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Optimal Bus Stop Spacing for Minimizing Transit Operation Cost

Huan Li¹ and Robert L. Bertini²

Abstract

With the increasing attention to finance issues relative to transit operation, a bus stop spacing model is generated with the aim at minimizing the operation cost without impact on transit accessibility. Two cost functions are considered in the model including passenger access cost and in-vehicle passenger stopping cost aiming at minimizing total cost. A bus route in Portland, Oregon, USA is examined as an example using Archived Bus Dispatch System (BDS) data provided by TriMet, the regional transit provider for the Portland, Oregon metropolitan area. Based on the optimization model, the theoretical optimized bus stop spacing is 930 feet comparing to the current value 802 feet.

Key Words: Bus Stop Spacing; Access Cost; Stopping Cost; Optimization; Bus Dispatch System

Introduction

As transportation funding becomes increasingly competitive, transportation operational issues have been receiving a high level of attention from transportation professionals and decision-makers. The classical operational issues include congestion mitigation, travel-time reduction, air-quality improvement, reduction of operating costs, and safety improvement. Conformance to one or more of these operational issues is a requirement for receiving most transportation-related federal funding.

Public transit is widely considered as being environmentally friendly because of its high loading capacity. The number of passengers carried by a typical bus in some urban areas can exceed the equivalent of 40 passenger cars during rush hours. Buses are known to make frequent stops, particularly during peak hours, to provide services to transit patrons. Among the impacts are delays to through riders, increased operating cost because of stopping delays, and shorter walking times parallel to the route. One current service characteristic is that bus stop spacing is too close on many routes, slowing bus operation.

Frequent stops are also costly to transit operators because travel times are increased as the number of times buses stop and accelerate/decelerate increase. Conversely, transit operators risk providing inaccessible services which may lead to loss of patrons when bus stops are distantly spaced to avert the problems associated with closely spaced stops. As an effort to encourage transit patronage by providing highly accessible bus services, transit operators typically provide too many stops, particularly at high-density land use locations, which sometimes are counter-

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productive. Bus stop consolidation programs have begun in some cities. Based on Newell (1994), this paper generated a bus stop spacing model for minimizing the operation cost without impact on the transit accessibility. A bus route is examined as an example using Archived Bus Dispatch System (BDS) data provided by TriMet, the regional transit provider for the Portland, Oregon metropolitan area.

Previous Research

The operational effect of bus-stop spacing has been a critical issue. Closely spaced bus stops not only make the passenger's in-vehicle time longer, but disrupt traffic flow on the bus route, particularly during peak hours because buses make frequent stops to serve customers. There has been some research on optimal bus stop spacing using different methods. Furth and Rahbee (2000) studied the optimal bus stop spacing through dynamic programming and geographic modeling. A geographic model was used to distribute the demand observed at existing stops to cross-streets and parallel streets in the route service area, resulting in a demand distribution that included concentrated and distributed demands. A dynamic programming algorithm was used to determine the optimal bus-stop locations. A bus route in Boston was modeled, in which the optimal solution was an average stop spacing of 400 m (4 stops/mi), in sharp contrast to the existing average spacing of 200 m (8 stops/mi).

Saka (2001) built a model for determining optimum bus stop spacing in urban areas. The proposed model was derived from the fundamental relationships that exist among velocity, uniform acceleration/deceleration, and displacement, and among the average bus operating speed, headway, required fleet size, and potential system capacity.

Some U.S. cities have evaluated the proper bus stop spacing toward improving bus service. Kemp (1982) discussed an analysis of data describing 40 months' operating experience for the San Diego Transit Corporation. The analysis used a simultaneous-equations model estimated by using a pooled time-series/cross-sectional database. The model related ridership on a specific bus route in a specific month to various influencing factors, particularly the service and fare policies adopted by the system.

