Assessing a Model for Optimal Bus Stop Spacing with High-Resolution Archived Stop-Level Data

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With increasing attention given to performance and financial issues related to the operation of public transportation systems, tools are needed to improve the efficiency and effectiveness of service offerings. High-resolution archived stop-level bus performance data can be used to generate and test a bus stop spacing model with the goal of minimizing operating cost while maintaining a high degree of transit accessibility.

Two cost components are considered in the spacing model: passenger access cost and in-vehicle passenger stopping cost. These are combined and optimized to minimize total cost. A case study was made of a bus route in Portland, Oregon, by using 1 year of stop-level archived data from the Tri-County Metropolitan Transportation District of Oregon, the regional transit provider of the Portland metropolitan area. The case study indicates that the theoretical optimized bus stop spacing is 1,200 ft, compared with the current value of 950 ft. Trade-offs are discussed, and an estimate is presented of transit operating cost savings based on optimized spacing. It is shown that because of availability of high-resolution archived data, this modeling tool can be applied routinely across multiple routes as part of an ongoing service-planning and performance-measurement process.

As transportation funding becomes increasingly competitive, operational issues of public transit are receiving attention from transportation professionals and decision makers. Buses are designed to make frequent stops, particularly during peak hours, to provide service to transit patrons. Among the effects of frequent stops are delays to through riders and shorter walking times parallel to the route. Frequent transit stops are costly to transit operators because of travel times increase with each stop and its attendant acceleration and deceleration. At some stop locations, it may be difficult for a bus to reenter the traffic stream during congested periods. Clearly there is a trade-off between providing sufficient access to the public transit system and stopping too frequently.

Transit service generally favors bus stop accessibility, sometimes because of history and tradition rather than rigorous ongoing analysis at the stop level. It is generally held that bus stops are too close to one another on many routes, slowing bus operations and increasing operation expenditures. However, by reducing the number of stops, transit operators risk making service inaccessible, in perception or reality, which may lead to loss of patrons when bus stops are moved or distantly spaced to avert the problems associated with closely spaced stops. Bus stop spacing has been studied in the United States (1–7), including in work by Furth and Rahbee (5), in which the optimal solution was an average stop spacing of 1,300 ft, in sharp contrast to the actual average spacing of 650 ft. Another proposed model considered relationships among velocity, uniform acceleration and deceleration, and displacement and relationships among average bus operating speed, headway, required fleet size, and potential system capacity (8). In Portland, Oregon, a corridor on which stop consolidation had been applied was analyzed to measure the costs and benefits of such a program (9).

Like many urban transit providers, the Tri-County Metropolitan Transportation District of Oregon (TriMet), the regional transit provider for the Portland metropolitan area, has faced challenges in delivering reliable and timely bus service across a regional road system that has become increasingly congested. This paper describes the application of an optimal stop spacing model (10) within the constraints of access and riding costs to minimize the total user cost. By using a rich set of TriMet’s archived stop-level data, a bus route was examined for 1 year as a case study.

METHODOLOGY

The operational effects of bus stop spacing are critical in public transportation operations. Many objectives and constraints can affect bus stop spacing. Closely spaced stops provide short distances for passenger access (11, 12) but increase trip times (13). Large stop spacing minimizes passenger in-vehicle time but reduces accessibility of the system. Stop spacing has been studied for minimizing transit-user time and evaluating trade-offs between access and in-vehicle time (5, 8, 11, 14–17). In particular, based on the work of Newell (10), an aggregate total cost function is developed that includes:

- Minimizing access cost $C_a$, which favors small spacing, and
- Minimizing riding cost $C_r$, which favors large spacing.

The total cost of access and riding per unit length is convex in $s$ and can be minimized as shown in Figure 1. The cost over some trip length $L$ can be minimized by minimizing cost per unit length $ps$.

