Factors Influencing Effectiveness of Transit Signal Priority and Late-Bus Recovery at Signalized-Intersection Level

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Transit priority systems have the potential to improve transit performance and address capacity constraints by giving priority to transit movements over other traffic. This research focused on the effectiveness of conditional transit priority or the manipulation of traffic signal timing plans to reduce delay of late transit buses. The integration of two transportation subsystems—traffic signals and public transit systems—was studied. These subsystems interact along a congested corridor where they share a common roadway infrastructure and transit signal priority (TSP) regulates the interaction between traffic signals, passenger traffic, and buses. Previous research has focused on the evaluation of bus TSP performance at the route level. In practice, it is important to understand not only TSP performance at the route level but also the impact of TSP at the level of the traffic signal intersection (e.g., to allow progression in major cross streets). TSP can significantly improve performance at specific intersections, even though at the route level TSP shows a more modest impact. This study proposed the integration of several data sets such as bus scheduling and location, passenger flows, and TSP requests to evaluate schedule adherence at the stop level and TSP performance at the level of the signalized intersection. A congested arterial corridor was analyzed and regression analysis was used to determine the key factors that affect bus travel time and schedule recovery for late buses. TSP was found to be most effective at lower-volume intersections where queuing was less problematic. Implications of the findings are analyzed and discussed.

Constraints to congestion mitigation and roadway capacity are at the forefront of issues facing transportation professionals. These challenges along with budgetary restraints require thoughtful and innovative use of current facilities to maximize capacity. Multimodal strategies have now become the norm, replacing the considerations of single-occupancy vehicles for those of pedestrians, cyclists, and transit users. This shift promotes priority for those modes that maximize user allocation while minimizing roadway capacity constraints. Public transit systems such as bus networks, light rail lines, and streetcars are able to allocate roadway access to more users without the extra capacity requirements of single-occupancy vehicles (*1*). These modes allow the transportation system to provide additional benefit to users with fewer costs and therefore should be encouraged and sustained. Transit signal priority (TSP) can improve transit operations and address capacity constraints by prioritizing the movement of buses over passenger vehicles (*2–4*). For instance, during peak demand periods in which the potential for queuing is high, TSP can allocate more green time for transit vehicles to travel through intersections and remain on schedule.

Previous research has mostly focused on the study of TSP performance at the route level; however, in some practical situations, it is important to identify the location of the signalized intersections that significantly affect TSP performance. For example, a bus transit corridor may intersect several major cross streets for which traffic signal progression can be desirable. By understanding TSP performance at the level of signalized intersections, it is possible to provide progression for cross-street signals for which TSP does not play a significant role while keeping TSP on major crossings, where TSP plays a significant role in the schedule recovery of late buses. As this research indicates, it is also possible that TSP shows modest improvements at the aggregated-route level but significant improvement and bus recovery at specific intersections.

Unfortunately, because of the stochasticity associated with bus schedules and operations, it is not possible to identify a priori the signalized intersections that perform a key role in TSP performance and late-bus recovery. This research aims to fill that research gap. The study used a diverse group of data sets to identify methods for analyzing TSP effectiveness: bus scheduling and routing data, passenger boarding and alighting data, and TSP request data.

The goals of this research were (*a*) to determine specific periods and traffic signals for which TSP has enabled schedule recovery, (*b*) to develop a method for identifying factors influencing TSP effectiveness, and (*c*) to create a model to determine the statistical effect TSP and other factors have on bus performance. This method is applied to a congested arterial, southeast Powell Boulevard in Portland, Oregon.

BACKGROUND

In the stochastic environment of a transportation network, transit vehicles are subject to a wide array of unpredictable factors that affect their ability to adhere to a predetermined schedule. Transit priority is the process by which the movement of transit vehicles is given preference or advantages over other vehicle movements. For example, transit vehicles can be given exclusive or separated right-of-way, or changes to transit schedules may depend on peak period traffic volumes. TSP is a specific implementation of transit priority at signalized intersections. TSP strategies can be categorized in three ways (*5*):

1. TSP can be executed with passive or active techniques. Passive TSP techniques involve signal-timing and coordination plans that

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favor transit as well as geometric design features such as bus bays and queue-jump lanes that alleviate transit's impact on roadway capacity. Active TSP is the process of detecting transit vehicles approaching an intersection and adjusting the signal-timing plan to grant immediate right-of-way to the transit vehicle or to reduce any necessary delay.