Ercolano (1984) evaluated limited-stop bus operations in Manhattan by comparing performance characteristics and passenger use to those of local service on the same routes. Among the types of service-related cost savings cited from employing limited scheduling, annual savings from peak vehicle reductions amount to more than 60 percent of total possible economies expected through using limited bus runs for roughly half the peak period trips on suitable routes. Two sets of bivariate regression models were calibrated to serve as sketch-planning guides for reviewing routes that could benefit from limited-service implementation. Five warrants explaining what service revisions and performance modifications are essential if limited bus operations are to be feasibly used to cut costs and attract ridership are presented.

Like many urban transit providers, TriMet has faced a growing challenge in its efforts to deliver reliable and timely bus service over a regional road system that has become increasingly congested. The Streamline project, initiated in 1999 (El-Geneidy, et al., 2006), aimed to reduce operating costs while maintaining service frequency—to optimize bus stop spacing for stop consolidation. This paper built a model with the constraint of access and riding cost for minimizing the total cost. Using TriMet's archived data, a bus line was examined as an example.

Methodology

The operational effect of bus-stop spacing has been a critical issue. There are many objectives that might impact bus stop spacing. Closely spaced bus stops provide a short distance for passenger access. Large spaced bus stops minimize passenger's in-vehicle time. Thus, expressions are derived for an aggregate total cost function including:

- Minimizing access cost C_a favors small *spacing*
- Minimizing riding cost C_r 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 longer trip length L can be minimized by minimizing cost per unit length.

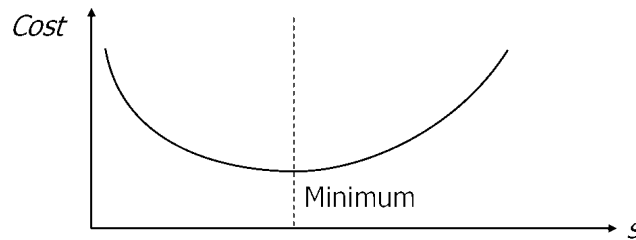


Figure 1. Concept of spacing optimization.

Dimensional analysis is used to set up equations in terms of dimensionless parameter ps , where:

s = stop spacing (distance)

p = density of trip origins plus density of trip destinations for passengers who board the same bus (Number of passengers /distance)

ps = Expected number of passengers boarding and alighting per stop

The objective function is examined for choosing s . The trip origins and destinations are considered to be distributed in two-dimensional plane. As shown in Figure 2, to travel to a stop, passenger walks both perpendicular and parallel to route.

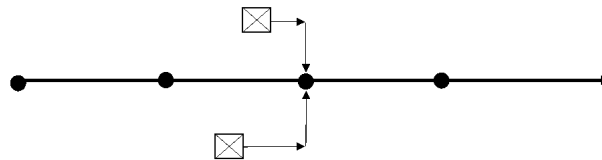


Figure 2. Dimensional plane.

For optimizing spacing, the model is based on the following assumptions:

- Number of passengers boarding or alighting at a stop is Poisson distributed;
- $E[\text{number of board or alight}] = ps$
- $P_r[\text{number of boarding/alighting} = x]$ is approximately Poisson distributed
- The probability that vehicle does not stop (no passenger wants to board or alight) = $1 - P_r[\text{number boarding/alighting} = 0] = e^{-ps}$ ($x=0$), so $P_r = 1 - e^{-ps}$
- Travel demand is uniformly distributed over s ;

- For analyzing spacing, it is imagined that origins and destinations are distributed along the route in one dimension. The perpendicular access is ignored;
- Average access distance (parallel only) $l = \frac{s}{4}$, see Figure 3.

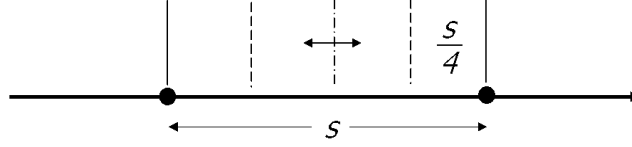


Figure 3. Access distance.