Dimensional analysis is used to set up equations for a dimensionless parameter $ps$, where

$$s = \text{stop spacing (distance)}$$

$$p = \text{density of trip origins plus density of trip destinations for passengers who board the same bus (number of passengers/distance)}$$

And

$$ps = \text{expected number of passengers boarding and alighting per stop}$$
The objective function is examined for choosing s. Trip origins and destinations are considered to be distributed in a two-dimensional plane. As shown in Figure 2, to travel to a stop, a passenger walks both perpendicular to and parallel to the route.

When used to estimate optimal spacing, the model is based on several assumptions (4):

- Number of passengers boarding or alighting at a stop is Poisson distributed;
- \( E \) [number of boarding or alighting] = \( ps \);
- \( P_r \) [number of boarding and alighting = \( x \)] is approximately Poisson distributed;
- The probability that a vehicle does not stop (no passenger wants to board or alight) = 1 – \( P_r \) [number boarding and alighting = 0] = \( e^{-\lambda} (x = 0) \), so \( P_s = 1 – e^{-\lambda} \);
- Travel demand is uniformly distributed over \( s \);
- For analyzing spacing, origins and destinations are considered to be distributed along the route in one dimension—perpendicular access is ignored because it is the same no matter where the stops are located; and
- Average access distance (parallel only) is given by \( l = s/4 \), as shown in Figure 3.

On the basis of this basic model conceptualized by Newell (10, 14), the spacing of a TriMet bus route is examined by using data archived by TriMet’s bus dispatch system (BDS). An optimal spacing is computed for the route as a basis for transit service improvement, and a sensitivity analysis is performed to assess the costs and benefits of changing the spacing of stops. This framework is used to demonstrate that a rich set of archived stop-level data can facilitate useful and regular assessments of transit service (18). Assumptions made here can be loosened or varied according to the analyst’s needs.

**MODEL DESCRIPTION**

After Newell (10), the total cost expression is formulated with two cost components: access cost and riding and stopping cost. Access cost depends on the number of passenger boardings and alightings at each stop and on the access speed \( v \). Stop spacing affects passenger walking distance; thus, the cost is formulated by unit distance. According to the previous assumptions, the access cost \( C_a \) over an interval of length \( s \) is

\[
C_a = n l \lambda = \left[ ps \right] \times \frac{s}{4} \times \left[ \frac{\gamma_v}{v} \right] = \frac{ps \gamma_v}{4v} \tag{1}
\]

where

- \( n \) = average number of passengers boarding and alighting per stop = \( ps \),
- \( l \) = average distance traveled \( s/4 \),
- \( \lambda \) = cost per unit distance,
- \( v \) = passenger access speed, and
- \( \gamma_v \) = average cost per unit time per person for access.

The riding and stopping cost comprises the in-vehicle waiting time for bus passengers during boarding and alighting times. With closer spacing, more time is consumed by boardings and alightings because of the fixed deceleration and acceleration time needed to stop. The in-vehicle time required for a bus to stop for passenger boarding and alighting is the dwell time plus the time lost to vehicle deceleration and acceleration. The total riding and stopping cost \( C_r \) in an interval of length \( s \) is then

\[
C_r = N(t_r + t_l) \lambda = N \times \left[ \frac{s}{V} - \tau P_s \right] \times [\gamma_r] \]

\[
= \frac{N s \gamma_r}{V} + N \gamma_r (1 - e^{-\beta}) \tag{2}
\]

where

- \( N \) = expected number of passengers on the vehicle,
- \( t_r \) = riding time,
- \( t_l \) = lost time,
- \( V \) = vehicle cruise speed,
- \( \tau \) = time lost in stopping to serve passengers,
- \( \gamma_r \) = average cost per unit time per person for riding, and
- \( P_s \) = probability that vehicle actually stops (1 – \( e^{-\beta} \)).