2. TSP can be divided into relative, partial, or full applications. Relative priority assigns relative costs to transit vehicles and other vehicles in the system and attempts to minimize costs, usually delay, over all vehicles. Partial priority takes a less intrusive approach and attempts to lessen impacts on other vehicles by limiting actions to green extension and phase truncation. Full priority makes every effort, including immediate truncation of green and skipping of phases in conflict with transit vehicles' movements, to minimize the delay of those vehicles at intersections.

3. TSP can be categorized as unconditional or conditional. Unconditional priority grants priority requests no matter the state of the intersection or bus; conditional priority grants priority only if the state of the bus and intersection meets certain requirements. For instance, TSP would be granted only if the following criteria were met: the bus was more than 3 min late, the bus was occupied with passengers, and the intersection did not have a priority request during the previous cycle.

LITERATURE REVIEW

A large body of research focuses on the effectiveness of TSP applications. However, most studies provide values and performance measures that are specific to the particular characteristics of each installation. These installations can be described by the arrangement of the signalized intersections (single, in series, or networked) and the applied signal-timing strategy (fixed control, traffic responsive, coordinated, or adaptive). For instance, delay time and number of stops were used to evaluate TSP at a single intersection controlled by the signal priority procedure for optimization in real time (SPPORT) adaptive signal control system (*6*); the SPPORT system was found to reduce passenger delays compared with fixed-time and actuated-control systems, but TSP impact was limited to delay reduction over the actuated system and not over the coordinated system. Furth and Muller also evaluated TSP for a single intersection (*5*). The focus of their research was the effectiveness of conditional priority and the impact on passenger vehicles. The results showed that conditional priority provided TSP benefits to late buses but reduced vehicular delay to the same level as signal control with no priority.

Some research efforts have focused on arterials. Columbia Pike, an arterial corridor in Arlington, Virginia, was the focus of a TSP study in 2004. Simulation was used to evaluate types of priority in a fixed, coordinated system. The study found that the impacts on other vehicles were not significant and that buses generally benefited from TSP (*7*). Skabardonis evaluated several TSP control strategies, both passive and active, for coordinated intersections (*8*); in that study, both passive and active priority were shown to provide modest improvement on a coordinated corridor with 21 signalized intersections.

Work at the network level includes the evaluation of a strategy for adaptive signal optimization: dynamic allocation of right-of-way for transit vehicles in urban networks (DARVIN) (*9*). DARVIN produced a second green wave for transit vehicles that drop out of vehicle platoons to service bus stops and was shown to reduce person delay significantly. TSP has been evaluated in Portland at the aggregated-route level (*10*). Kimpel et al. evaluated southeast Powell Boulevard; however, the focus was on performance measures related to the variability in bus run times at the route level; these authors did not find a significant systemwide improvement in routes with TSP (*11*). In contrast, the results presented in this paper show significant improvements at some signalized intersections. The key performance measures for some of these studies are shown in Table 1. An evaluation of the performance of TSP appears to have little consistency or a defined approach. While most evaluations show some improvements in performance measures, they do so largely from a segment- or route-level approach.

Unlike previous research efforts, this research focuses on schedule adherence at the level of the bus stop or signalized intersection; the arterial corridor under study is divided into segments between traffic signals. While route-level analysis is useful for understanding the effects on transit vehicles through the entire system, stop-level analysis allows for identification of the signalized intersections along the corridor at which TSP is more effective. In some cases [i.e., Southeast (SE) Powell Boulevard and SE 82nd Avenue], TSP cannot be provided because signal progression at SE 82nd Avenue—a major north–south corridor—receives higher priority from the City of Portland. The proposed intersection and stop-level analysis helps in understanding of the impacts of TSP at intersections near SE 82nd Avenue.