Based on this method, the bus stop spacing of a bus route in Portland, Oregon is examined using archived Bus Dispatch System (BDS) data provided by TriMet. Comparing the status, a theoretically optimized spacing is put forward as a reference for transit service improvement.

Model Description

The total cost expression is formulated with two cost functions:

- Access cost
- Riding and stopping cost

The access cost depends on the number of passenger ons and offs at a stop, and on the access speed v . The spacing is related to the passenger's walking distance. Thus, the cost is formulated by unit distance. According to the previous assumptions, the access cost C_a in interval of length s can be written as:

$$C_a = n l \lambda_a = [ps] \times \left[\frac{s}{4} \right] \times \left[\frac{\gamma_a}{v} \right] = \frac{ps^2 \gamma_a}{4v} \quad (1)$$

n = average number of passenger boarding and alighting per stop = ps

l = average distance traveled $\frac{s}{4}$

λ_a = cost per unit distance

v = passenger access speed, assumed to be 4ft/s

γ_a = average cost per unit time per person for access

The riding and stopping cost is determined by the in-vehicle time of passengers on vehicle waiting the ons and offs. The closer spacing the more time consumes on the ons and offs. The formulated in-vehicle time a bus stopping for passengers boarding and alighting is the dwell time plus lost time for acceleration and deceleration. The riding and stopping cost C_r in interval of length S can then be formulated as:

$$C_r = N(t_r + t_l) \lambda_r = N \times \left[\frac{s}{V} + \tau P_r \right] \times [\gamma_r] = \frac{Ns \gamma_r}{V} + N \tau \gamma_r (1 - e^{-ps}) \quad (2)$$

N = expected number of passengers on vehicle
 t_r = riding time
 t_l = lost time
 V = vehicle cruise speed
 τ = time lost in stopping to serve passengers
 γ_r = average cost per unit time per person for riding
 P_r = probability that vehicle actually stops ($1 - e^{-ps}$)

And then, the average cost per unit length s is:

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

Given that $\beta = 4 \frac{\gamma_r}{\gamma_a} v \tau pN$ (unitless)

$\frac{\gamma_r}{\gamma_a}$ = value of riding time compared to access time (<1 , maybe $\frac{1}{3} - \frac{1}{4}$)

τpN = number of passengers with origins or destinations that lie within a distance one can travel by access (walking) in lost time τ

Then, the average cost per unit length can be formulated as:

$$C = \left[\frac{ps}{\beta} + \frac{(1 - e^{-ps})}{ps} \right] \gamma_r \tau pN + \frac{N\gamma_r}{V} \quad (4)$$

From equation 4, it indicates that bus stop spacing s is independent of V and $\gamma_r \tau pN$. Therefore, the choice of bus stop spacing S depends solely on β . As shown in Figure 4, the optimized s changes with β . The objective of optimizing bus stop spacing with the constraint of minimizing the total cost can then be formulated as:

