is about 150 passengers) articulated LRVs. There are six doors per car, three on each side; the middle and rear doors are 35-in. wide, whereas the front door is 32-in. wide. The great majority of trains are composed of either one or two cars, depending on time of day, although some three-car trains are now being introduced. Virtually all stations have single (low-level) platforms for passenger movements, thus three doors are available for passengers alighting and boarding in any one-car train and six doors in any two-car train. Typical scheduled headways in the central subway are in the range of 1 to 2 min, depending on time of day.

For this analysis, a special detailed data set was gathered, with each observation including the following data: the number of passengers boarding and alighting through each door, the time the front door was opened and closed for each car, and the departing passenger load for each car. Because of the unusual level of detail required, it was necessary to have a two-person team per car, or a four-person team for a two-car train, to collect the data. For the two-car observations, the train dwell time was taken to be the larger of the dwell times observed for each car. A total of 122 observations of one-car train dwell times and 51 samples of two-car train dwell times were taken in April 1988 and 1989 at two subway stations.

A preliminary analysis was carried out that confirmed that dwell time is related to the number of passengers boarding and alighting as well as to the passenger load. This analysis also determined that the hypothesis that the mean dwell times were equal for one- and two-car trains that had similar levels of passenger movements or similar passenger loads could not be rejected. For the two-car trains this conclusion was based on the passenger movements and passenger load observed for the car having the longer dwell time. Tables 1 and 2 summarize the dwell times observed for one- and two-car trains as a function of the (leaving) passenger load and the sum of boarding and alighting passengers.

Based on the preliminary analysis and theory, two major factors, the number of passengers boarding and alighting, and crowding on board, were expected to enter into the dwell time function. However each factor can be represented in different forms and may interact in different ways. Accord-

TABLE 1 One-Car Train Dwell Times

Total Sample:	n = 122	Mean = 23.31	Standard Deviation = 11.41	
a) Analysis based on leaving passenger load (LPL)				
LPL	< 53	53-80	81-108	> 108
Sample Size	41	37	16	28
Mean LPL	32	65	94	132
Mean TONOFFS	10	15	20	21
Mean (Dwell Time)	16.83	20.60	24.00	36.00
Std. Dev. (Dwell Time)	5.65	8.35	6.68	13.31
b) Analysis based on sum of passengers boarding and alighting (TONOFFS)				
TONOFFS	< 10	10-17	18-25	>25
Sample Size	37	39	30	16
Mean LPL	47	75	89	101
Mean TONOFFS	6	13	21	32
Mean (Dwell Time)	15.81	20.03	27.10	41.56
Std. Dev. (Dwell Time)	6.65	6.32	5.90	14.98

TABLE 2 Two-Car Train Dwell Times

Total Sample:	n = 51	Mean = 26.57	Standard Deviation = 8.40	
a) Analysis based on LPL for longer dwell time car				
LPL	< 53	53-80	81-108	> 108
Sample Size	11	13	16	11
Mean LPL	41	69	98	132
Mean TONOFFS	11	15	21	27
Mean (Dwell Time)	20.36	23.15	27.50	35.46
Std. Dev. (Dwell Time)	5.68	7.39	6.81	6.31
b) Analysis based on TONOFFS for longer dwell time car				
TONOFFS	< 10	10-17	18-25	>25
Sample Size	12	14	11	14
Mean LPL	61	74	97	109
Mean TONOFFS	6	14	21	32
Mean (Dwell Time)	19.33	22.79	28.73	34.87
Std. Dev. (Dwell Time)	5.69	4.87	6.81	6.56

ingly a series of linear regression models of passenger processing were estimated to identify the strongest functional form. In the following discussion of the estimation results, the variables used to explain the variation in the dependent variable DT (dwell time measured in seconds) are as previously defined, with the following additions:

$TONOFFS$ = sum of $TONS$ and $TOFFS$,
AS = number of arriving standees,
LS = number of departing standees,
$TOFFAS$ = product of $TOFFS$ and AS, i.e., $TOFFS*AS$,
$TONLS$ = product of $TONS$ and LS, i.e., $TONS*LS$, and
$SUMASLS$ = sum of $TOFFAS$ and $TONLS$.

In all cases of two-car trains, the variables refer to passenger movements and loads on the entire train.