The average cost per unit length \( s \) is then

\[
C = \left( \frac{C_a + C_r}{s} \right) = \left[ \frac{ps \gamma_v}{4v \gamma_r \tau} + \frac{(1 - e^{-\beta})}{ps} \right] \gamma_r \tau \beta N + \frac{N \gamma_r}{V} \tag{3}
\]

where

- \( \beta = 4 \gamma_r / \gamma_v \tau \beta N \) (unitless),
- \( \gamma_v = \) value of riding time compared with access time (<1, maybe \( \gamma_v \propto 1/\gamma \)), and
- \( \tau N \) = number of passengers with origins or destinations that lie within a distance one can travel by access (walking) in lost time \( \tau \).
Note that $\frac{\gamma_r}{\gamma_a}$ is approximately 1 for walking. In addition, walking speed $v$ is approximately 4 ft/s. So the optimal spacing can now be written as

$$s \approx \frac{4 \tau N_p}{p v}$$

The number of passengers on the bus and the density of origins and destinations are both related to headway $h$. But the effects of $h$ are canceled out here. Thus stop spacing $s$ is independent of $h$ for $\beta > 2$.

These results are now used in a case study that uses high-resolution stop-level data for one route.

### DATA COLLECTION

TriMet began using an automated BDS in the late 1990s to manage and collect data about the performance of its fleet. These data provide TriMet with abundant information that it has used to improve the performance and efficiency of its transit system. Each day, about 700 TriMet buses travel Portland’s city and suburban streets on more than 90 different bus routes, collecting data at each scheduled and unscheduled stop. The entire fleet is equipped with the BDS system, and about 75% of the buses also are equipped with automatic passenger counters. TriMet’s BDS database includes the following data fields for each stop (19–21):

- Date: service date;
- Train: in assigning trips, TriMet blocks the scheduled trips together to form what is known as a train, each with a unique identification number;
- Route: route number;
- Direction: inbound or outbound (1 is inbound, 0 is outbound);
- Trip: each trip has a unique number;
- Arrive time: time bus arrives at stop or time door opens;
- Depart time: time bus leaves stop;
- Location: unique geocoded identification number for each scheduled stop;
- Distance: odometer reading of cumulative distance traveled (in miles);

The average cost per unit length is then

$$C = \frac{ps}{\beta} + \frac{(1 - e^{-\gamma})}{ps} \gamma_r \tau N_p + \frac{N_p}{V}$$

Equation 4 indicates that stop spacing $s$ is independent of $V$ and $\gamma_r \tau N_p$. Therefore, the choice of stop spacing $s$ depends solely on $\beta$. As shown in Figure 4, the optimal $s$ changes with $\beta$. The objective of optimizing stop spacing with the constraint of minimizing the total cost is then

$$C_s = \frac{ps}{\beta} + \frac{(1 - e^{-\gamma})}{ps}$$

It is assumed that the total cost $C_0 = 1$ in Equation 5 when the number of passengers $ps$ is zero. The minimized total cost is determined by two functions: $ps/\beta$ and $(1 - e^{-\gamma})/ps$.

The total cost reaches a minimum when $ps/\beta$ is equal to $(1 - e^{-\gamma})/ps$. Note that $ps = ps^*$ when the total cost reaches the minimum, as shown in Figure 5a.

Figure 5a shows that if $\beta < 2$, the sum can be increasing at $ps = 0$; that is, let passengers on and off wherever they want in a demand-responsive format. If $\beta > 2$, then $ps > 1$ and $(1 - e^{-\gamma})/(ps)$ can be approximated by $1/(ps)$, as shown in Figure 5b. If $P$, is treated as 1 for a large $\beta$,

$$\frac{1}{ps} \Rightarrow ps^* = \sqrt{\frac{\beta}{\gamma_r \tau N_p}}$$

Note that $4(\gamma_r/\gamma_a)$ is approximately 1 for walking. In addition, walking speed $v$ is approximately 4 ft/s. So the optimal spacing can now be written as

$$s = \sqrt{\frac{4 \tau N_p}{p v}}$$

The number of passengers on the bus and the density of origins and destinations are both related to headway $h$. But the effects of $h$ are canceled out here. Thus stop spacing $s$ is independent of $h$ for $\beta > 2$. These results are now used in a case study that uses high-resolution stop-level data for one route.