$$C_0 = \frac{ps}{\beta} + \frac{(1 - e^{-ps})}{ps} \quad (5)$$

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

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

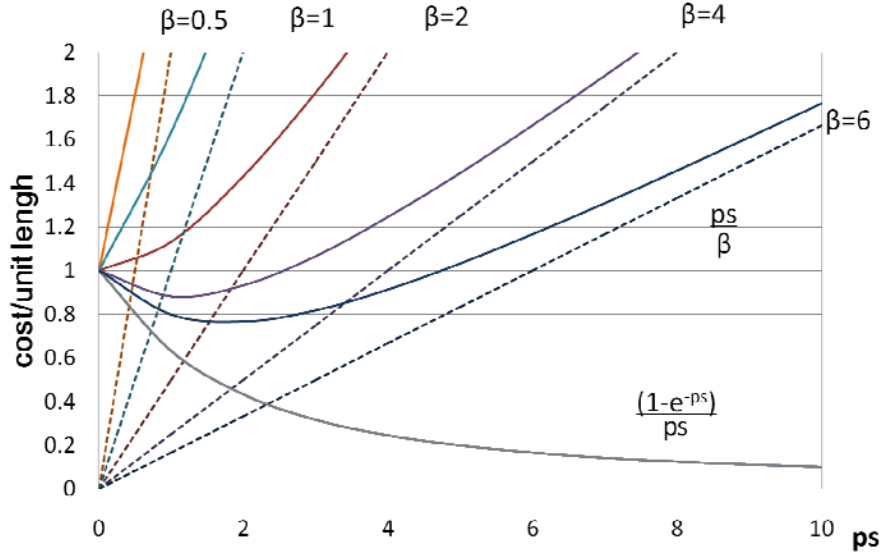


Figure 4. Cost function.

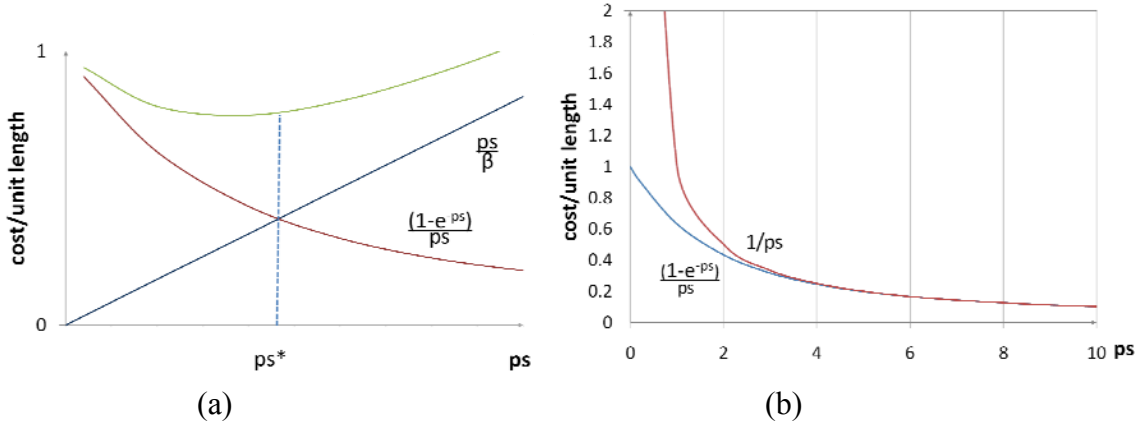


Figure 5. Model description.

It can be seen from Figure 5(a) that if $\beta < 2$, sum can be increasing at $ps = 0$, that is, let passengers on and off wherever they want; if $\beta > 2$, then $ps^* > 1$ can approximate $\frac{(1-e^{-ps})}{ps}$ as $\frac{1}{ps}$ (shown in Figure 5(b)). P_r is treated as 1 for large β .

$$\text{Then, } \frac{1}{ps} = \frac{ps}{\beta} \Rightarrow ps^* = \sqrt{\beta} \Rightarrow s^* = \frac{\sqrt{\beta}}{p} = \frac{\sqrt{4 \frac{\gamma_r}{\gamma_a} v \pi N p}}{p} \quad (6)$$

It is noted that $4 \frac{\gamma_r}{\gamma_a}$ is approximately to be 1 for walking. In addition, walking speed v is approximately 4 ft/s. So the optimized spacing is written as:

$$s^* = \frac{\sqrt{4\tau N p}}{p} = \sqrt{\frac{4\tau N}{p}} \quad (7)$$

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

Data Collection

Portland’s local transit provider TriMet began using an automated bus dispatch system to manage and collect data about the performance of its fleet of buses in the late 1990s. These data provide TriMet with an abundance of useful information that it has used to successfully improve the performance and efficiency of its transit system. Each day, TriMet buses travel Portland’s city and suburban streets on more than 90 different bus routes, collecting data at each scheduled and unscheduled stop. This rich source of transit data including time, number of passenger ons and offs, number of passenger load, dwell time and so on for each stop and each trip, also has the potential to aid traffic engineers in evaluating arterial performance using the bus fleet as probes.