As discussed in the theory section, the dwell time processes for one- and two-car trains are different and so separate models were estimated for the one-car train data set and the two-car train data set. The statistical packages SST (*14*) and MINITAB (*15*) were used for the regression analysis. The resulting models shown below include t-statistics (in parentheses) and corrected coefficient of determination (R^2). The t-statistics are used to determine the contribution of each variable used in model estimation, and the corrected R^2 is used to measure how well the model estimation fits the sample data.

ONE-CAR TRAIN MODELS

Although the one-car train data set was collected at two stations, a dummy variable introduced in the regression analysis to reflect possible differences between the stations was not statistically significant, and thus is omitted from all models shown here.

Models were estimated based on three approaches: all data together, the data set with $TONS$ being equal to or greater than $TOFFS$ ($TONS \geq TOFFS$), and that with $TOFFS$ being greater than $TONS$ ($TOFFS > TONS$). The available sample points for these three approaches are 122, 83, and 39, respectively. In the following analysis, model estimations are conducted based on these three approaches, with the second and third approaches referred to by subscripts a and b, respectively.

Model A: $DT = f(TONS, TOFFS)$

Model A assumes that only the number of passengers boarding and alighting affect the dwell time and that there is no effect of passenger crowding on board. The resulting models are shown below:

$$\text{A1: } DT = \underset{(5.96)}{9.07} + \underset{(8.46)}{1.15}*TONS + \underset{(5.58)}{0.63}*TOFFS \quad (R^2 = 0.48) \tag{7}$$

$$\text{A1a: } DT = \underset{(3.91)}{8.67} + \underset{(4.03)}{0.90}*TONS + \underset{(5.28)}{1.41}*TOFFS \quad (R^2 = 0.52) \tag{8}$$

$$\text{A1b: } DT = \underset{(8.51)}{11.98} + \underset{(4.61)}{0.88}*TONS + \underset{(3.82)}{0.43}*TOFFS \quad (R^2 = 0.64) \tag{9}$$

Although all coefficients are strongly significant in all three models (as indicated by the *t*-statistics), the models have rather low coefficients of determination (corrected R^2). It does appear, however, that Models A1a and A1b using two data sets based on the relative magnitude of *TONS* and *TOFFS* are a significant improvement over A1, which pools all data. In light of the poor overall goodness of fit measures, all subsequent models include terms representing passenger crowding, and all three modeling approaches are retained.

Model B: *DT* = *f(TONS, TOFFS, SUMASLS)*

Model B recognizes that movement of alighting passengers would be affected by arriving standees, whereas movement of boarding passengers would be affected by departing standees. Therefore the crowding effect may be represented by the variables *TOFFAS* and *TONLS*, which are combined in the variable *SUMASLS*, producing the following results:

$$\text{B1: } DT = \underset{(8.94)}{12.50} + \underset{(3.76)}{0.55}*TONS + \underset{(2.03)}{0.23}*TOFFS + \underset{(6.70)}{0.0078}*SUMASLS \quad (R^2 = 0.62) \tag{10}$$

All coefficients are strongly significant in this model with an R^2 of 0.62 showing that adding the variable *SUMASLS* to reflect the effect of crowding on board significantly improves the explanatory power of the model. The marginal boarding time in this model is more than twice the marginal alighting time and the contribution of the crowding term is that dwell time would be increased by about 7 sec at a typical stop when half the train passengers are standing.

When boardings are greater than alightings:

$$\text{B1a: } DT = \underset{(6.33)}{12.32} + \underset{(2.78)}{0.56}*TONS + \underset{(8.25)}{0.01}*SUMASLS \quad (R^2 = 0.65) \tag{11}$$

In this model the term for alighting passengers has been dropped because of its low statistical significance, although the contribution of alightings is included in the *SUMASLS* term. All remaining coefficients are significant at 0.05 level with an R^2 of 0.65, which implies that adding the variable *SUMASLS* to reflect the effect of crowding on board is a significant improvement over model A1a.