![Figure 4 Cost function.](image)

![Figure 5 Model description (cost and passengers).](image)
Maximum speed: maximum speed achieved between stops;
Dwell: time door is open;
Door: door status (front and rear);
Lift: lift use flag;
On: number of passengers boarding;
Off: number of passengers alighting;
Vehicle: vehicle number; and
Load: calculated estimated passenger load.

CASE STUDY

The preceding model is applied to a case study on inbound Route 19. A basic almanac of the Route 19 data include

- Direction: all inbound trips;
- Analyzed data: February 20, 2007, to January 5, 2008 (370 days);
- Route length: 9.27 mi;
- Number of stops: 52;
- Current mean spacing: 942 ft;
- Mean trip time: 29.2 min;
- Number of trips: 19,344;
- Mean weekday headway with 66 trips over 20.5 h service: 18 min (higher on weekends);
- Mean number of stops per trip: 18.3;
- Mean boardings and alightings per trip: 33.2 passengers;
- Mean boardings and alightings per mile: 3.6 passengers;
- Mean passengers on bus per stop: 7.9 passengers; and
- Mean lost time: 33.6 s.

The inbound direction follows Glisan Street, an arterial parallel to Interstate 84, toward downtown Portland, as shown in Figure 6. Land use patterns are also visible in Figure 6. With a street grid based on 20 blocks per mile in many Portland neighborhoods (264 ft per block), and an average of 942 ft stop spacing, there is approximately one bus stop every 3.5 blocks along the route. After data were cleaned, a total of 17,076 inbound trips from February 20, 2007, to January 5, 2008, more than 370 days, were examined.

Current Bus Stop Spacing

First, a basic statistical analysis on the current bus stop spacing is shown to characterize the situation. As mentioned, the variables, including number of passengers on bus \( N \), density of origins and destinations \( p \), and time lost due to stopping to serve passengers \( \tau \), are analyzed on the basis of 1 year’s archived data. Figure 7 shows the sequential stop spacing as well as the mean passenger load for the entire year by stop. Over the 52 inbound stops, the mean spacing is 942 ft, and the mean load ranges between 1 and 12 passengers. On the basis of the described spacing model, the current total user cost can be estimated by assuming a value of $16/h for access cost (waiting + walking) and $8/h for riding cost (22). Travel time generally is valued at half the average wage rates and at two or three times higher for time spent driving in congestion, walking to a transit stop, waiting for a bus, or traveling in unpleasant conditions such as in a crowded vehicle (22). This translates to a cost per passenger per unit length of $0.64 for access cost and $2.30 for riding cost. The higher riding cost is due to time lost at more than the optimal number of stops, and the lower access cost indicates that the bus stop frequency provided a higher level of accessibility. From the perspective of spacing optimization shown in Figure 1, current spacing has not reached the minimum user cost and has potential for optimization. At the same time, passenger load is increasing as the bus approaches downtown. Figure 8 shows the results of an analysis testing the statistical significance of the association between stop spacing and passenger load for Route 19.

Figure 8 shows the correlation between passenger load and stop spacing, to identify whether a change in passenger load is associated with a change in current spacing. As shown in Equation 7, the spacing...
FIGURE 7  Current Route 19 inbound bus stop spacing and mean passenger load (number of stops, n = 52; average stop spacing, \( \mu = 942 \) ft).

FIGURE 8  Correlation between passenger load on bus and current stop spacing.
is linear with the square root of passenger load. In Figure 8, the $x$-axis shows the square root of the number of passengers on the bus by stop, and the $y$-axis shows the corresponding spacing. The correlation coefficient $R$ is 0.0996, which is less than 0.273 with 50 degrees of freedom and probability 0.05 in the $R$ table. This means that the correlation between these two variables is insignificant; that is, the current spacing is not associated with the number of passengers on the bus. The passengers on the bus experience more frequent stops, adding additional travel time, which raises the total riding cost. Conversely, more stops increases accessibility by reducing walking distance and then decreases access cost. In other words, from an individual user’s perspective, total riding cost is higher than total access cost.