STUDY AND DATA DESCRIPTION

For this study, detailed data were collected for the following 4 days: March 22, April 5, April 8, and April 15, 2011. During these 4 days, researchers were on site during the peak periods (7:00 to 9:00 a.m. and 4:00 to 6:00 p.m.) collecting traffic and bus data and observing traffic flows along Powell Boulevard. Specific bus transit and TSP signal data were automatically collected by TriMet (the public transit agency for the Portland metropolitan area) and the Portland Bureau of Transportation, respectively.

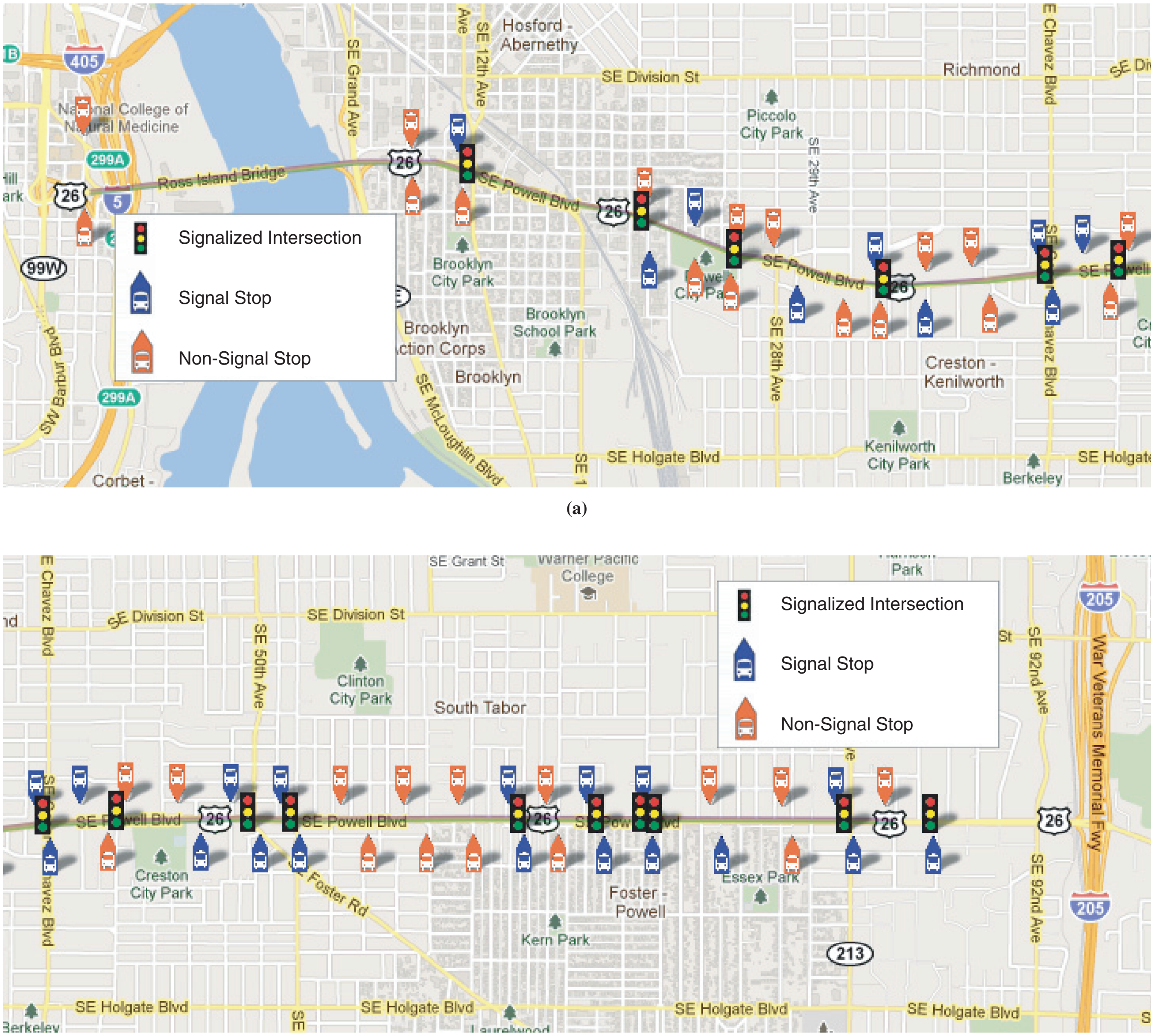
TABLE 1 Research on Transit Signal Priority