When alightings are greater than boardings, however, the effect of on board crowding is much less significant and the overall goodness of fit changes little as shown below:

$$\text{B1b: } DT = \underset{(8.60)}{12.46} + \underset{(2.43)}{0.65}*TONS + \underset{(3.43)}{0.39}*TOFFS + \underset{(1.25)}{0.002}*SUMASLS \quad (R^2 = 0.65) \tag{12}$$

Model C: *DT* = *f(TONS, TOFFS, LS)*

The Model C form assumes that the effect on dwell time of crowding on board could be represented simply by the leaving standees (*LS*). A rationale for this is that for a very crowded car (train) the operator may wait longer to see if any passengers are trying to alight—even if none finally do. In this case the contribution of crowding to dwell time may not be a function of the number of passengers boarding or alighting:

$$\text{C1: } DT = \underset{(7.19)}{9.24} + \underset{(5.40)}{0.71}*TONS + \underset{(5.35)}{0.52}*TOFFS + \underset{(6.98)}{0.16}*LS \quad (R^2 = 0.63) \tag{13}$$

$$\text{C1a: } DT = \underset{(4.13)}{8.10} + \underset{(4.65)}{0.88}*TONS + \underset{(7.61)}{0.22}*LS \quad (R^2 = 0.62) \tag{14}$$

$$\text{C1b: } DT = \underset{(8.37)}{11.46} + \underset{(2.64)}{0.60}*TONS + \underset{(4.38)}{0.48}*TOFFS + \underset{(2.09)}{0.066}*LS \quad (R^2 = 0.67) \tag{15}$$

As indicated by the *t*-statistics, all coefficients are strongly significant in all three models of this form. Overall goodness of fit statistics are quite similar to those for Model B, and it is clear that, statistically at least, using the variable *LS* to reflect the crowding effect is a reasonable approach. However, if there were standees, but no passengers boarding or alighting, the number of standees should not have as significant an impact on dwell time as if there were passenger movements. For this reason, Model B may be preferred over Model C.

NONLINEAR MODELS

The previous models have assumed that the effect on dwell time of crowding is linear; however, it may well be nonlinear. To investigate this possibility, various nonlinear forms for the variables reflecting crowding were also estimated. Several of the more interesting nonlinear models are shown below:

$$\text{D1-1: } DT = \underset{(8.78)}{11.43} + \underset{(5.38)}{0.69}*TONS + \underset{(4.99)}{0.48}*TOFFS + \underset{(7.41)}{1.35*10^{-5}}*TONS*LS^{2.5} \quad (R^2 = 0.65) \tag{16}$$

$$\text{D1-2: } DT = \underset{(8.32)}{10.05} + \underset{(6.70)}{0.78}*TONS + \underset{(5.51)}{0.50}*TOFFS + \underset{(8.50)}{2.0*10^{-4}}*LS^{2.5} \quad (R^2 = 0.68) \tag{17}$$

$$\text{D1a}: DT = \underset{(5.44)}{9.71} + \underset{(5.69)}{0.94}*TONS + \underset{(9.34)}{1.1*10^{-4}}*LS^{2.7} \quad (R^2 = 0.69) \tag{18}$$

$$\text{D1b}: DT = \underset{(8.47)}{11.45} + \underset{(3.17)}{0.66}*TONS + \underset{(4.46)}{0.49}*TOFFS + \underset{(2.26)}{7.7*10^{-4}}*LS^{2.0} \quad (R^2 = 0.68) \tag{19}$$

These models show that nonlinear forms of the crowding term with passenger load raised to a power of about 2.5 gives a slightly better representation of observed dwells than the standard linear form.

TWO-CAR TRAIN MODELS

Model A: *DT = f(TONS, TOFFS)*

Model A assumes that only the numbers of passengers boarding and alighting affect the dwell time, so there is no effect of passenger crowding on board. The resulting models based on the three approaches discussed earlier are referred to as A2, A2a, and A2b, respectively, in this (and subsequent) specifications:

$$\text{A2}: DT = \underset{(7.44)}{11.73} + \underset{(7.59)}{0.42}*TONS + \underset{(6.22)}{0.49}*TOFFS \quad (R^2 = 0.68) \tag{20}$$

$$\text{A2a}: DT = \underset{(4.32)}{9.69} + \underset{(4.49)}{0.42}*TONS + \underset{(3.99)}{0.66}*TOFFS \quad (R^2 = 0.71) \tag{21}$$

$$\text{A2b}: DT = \underset{(7.46)}{14.39} + \underset{(6.29)}{0.56}*TOFFS \quad (R^2 = 0.68) \tag{22}$$

As indicated by the t-statistics, all remaining coefficients are strongly significant in all three models, with high R^2-values, although it should be noted that the boardings term was dropped from Model A2b because of its low significance.