As shown in Table 1, the date is shown in the first field, the vehicle number is displayed in the second field. In assigning trips, TriMet blocks the scheduled trips together in order to form what is known as a “train”. Each train has a unique identification number, and is displayed as part of any row that is obtained from the BDS, in addition to the operator identification number and the route number (Bertini and El-Geneidy, 2004; Berkow, et al., 2007). Each scheduled stop is geo-coded and has a unique identification number linked to a map database.

Table 1. Sample TriMet bus dispatch system data.

Service date	Train	RTE	DIR	TRIPNO	ARRTime	DEPTTime	LOC_ID	Distance	Max speed	Dwell	Door	Lift	ONS	OFFS	VEHNO	Estload
09/17/06	1935	19	1	1050	5:59:16	5:59:34	10860	0	24	0	0	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:00:44	6:00:48	10955	0.30	29	0	0	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:01:56	6:02:04	2156	0.67	33	0	0	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:02:14	6:02:38	2153	0.81	33	9	1	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:03:06	6:03:10	2149	1.09	34	0	0	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:03:16	6:03:40	2148	1.24	32	7	1	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:03:50	6:03:56	2145	1.10	30	0	0	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:04:02	6:04:08	2143	1.40	30	0	0	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:04:24	6:04:54	11831	1.56	36	0	0	0	0	0	2810	0
09/17/06	1935	19	1	1050	6:05:10	6:05:14	2137	1.71	30	0	0	0	0	0	2810	0

This paper represents an example of using Trimet data to evaluate and improve transit service in terms of bus stop spacing. Route 19 (inbound) was selected to examine the bus stop spacing along this route. Data from one half month (September 17–30, 2006) was used to calculate the theoretical spacing.

Case Study

The model presented in the previous section is applied to a case study on inbound Route 19, which is 6.38 miles long, with a total of 43 stops in the city of Portland, Oregon. Based on the archived mileage and distance field data, the current average bus stop spacing is 802 feet, as shown in Figure 6. With 20 blocks/mile in Portland (264 feet per block) there is approximately one bus stop every three blocks.