Study	Vehicle Delay	Transit Delay	Person Delay	Travel Time	Transit Travel Time	Passenger Wait Time	Stops	Schedule Adherence	Ridership	Wasted Green
Nash (*3*)									X	X
Furth and Muller (*5*)	X	X						X		
Dion and Hellinga (*6*)			X	X			X			
Dion et al. (*7*)			X	X			X			
Duerr (*9*)			X							
Kimpel et al. (*11*)					X	X		X		

TSP implementation characteristics are contingent on the structure and signalization of the transportation facility selected. This study focuses on TriMet's Route 9, a high-demand route that runs along the SE Powell Boulevard corridor and connects the city of Gresham, southeast Portland, downtown Portland, and north Portland. The route segment studied, including the location of stops and the locations of all signalized intersections, is shown in Figure 1. Stops are defined as signal and nonsignal stops, with signal stops being the set of stops directly downstream from an intersection with a TSP-equipped signal. Although Route 9 can be characterized as a medium-frequency route during off-peak hours, high-frequency service is available during the peak-demand hours (*12*). From 6:00 to 9:00 a.m. and from 3:00 to 7:00 p.m., scheduled headways on SE Powell can be as low as 4 to 5 min. This study focuses on a Powell segment that extends between the Ross Island Bridge and the intersection of SE 86th and SE Powell, just before the I-205 freeway. The westbound corridor is defined by the stop at 84th and SE Powell to the Southwest Kelly and Corbett stop. The corridor is approximately 5 mi long, with 14 signalized intersections, two pedestrian crossing signals, and several midblock crosswalks. The segment under study has 54 bus stops split evenly on each side of the street, as shown in Figure 1.

Data Description

The advantage of using the SE Powell corridor as a basis for this study is access to a variety of data sets maintained by several agencies, such as TriMet and the Portland Bureau of Transportation. TriMet's



(a)

(b)

FIGURE 1 SE Powell Boulevard corridor in southeast Portland: (*a*) segment from Ross Island Bridge to 39th Avenue (Cesar Chavez Boulevard) and (*b*) segment from 39th Avenue to I-205 freeway. (Source: Google Maps.)

bus dispatch system comprises automatic vehicle location (AVL) and automatic passenger count (APC) data and records real-time stop-event data on each bus as it leaves a bus stop (*12, 13*).

TriMet Stop-Event Data

Stop-event data are recorded after a bus leaves a stop and details stop-level information, such as location, arrival time, leave time, and scheduled time, and passenger information, such as the number of passengers boarding and alighting as well as lift usage. Stay time is calculated at each stop as departure time minus arrival time, and dwell time is reported as the time doors are open at the stop for passenger boarding and alighting. Scheduled times in the data are scheduled departure times from the bus stop; the buses do not have scheduled arrival times.

TriMet Priority-Request Data

TriMet also logs transit priority-request data made by late buses. When a bus meets the priority-request criteria (discussed in next section), priority is requested by an Opticom light emitter. The interval from the time the Opticom light is activated to the time the priority request is canceled is logged by each vehicle with a bus trip identifier.

Portland TSP

TSP is enabled at all signals in the corridor except SE Powell and SE 82nd, where signal progression is timed for SE 82nd over SE Powell. At these intersections, the priority actions available are green extension and red truncation. TSP is available 24 h/day; however, it is conditional and available only to those buses that meet the following three conditions:

1. The bus is en route. This condition ensures that priority is given only to buses actively serving passengers.
2. The doors are closed. Priority should not be given to a bus that cannot move. For instance, a bus stopped at a nearside bus stop should not affect the timing plan for that intersection. In that situation, when the doors close and the bus is able to move through the intersection, priority can then be requested.
3. The bus is late by at least 30 s (departure time from the last stop is 30 s greater than scheduled). TriMet and the City of Portland have chosen 30 s as the threshold that activates TSP.