Comparing these models with the corresponding one-car train models, several points should be noted. First, the constant terms imply that there is a greater station "overhead" for a two-car train. Second, the coefficients for the variables *TONS* are much lower, because twice as many doors are available to boarding passengers. Note that this effect does not necessarily apply to the alighting process because passengers cannot move between cars once on board, and so imbalance between cars is more likely to arise in alighting than in boarding. It also appears that these two-car models better explain the dwell times using only two variables than the corresponding one-car models, implying that the crowding effect is less significant in the two-car train dwell process.

Model B: *DT = f(TONS, TOFFS, SUMASLS)*

Model B introduces the variable *SUMASLS* (the sum of *TOFFAS* and *TONLS*) to express the marginal effect on dwell time of crowding on board:

$$\text{B2}: DT = \underset{(7.43)}{13.93} + \underset{(2.92)}{0.27}*TONS + \underset{(3.79)}{0.36}*TOFFS + \underset{(2.03)}{0.0008}*SUMASLS \quad (R^2 = 0.70) \tag{23}$$

$$\text{B2a}: DT = \underset{(3.83)}{11.31} + \underset{(2.62)}{0.34}*TONS + \underset{(2.23)}{0.52}*TOFFS + \underset{(0.85)}{0.0005}*SUMASLS \quad (R^2 = 0.70) \tag{24}$$

$$\text{B2b}: DT = \underset{(8.10)}{15.69} + \underset{(3.50)}{0.41}*TOFFS + \underset{(1.88)}{0.0008}*SUMASLS \quad (R^2 = 0.72) \tag{25}$$

In Model B2, all coefficients are significant at the 0.05 level, and adding the variable *SUMASLS* is an improvement over Model A2. In Model B2a, the crowding term coefficient is not statistically significant, and it is only marginally significant in Model B2b.

Compared with the corresponding one-car train models, the most striking difference is the ratio of marginal boarding to marginal alighting time between the corresponding models. The boardings coefficients for the two-car train models are about half the values for the corresponding one car models, as would be expected given twice as many doors through which boarding can occur. However, the alighting coefficient is greater for two-car trains than for one-car trains. This can only be explained by passengers who are getting off at a specific station being concentrated in one of the two cars—presumably the most convenient to the station exit.

Model C: *DT = f(TONS, TOFFS, AS, LS)*

The only Model C that produced interesting results was for the cases in which there were more alightings than boardings:

$$\text{C2b}: DT = \underset{(8.43)}{15.00} + \underset{(4.23)}{0.43}*TOFFS + \underset{(2.11)}{0.037}*AS \quad (R^2 = 0.74) \tag{26}$$

As indicated by the t-statistics, all coefficients are significant at 0.05 level in this model with an R^2 of 0.74. Compared with Model A2b, it is clear that adding the variable *AS* to reflect the effect of crowding on board significantly improves the explanatory power of the model.

NONLINEAR MODEL FORMS

As for the one-car train models, various nonlinear models were estimated to reflect possible nonlinearities in the crowding effect. Several of the more interesting nonlinear models are presented below:

$$\text{D2-1: } DT = \underset{(8.06)}{13.54} + \underset{(3.70)}{0.28}*TONS + \underset{(5.65)}{0.44}*TOFFS + \underset{(2.41)}{6.0*10^{-6}}TONS*LS^2 \quad (R^2 = 0.71) \tag{27}$$

$$\text{D2-2: } DT = \underset{(7.94)}{12.72} + \underset{(6.08)}{0.36}*TONS + \underset{(5.01)}{0.42}*TOFFS + \underset{(2.03)}{1.3*10^{-6}}*AS^{2.5} \quad (R^2 = 0.70) \tag{28}$$

No interesting nonlinear model forms were found for the separate data sets in which boardings or alighting dominated.

It is clear from these results that passenger crowding has a lesser effect on dwell time in two-car train operations than in one-car operations.

COMPARISON OF ONE- AND TWO-CAR TRAIN MODELS

Tables 3, 4, and 5 compare the parameter estimates for the one- and two-car linear models for all three model series.