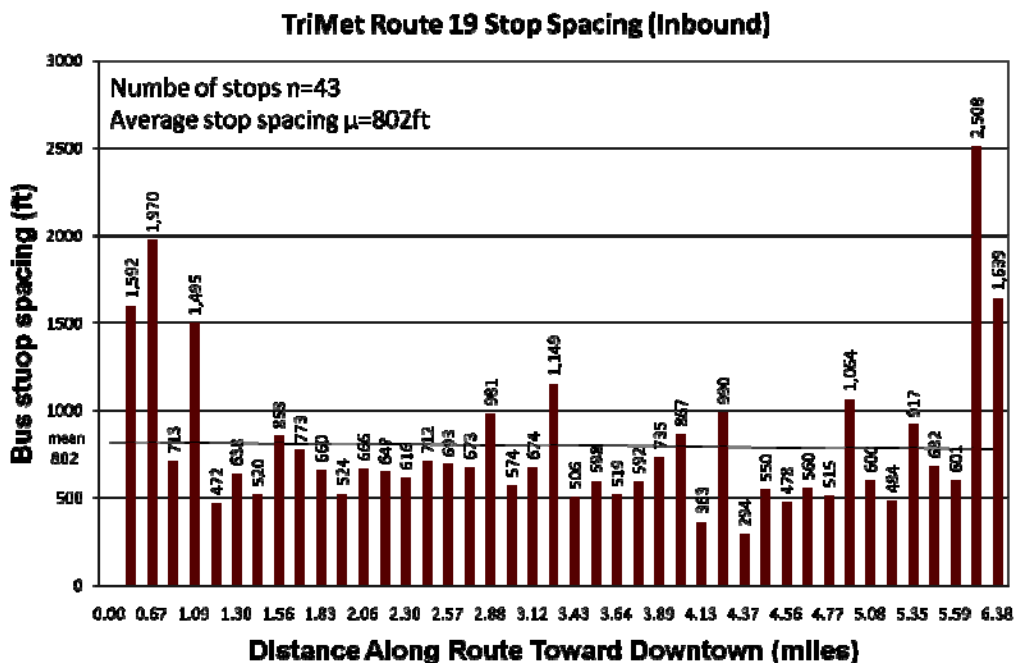


Figure 6. Current bus stop spacing.

As mentioned above, the value of variables including density of origins and destinations p , time lost in stopping to serve passengers τ and number of passengers on vehicle N are calculated based on the archived data. A total of 743 trips from September 17–30, 2006 were examined.

The density of origins and destinations p can be calculated by the number of ons and offs in the data file. The average number of ons and offs is 36.8 persons per trip. So the density p was 5.77 persons/mile.

The time lost in stopping to serve passengers τ in the model can be obtained from the value of mean delay due to stopping including the dwell time for serving passenger boarding and alighting bus, door open and close time and acceleration and deceleration time illustrated by a hypothetical time-distance trajectory in Figure 7.

Consider a hypothetical trajectory of a vehicle traveling between two stops which the distance is D_i as in Figure 7. 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 , or when it is fully open, o_2 , when it first starts to close, c_1 , or when fully closed, c_2 . The delay due to stopping is the free flow time subtracted by the stop time, that is, $t_{stop} - t_{free}$ assuming that acceleration time is equal to deceleration time. Using the recorded arrival time, departure time, maximum speed and stop mileage data, the mean

delay due to stopping τ was calculated as 28.4 s. The number of passengers on the vehicle N also can be directly obtained from the passenger load record in the data file. The maximum passenger load at each stop was 59 passengers.

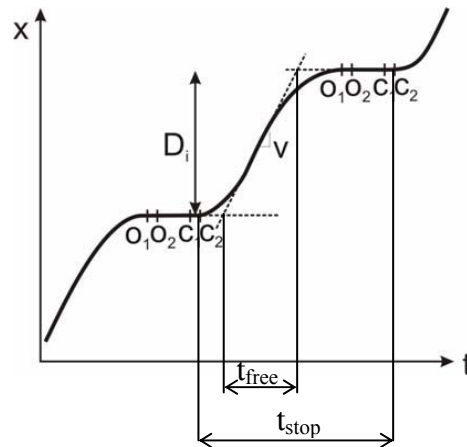


Figure 7. Bus trajectory between two stops.

With the value of variables including density of origins and destinations p , time lost in stopping to serve passengers τ and number of passengers on vehicle N calculated, the optimized bus stop spacing can be obtained based on Equation 7. The outcome is shown in Figure 8. The step function 20 blocks/mile is added to show that how many blocks are appropriate to the optimized spacing.