**Passenger Load**

The distribution of number of passengers on the bus for the entire year every time a bus stopped at each bus stop also was analyzed. As shown in the histogram in Figure 9a, the $x$-axis is the bin containing the number of passengers, and the $y$-axis is the percentage of data falling into the corresponding bin. With the normal distribution fitting, the average value every time a bus stopped at each bus stop during the entire year was 7.9 passengers with a standard deviation of 2.8 passengers. The maximum number of passengers on the bus at each stop is 34 passengers within a 95% confidence interval.

**Boardings and Alightings**

More than 566,000 passenger movements were analyzed. The distribution of passenger boardings and alightings for each trip was also analyzed to better understand the distribution, as shown in Figure 9b. The density of origins and destinations $p$ can be calculated from the archived boardings and alightings in the BDS database. The mean number of boardings and alightings was 33.2 persons per trip, and thus the passenger density $p$ was 3.6 persons/mi.

**Lost Time**

The time lost to stopping to serve passengers $\tau$ in the spacing model can be obtained from the value of mean delay due to stopping, including dwell time for serving passenger boarding and alighting, the time during which the door is opened and closed, and the deceleration and acceleration times. This is illustrated by a hypothetical time–space trajectory, shown in Figure 10. Consider a hypothetical trajectory of a vehicle traveling between two stops of which the distance is $D_i$, as in Figure 7. The $x$-axis in the figure is time and the $y$-axis is distance. There are certain points along this trajectory that an observer in the vehicle or at a boarding point can measure quite accurately, namely, the time (and location) when the door of the vehicle first starts to open, $o_1$; when it is fully open, $o_2$; when it first starts to close, $c_1$; and when it is fully closed, $c_2$. The delay due to stopping is the free-flow trip time subtracted from the stop time, that is, $t_{\text{stop}} - t_{\text{free}}$, assuming
that the acceleration time is equal to the deceleration time. By using recorded arrival time, departure time, maximum speed, and stop mileage data, the mean delay due to stopping $\tau$ was calculated as 33.6 s. The number of passengers on bus $N$ also can be directly obtained from the passenger load record in the database.

**Optimized Stop Spacing**

Once the value of variables is calculated, including density of origins and destinations $p$, time lost in stopping to serve passengers $\tau$, and number of passengers on bus $N$, the optimal bus stop spacing can be obtained from the model by using Equation 7. The results are shown in Figure 11. Solid lines show the optimized stop spacing with different values for passenger boardings and alightings, indicating the accessibility of bus stops. The $x$-axis shows the range of passenger load indicating the riding cost. With the distribution of number of passengers on the bus along the route, the optimized spacing can be obtained by intersecting the passenger load. For Route 19, given the average load of 7.9 passengers and a mean of 33.2 passenger movements, an optimal stop spacing of 1,222 ft can be read from Figure 11. A step function indicating 20 blocks/mi is added to the figure to illustrate that actual stops would be placed according to the actual street grid, resulting in a sense of how many blocks are appropriate for the optimized spacing. Any decision-making process for bus stop consolidation and removal can be made over the entire route or for particular segments by using this tool.

To identify consolidated or removable stops along inbound Route 19, the distribution of the passenger load was plotted in the time–space plane as shown in Figure 12. From the load data from the 17,076 trips analyzed over the year studied, the $x$-axis is time and the $y$-axis is the distance along the route. As the bus approaches downtown, it is obvious that the downtown area has a higher passenger load during the morning peak hours. To minimize user cost, inbound Route 19 should have larger stop spacing near the downtown area. This figure illustrates that further analysis could focus on peak periods, weekdays, or weekends or could divide the route into specific regimes according to land use patterns and passenger load information revealed directly from such a plot.