Table 3 indicates that the constant terms in the two-car dwell time models are greater than those in the corresponding one-car models, but the marginal dwell time for boarding is significantly smaller. The coefficient of *TONS* for the two-car model is half that for the corresponding one-car model because there are about half as many *TONS* per door when the same passengers board a two-car train compared with a one-car train. The marginal dwell time for alighting varies between the one- and two-car models, depending on what model form is chosen, but it depends on the passenger load distribution between cars. It is also clear that the coefficients of the variables reflecting the crowding effect in the one-car train models are greater and more significant than those in the two-car models, implying that the marginal dwell time

TABLE 3 Comparison of Parameter Estimates for All Observations

	One Car Trains			Two Car Trains		
Model	A1	B1	C1	A2	B2	C2
Constant	9.07 (8.87)	12.50 (8.94)	9.24 (7.19)	11.73 (7.44)	13.93 (7.43)	12.37 (7.73)
TONS	1.55 (8.46)	0.55 (3.76)	0.71 (5.40)	0.42 (7.59)	0.27 (2.92)	0.35 (5.20)
TOFFS	0.63 (5.58)	0.23 (2.03)	0.52 (5.35)	0.49 (6.22)	0.36 (3.79)	0.41 (4.46)
SUMASLS		0.0078 (6.70)			0.0008 (2.03)	
LS			0.16 (6.98)			0.027 (1.61)
Corrected R-Square	0.48	0.62	0.63	0.68	0.70	0.69

TABLE 4 Comparison of Parameter Estimates for Net Boardings Only

	One Car Trains			Two Car Trains		
Model	A1a	B1a	C1a	A2a	B2a	C2a
Constant	8.67 (3.91)	12.32 (6.33)	8.22 (4.37)	9.69 (4.32)	11.31 (3.83)	9.90 (4.21)
TONS	0.90 (4.03)	0.56 (2.78)	0.69 (3.55)	0.42 (4.49)	0.34 (2.62)	0.41 (3.98)
TOFFS	1.41 (5.28)		0.73 (2.83)	0.66 (3.99)	0.52 (2.23)	0.60 (2.67)
SUMASLS		0.01 (8.25)			0.0005 (0.85)	
LS			0.18 (5.67)			
AS						0.01 (0.36)
Corrected R-Square	0.52	0.65	0.65	0.71	0.70	0.70

TABLE 5 Comparison of Parameter Estimates for Net Alightings Only

	One Car Trains			Two Car Trains		
Model	A1b	B1b	C1b	A2b	B2b	C2b
Constant	11.98 (8.51)	12.46 (8.60)	11.46 (8.37)	14.39 (7.46)	15.69 (8.10)	15.00 (8.43)
TONS	0.88 (4.61)	0.65 (2.43)	0.60 (2.64)			
TOFFS	0.43 (3.82)	0.39 (3.43)	0.48 (4.38)	0.56 (6.29)	0.41 (3.50)	0.43 (4.23)
SUMASLS		0.0022 (1.25)			0.0008 (1.88)	
LS			0.066 (2.09)			
AS						0.037 (2.11)
Corrected R-Square	0.64	0.65	0.67	0.68	0.72	0.74

effect of crowding is greater in one-car trains than in two-car trains. Part of this difference is explained by the implied difference in passenger movements and crowding at each door, but this would account for only a factor of four difference in the terms. The remaining difference is most likely because of load imbalances between cars, allowing boarding passengers to board the less crowded car, thus experiencing less congestion. As indicated by the corrected R^2 shown in Table 3, it is clear that adding either proposed crowding variable significantly improves the explanatory power of the one car train model.

The most striking observation from Table 4 is that the crowding effect is insignificant in the two-car train models, whereas it is highly significant in the one-car train models for the net boarding sample. The second observation is that the alighting time coefficient is greater than the boarding time coefficient. This again reflects the greater imbalance in alightings than in boardings, and the sequential nature of alightings and boardings through the governing door.

Table 5, for the net alightings sample, clearly shows the higher constant term for all two-car train models. In the two-car train models boardings are accommodated in parallel with alightings (presumably at other doors), whereas in one-car trains the marginal contribution of boarding time is significant. The marginal alighting times are very similar in one- and two-car trains, again reflecting imbalance in alighting load between cars in the two-car trains. Finally although the crowding terms are only marginally significant, their magnitude is very similar for one- and two-car trains when the variables are interpreted on a per door basis.

To provide a better understanding of the differences between the dwell times for one- and two-car trains, Table 6 uses Model Form B to estimate dwell time for some hypothetical train movements, for both one- and two-car trains. By comparing dwell times along a single row, one can see the difference in dwell time between a one- and two-car train with identical passenger movements and passenger load. This difference in dwell time increases with number of passengers boarding and alighting, and with passenger load, indicating the substantial dwell time reductions that result from operating two-car trains when the alternative would be a heavily loaded one-car train. These time savings can be half a minute, or more when the one-car train is operating close to practical capacity.