TriMet buses' activation of an Opticom light emitter is linked to the AVL and APC systems on each bus, and these conditions are checked in real time. The priority light is deactivated when late buses are less than 30 s late. The signal controllers in use at these intersections are unable to log TSP events, and therefore this research relies on TSP request data provided by TriMet. (It is assumed that TSP requests are provided whenever possible.)

BUS ADHERENCE TO SCHEDULE

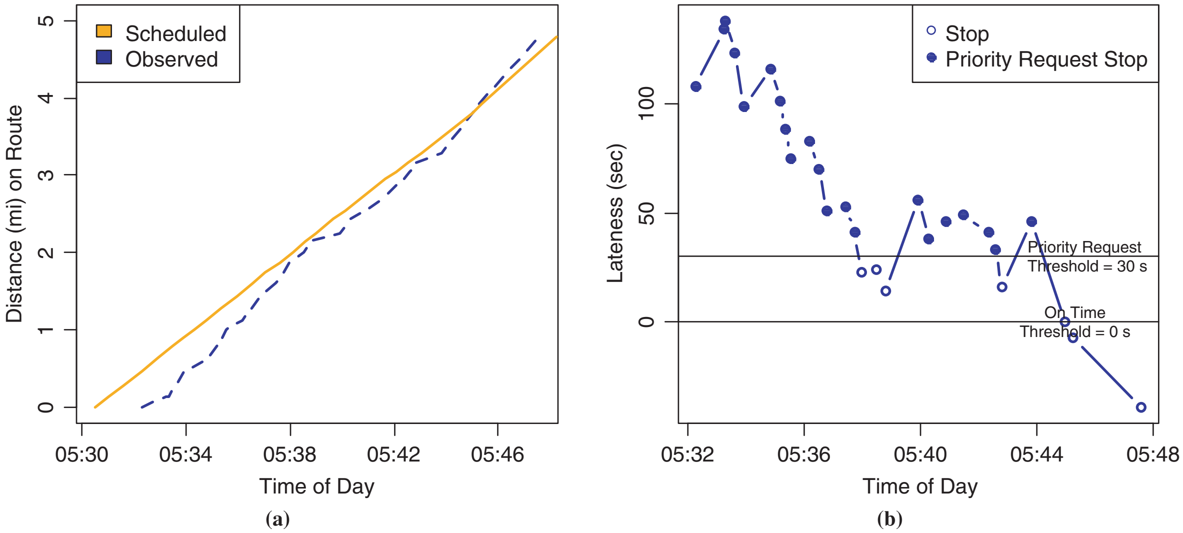
A review of the basic relation between a bus schedule and its actual trajectory is necessary to introduce concepts related to TSP evaluation. Figure 2*a* shows a time–space diagram of active Bus 2012. The dashed line in the figure represents the observed departure times, and the solid line represents the schedule departures; where the two lines intersect, the bus is on schedule.

Calculation of Lateness and Recovery

When the scheduled line is above the observed line, the bus is late; conversely, when the observed line is below the scheduled line, the bus is early; at any y value (distance or location) the difference in x values (time) is the lateness or earliness of the bus, respectively. At any stop i, the parameter lateness, $t_{\text{lateness}}(i)$, is defined as the observed departure time minus the scheduled departure time (Equation 1):

$$t_{\text{lateness}}(i) = \text{actual departure time}(i) - \text{scheduled departure time}(i) \tag{1}$$

A positive lateness value indicates a late bus, and a negative value an early bus. Figure 2*b* shows the lateness of Bus 2012 as it moves



(a) (b)

FIGURE 2 Bus 2012 schedule adherence: (*a*) actual versus scheduled bus trajectories and (*b*) bus lateness.

through the corridor. Each point marks a stop, and the difference in y values between any two stops indicates the recovery between these two stops. For instance, when Bus 2012 leaves Stop 12, it is 50 s late, but when it leaves Stop 13, it is 40 s late; the recovery is 10 s at Stop 13. Thus, $t_{\text{recovery}}(i, j)$ is defined as the difference between lateness values, as shown in Equation 2.

$$t_{\text{recovery}}(i, j) = t_{\text{lateness}}(i) - t_{\text{lateness}}(j) \tag{2}$$

A positive value denotes a schedule recovery, and a negative value denotes a worsening adherence to the schedule between stops i and j (stop j is always assumed to be downstream from i).