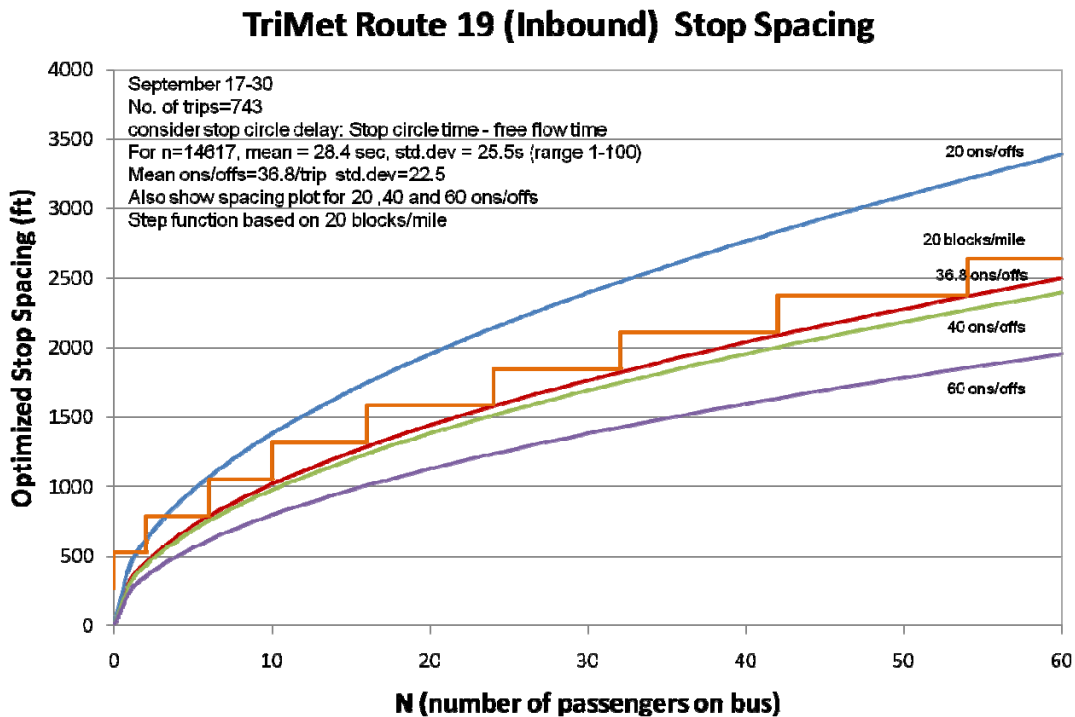
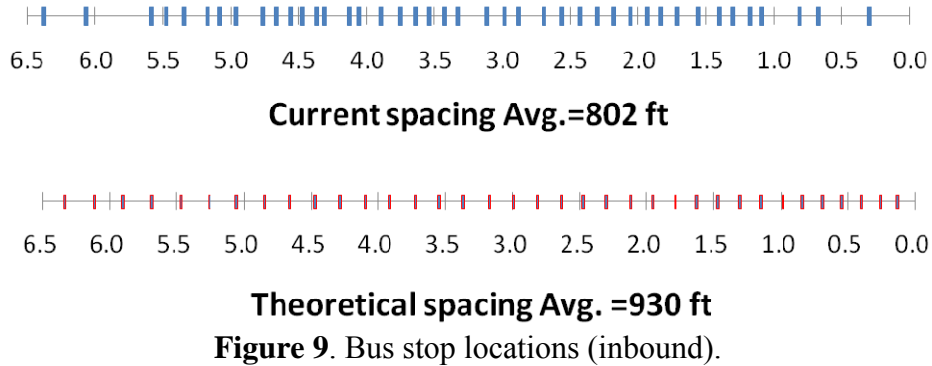


Figure 8. Optimized bus stop spacing.

Compared to the current stop spacing, the average value 802 feet, the theoretical optimized spacing is 930 feet. And the location is illustrated in Figure 9.



Conclusion

Transit operators face the challenging task of increasing farebox revenue to offset operating deficits with minimizing impact on the passenger accessibility. In order to provide a useful ground for bus stop consolidation, the optimized bus stop spacing model is built in this paper with the constraints on access cost and riding cost. The bus line from Woodstock to Downtown in the city of Portland, Oregon is examined as an example for optimizing spacing. The archived BDS data provided by TriMet is used to do the evaluation. According to the model calculation, the theoretical average spacing is 930 feet, 128 feet longer than the current value. The theoretical value is provided for the decision-makers as a powerful reference considering the farebox revenue. In addition, the choice of stop location and the stop consolidation are re-examined with the geography and many practical factors.

Acknowledgement

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