TABLE 6 Comparison of Predicted Dwell Times for Models B1 and B2

Boardings	Alightings	Passengers on board	One Car Trains Model DT (sec)	Two Car Trains Model DT (sec)
0	0	any #	12.5	13.9
10	10	<53	20.3	20.2
10	10	100	27.8	20.2
10	10	150	35.6	21.0
20	20	<53	28.1	26.5
20	20	100	43.1	26.5
20	20	150	58.7	28.1
30	30	<53	35.9	32.8
30	30	100	58.4	32.8
30	30	150	81.8	35.1

COMPARISON WITH OTHER DWELL TIME MODELS

The only directly comparable model found in the literature was a study by Koffman et al. (*12*) that included the following dwell time model for single-car, surface, outbound (no on-board fare payment) MBTA Green Line operations (the parameters presented are averages of those obtained separately by Koffman on two different branches of the Green Line):

$$DT = 3.0 + 0.75(TONS) + 0.56(TOFFS) + 0.035(PASS)$$

where *PASS* is total passengers on board arriving at the stop.

For comparison purposes the most similar model developed under this study is Model C1:

$$DT = 9.24 + 0.71(TONS) + 0.52(TOFFS) + 0.16(LS)$$

Comparing these models, the marginal boarding and alighting times are quite similar, with the slightly lower times estimated in the model developed under this study most likely resulting from the significantly higher observed boardings and alightings in the data set (15.3 versus 9.4). The other striking differences are in the size of the constant term and in the structure of the crowding term. These differences are somewhat offsetting given the structural difference in the terms.

Table 7 compares predicted dwell times using both models for some hypothetical operating circumstances. Substantial differences exist between the model predictions, particularly with respect to the effect of heavy passenger loads on dwell

TABLE 7 Comparison of Predicted Dwell Times for Koffman Model and Model C1 from This Paper

Boardings	Alightings	Pass on Board (Leaving Standees)	Lin, Wilson Model DT	Koffman Model DT
0	0	10 (0)	9.2	3.3
0	0	60 (8)	10.5	5.1
0	0	110 (58)	18.5	6.9
10	10	10 (0)	21.5	16.4
10	10	60 (8)	22.7	18.2
10	10	110 (58)	30.8	20.0
20	20	60 (8)	35.0	31.3
20	20	110 (58)	43.1	33.1
30	30	60 (8)	47.2	44.4
30	30	110 (58)	55.3	46.2

time. This effect of heavily loaded trains is even more pronounced in some of the nonlinear dwell time models and would be even more marked for trains operating closer to capacity.

OPERATIONAL IMPLICATIONS

The sensitivity of dwell time to both numbers of passengers boarding and alighting and the number of standees on the train has several important implications on operations. First the difference in dwell times of up to half a minute, or more, between heavily loaded trains and lightly loaded trains for the same number of passenger boardings and alightings means that an initial ideal headway of (for example) 1 to 2 min can rapidly deteriorate if initial train loadings vary greatly. This deterioration becomes much more rapid as the shorter headway results in fewer boardings and alightings and the longer headway results in greater boardings and alightings. Furthermore the whole line is slowed by the heavily loaded train operating with a long headway. Thus effective real-time operations monitoring and control become a critical requirement for maintaining high quality service on this type of high-frequency, high-ridership light rail system.

Another observation is the difficulty of running different length trains on the same service at the same time. Unless headways are closely controlled there will be a strong tendency for the shorter trains to become heavily loaded and thus run more slowly than the longer trains. This leads to bunching and poor service quality.

CONCLUSIONS

This research has estimated dwell time models for one- and two-car light rail operations. The resulting models showed that both the numbers of passengers boarding and alighting and the level of passenger crowding on board the train significantly affect dwell times. Several forms of the crowding variable were shown to be effective, all based on the number of standees. Evidence was also found that the crowding effect may be nonlinear with the marginal delay increasing with the number of standees. A basis for formulating and estimating dwell time models for multicar trains was also laid out and showed that important differences exist between dwell time models for one- and two-car trains as a result of typically uneven distribution of passenger movements and passenger loads between cars in a two-car train. Finally some of the implications of the dwell time models for maintaining high-quality service on high-frequency, high-ridership light rail lines were pointed out.

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