During the study period, 15,345 stop events were recorded. Lateness and recovery were first calculated for each bus stop event. Then, the average lateness and average recoveries were calculated, and the number of stop events for which recovery was greater than 15 and 30 s was found. Results are shown in Table 2. The values reported in the column for average lateness give an idea of how all buses in the corridor fare against the schedule at each stop; the column for average recovery shows how lateness changes between stops. Because lateness and recovery distributions tend to have long tails (in both the positive and negative directions), median values are also included. The greatest average recoveries tend to occur during peak periods, especially during the morning peak period (westbound, travel toward downtown Portland) or afternoon peak period (eastbound, travel toward the eastern suburbs). More events occur in the morning westbound and afternoon eastbound because buses are added to meet the higher demand to and from the downtown area, respectively. The lateness in each direction by time of day is also influenced by the scheduled times. As the scheduled buffer time to deal with congestion or uncertain demand increases, lateness tends to decrease.

Stay Time Versus Passenger Movement Time

Stay time is defined as the time a bus remains at a bus stop. Dwell time is the time that doors are open at a stop for passenger boarding and alighting. The time a bus remains at a stop after the boarding of passengers has completed is called holding time, which is used for drivers who are ahead of schedule (early) or when the headway in relation to the previous bus is too short (bus bunching). Holding time can be calculated as stay time minus dwell time (both stay and dwell times are provided by TriMet). Holding time calculated this way may not necessarily be accurate because bus operators often may leave the doors open while holding, effectively extending dwell time and reducing calculated holding time. Therefore, a new parameter, passenger movement time (PMT), is proposed to model more accurately the time necessary for passengers to board and alight. To estimate PMT, the dwell data were filtered to include only records showing that the bus was late, as late buses are likely not to include any holding time. Then, a regression analysis of dwell time indicated that boarding time per passenger was approximately 4.0 s and alighting time per passenger was 2.1 s plus a fixed time of 4.0 s per bus stop. The formula for PMT is shown in Equation 3.

$$\text{PMT} = 4.0 + 4.0 * \text{passengers boarding} + 2.1 * \text{passengers alighting} \tag{3}$$

ATTRIBUTES CONTRIBUTING TO TSP EFFECTIVENESS

The following analysis attempts to characterize TSP effectiveness and to determine factors that contribute to bus schedule recovery. First, factors associated with bus recoveries are identified, and recovery is analyzed for sensitivity to those factors. Then, stops are categorized by proximity to signalized intersections, and a spatial analysis is used to locate types of stops at which TSP benefits are most likely to be gained. Finally, a linear regression is used to study the statistical significance of TSP for travel time.

Bus Recovery Factors

To explore initially the factors that may affect bus recovery at the stop level, the following bus dispatch system data attributes were used:

1. Corrected dwell time or PMT, the amount of time a bus remains at a stop during boarding or alighting;
2. Stay time, the total time spent at a bus stop;
3. Ons and offs, the number of passengers who board and alight the bus, respectively, at a stop;
4. Estimated load, the estimated passenger load based on ons and offs after the bus has left the stop;
5. Lift, the usage of the lift to assist passengers with disabilities;
6. Segment distance, the distance between the previous and the current stops; and
7. Segment travel time, the time to travel between the previous and the current stops.

TABLE 2 Average and Median Lateness and Recovery on SE Powell Boulevard

Period	Total Events	Average Lateness (s)	Median Lateness (s)	Average Recovery (s)	Median Recovery (s)	Percentage of Events	
						15-s Recoveries	30-s Recoveries
Eastbound							
a.m. peak	936.0	55.5	22.0	3.1	8.0	31.8	9.2
p.m. peak	1,501.0	81.5	56.0	4.6	9.0	40.9	19.3
Total	7,743.0	158.6	91.0	2.1	5.0	33.0	12.5
Westbound							
a.m. peak	1,450.0	−1.8	−13.0	3.5	9.0	41.6	16.9
p.m. peak	849.0	138.1	116.0	4.6	7.0	39.8	9.8
Total	7,602.0	86.1	42.0	2.0	7.0	34.1	10.1
Overall total	15,345.0	122.7	63.0	2.1	6.0	33.5	11.3