Considering solely the user cost, a conceptual plan for stop consolidation and removal can now be produced. Note that any real stop-consolidation program should involve the many stakeholders along a given route. The before-and-after optimized stop locations are given in Figure 13, which shows that optimal stop spacing is approximately 1,222 ft. TriMet’s service standards (23) call for stop spacing of 780 ft in fully developed residential areas (22 to 80 units per acre) and 100 ft in low-density residential areas (4 to 22 units per acre). In reality, a stop-consolidation plan must also consider other issues, such as land use, travel alternatives, the history and development of a neighborhood, and demographics.

**Sensitivity Analysis**

Optimizing bus stop spacing can help agencies reduce their fleet sizes, improve trip times, and increase service reliability (8, 17, 18, 24). The application of the optimal stop spacing model has resulted in a possibility of removing or consolidating twelve bus stops for Route 19, considering the desire to minimize user cost. It is now possible to examine the impact of the input parameters on the cost of providing transit service. In general, from TriMet’s perspective, consolidating stops is one strategy that can be used to reduce operating cost. To identify the time saved through bus stop consolidation, a basic trip-time model (19) developed in previous research was applied by using 1 year of BDS data. From the trip time model, with the average Route 19 trip time of 29.2 min, the time saved solely because of acceleration and deceleration would be 17 s per stop. With this savings, the trip time of each inbound trip for this route would be reduced by 3.4 min to 25.8 min after 12 stops are removed or consolidated. For the 370 analyzed days of bus runs, a total of 17,076 inbound trips, the time saved would be 977 h during the year. With a basic assumption of $60/h operating cost, about $60,000 could be saved by TriMet through stop consolidation for inbound Route 19. It is possible to assess a potential systemwide operations cost savings...
for the entire year by using this approach. These cost savings are hypothetical and might not be translatable to real savings since, for example, headways may be set by policy.

The time savings could be used to improve service by adding more trips. Given that TriMet provides 66 scheduled inbound trips per weekday on Route 19, the total savings due to consolidation could be up to 3.7 h service time per day. Without performing a complete operational analysis, this could allow the addition of approximately 7.6 additional trips per weekday on inbound Route 19. This would result in improved headways, whereby the mean weekday headway would drop from 18.0 min to 16.1 min.

Increased stop spacing after optimization would have to be balanced carefully against the additional walking or access distance for some passengers and the negative prospect of removing bus stops. Any stop-consolidation decision would have to consider existing passenger activity and land use patterns. The benefits and costs also are analyzed from the user perspective. As illustrated in the stop-spacing model in the previous section, the optimized spacing is related to the ratio of the value of access time to that of riding time.

Table 1 shows the relationship between the ratio of assumed access time to riding time and the corresponding user cost per unit length. As shown, with the optimized spacing the total user cost would be reduced at the expense of increased access cost. Some researchers debate that the value of access cost is weighted higher than riding cost. At this point, the spacing model included ratio of value of access time to value of riding time as a factor to illustrate the difference between access cost and riding cost. Although the calculated access cost is higher than the current condition, the value still appears to be reasonable after optimization.

CONCLUSION

Transit operators face the challenging task of increasing farebox revenue to offset operating deficits while minimizing impacts on passenger accessibility. To provide a useful basis for bus stop consolidation, an optimal stop-spacing model is applied in this paper based on minimizing access cost and riding cost. Inbound Route 19 along Glisan Street to downtown Portland, Oregon, was examined as a case study for optimizing spacing. The archived BDS data provided by TriMet was used to perform the evaluation. According to the model calculations, the theoretical average spacing is 1,222 ft, 280 ft larger than the current mean spacing. Per a benefit–cost assessment, there is potential for a $60,000 reduction in annual operating cost. Similarly, the entire bus system’s operating cost can be evaluated. The theoretical stop-spacing value is provided for planners and decision makers as a powerful performance metric. Future research should continue to exploit the valuable archived BDS data. Choices of stop location
and stop-consolidation programs should be carefully examined by considering demographics and many other practical factors.

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REFERENCES


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