TABLE 3 Sensitivity of Factors of Stop-Level Bus Recovery

	Low		Medium		High	
Factor	Threshold	% of Recoveries	Threshold	% of Recoveries	Threshold	% of Recoveries
Dwell time	>0.5 * mean	40	> mean	17	>1.5 * mean	7
Stay time	>0.5 * mean	42	> mean	24	>1.5 * mean	5
PMT	>0.5 * mean	37	> mean	16	>1.5 * mean	8
Estimated load	>0.5 * mean	69	> mean	52	>1.5 * mean	30
Lift	Not used	100	na	na	Used	0
Segment distance	>0.5 * mean	100	> mean	81	>1.5 * mean	54
Segment travel time	>0.5 * mean	92	> mean	75	>1.5 * mean	61

NOTE: Percentage of all recoveries >30 s; na = not applicable.

To understand how different factor levels are associated with bus recoveries of 30 s or more, three thresholds were used (low: .5 times the mean; medium: the mean; and high: 1.5 times the mean). Stop events meeting the thresholds were counted, and percentages were calculated from the total number of recoveries of 30 s or more. The results are shown in Table 3. Recoveries greater than 30 s are specifically included in this table because 30 s is the lateness threshold used by TriMet and the City of Portland to initiate priority requests. There was no lift usage for the low threshold, and one lift was performed for the high threshold; no medium threshold was determined for lift usage.

The results are intuitive. For example, 7% of stops with recovery greater than 30 s had long dwell times; dwell times that were medium or high had 17% of recoveries; and dwell times that were low, medium, or high had 40% of recoveries. Therefore, lower values of dwell times, stay times, ons–offs, and bus loads were associated with higher percentages of recoveries. These results also suggest that lift usage severely limits ability to recover at a bus stop; recovery is not possible if the lift is used. Furthermore, two additional factors were inversely proportional to recovery percentage: segment distance and segment travel time. The time and distance factors suggest that a longer distance between stops gives lower opportunity to recover. This can be explained by the diverse recovery behavior at the intersection level; in longer segments, it is harder to see significant recoveries, as recoveries (or lateness) tend to be fairly localized events. This observation may be counterintuitive, but it is explained in the next section.

Analysis of TSP-Affected Stops

The segment under study has 14 signalized intersections and 27 bus stops in each direction. To separate the (possibly TSP-related) recoveries at traffic signals from recoveries attributable to other factors, stops were categorized as one of two types: (*a*) signal stops, defined as the first stop located after a traffic signal with TSP, or (*b*) nonsignal stops, defined as the remaining stops not included in signal stops.

Table 4 shows data for signal stops only—with the addition of 82nd Avenue. The intersection of SE Powell and 82nd is included because it is the only exception along the corridor at which TSP is not

TABLE 4 Lateness at Signalized Intersection Stops

	a.m. Peak			p.m. Peak			Off Peak		
Intersection	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
Eastbound									
34th	52.1	4.0	123.1	85.0	36.0	205.4	187.2	112.0	323.2
39th	77.5	25.0	115.5	133.2	106.0	201.7	223.4	136.0	323.0
47th	57.7	6.0	120.5	98.9	103.0	205.2	196.9	111.0	326.0
75th	29.6	46.0	133.9	–9.9	–43.0	193.2	176.8	83.0	331.9
82nd	72.0	86.0	120.2	94.0	72.0	174.8	229.1	120.0	337.3
86th	39.0	38.0	128.1	72.0	41.0	180.2	217.6	102.0	343.4
Westbound									
82nd	61.8	31.0	92.1	197.9	200.0	164.5	130.7	90.0	163.8
71st	20.6	6.0	92.2	174.6	159.0	160.0	107.7	63.0	188.2
40th	–12.3	–30.0	133.2	123.9	105.0	165.9	78.8	21.0	198.2
39th	57.2	26.0	104.4	181.3	152.0	174.6	137.4	78.0	201.8
33rd	–6.0	–26.0	108.0	133.6	87.0	180.0	131.1	76.0	205.0

NOTE: SD = standard deviation.

TABLE 5 Mean Values of Factors Affecting Recovery at Signal Stops

Factor	Recovery Amount (s)	Eastbound						Westbound				
		34th	39th	47th	75th	82nd	86th	82nd	71st	40th	39th	33rd
Stay (s)	>30	—	—	7	5	3	16	8	7	2	—	8
	30 > x > 0	12	25	16	14	20	20	33	18	13	19	19
	<0	32	57	39	29	74	34	76	45	33	63	34
Holding (s)	>30	—	—	1	1	0	4	2	1	−2	—	1
	30 > x > 0	2	2	2	3	2	3	8	4	3	1	5
	<0	4	9	0	3	16	3	9	6	6	11	5
Passenger movement	>30	—	—	4	4	4	6	7	4	4	—	5
	30 > x > 0	5	18	6	6	10	7	15	7	6	12	8
	<0	12	24	9	8	26	8	26	12	11	24	13
Load (no. of passengers)	>30	—	—	15	12	5	6	8	12	9	—	20
	30 > x > 0	16	12	15	12	4	10	8	13	14	14	17
	<0	17	15	9	13	11	14	11	13	18	16	18
Travel time (seconds from previous stop)	>30	—	—	50	42	148	100	122	26	80	—	39
	30 > x > 0	33	29	48	41	39	102	45	33	33	21	34
	<0	34	47	65	50	65	116	64	35	40	48	40
Lift (no. of times lift used)[a]	>30	0	0	0	0	0	0	0	0	0	0	0
	30 > x > 0	0	0	0	0	0	0	0	0	0	0	0
	<0	2	10	0	0	13	0	7	2	0	8	1
Recoveries (no. of recoveries)[b]	>30	0	0	115	60	4	83	12	16	1	0	9
	30 > x > 0	161	6	164	208	11	149	25	156	218	3	144
	<0	126	281	8	19	272	55	243	110	63	279	129

NOTE: — = no stop events met recovery threshold; no. = number.

[a] Lift values are shown as actual number of lift instances in which recovery amount was seen.

[b] Recovery values show total number of recoveries at the stop meeting the recovery thresholds.

provided. As noted earlier, signal progression at 82nd is given higher priority by the City of Portland. Signals after the cross streets with the highest traffic volumes are highlighted (39th and 82nd Avenues). The table shows that lateness tends to vary significantly across intersections. Lateness tends to increase right after a bus passes major cross streets (39th and 82nd Avenues). This may explain why longer travel distances or times are not associated with more recoveries (Table 3); the recoveries and delays may be averaged along the segment.

To study the recovery factors at the intersection level, three recovery bins were defined: greater than 30 s, between 0 and 30 s, and less than 0 s; the last case represents a worsening of lateness. Table 5 shows the mean values of different factors at signal stops and the corresponding number of recoveries at those stops in the last three rows. In the

TABLE 6 Linear Regression Analysis of Travel Time

Factor	Eastbound Trips					
	Model 1. Bridge to 82nd		Model 2. Ross Island Bridge to 39th		Model 3. 39th to 82nd	
	Coefficient	P-Value	Coefficient	P-Value	Coefficient	P-Value
Intercept	838.8	.000	360.3	.000	275.2	.000
Stops	20.8	.000	19.4	.000	20.5	.000
Lifts	39.8	.017	—	—	42.3	.000
Ons	5.6	.000	4.9	.000	2.8	.000
Offs	—	—	—	—	1.5	.025
Priority	−122.3	.000	−44.2	.000	−24.1	.032
Very late	—	—	—	—	—	—
p.m. peak	250.7	.000	114.1	.000	48.7	.000
a.m. peak	—	—	—	—	—	—
Off peak	—	—	—	—	—	—
R^2		.675		.625		.620
Adjusted R^2		.668		.618		.610

NOTE: — = variables were excluded or not significant.

table, dashes mark factors for which no stop events met the recovery threshold. As expected, a higher value of stay, passenger movements, or passengers is associated with fewer recoveries that exceed 30 s. For travel time from the previous stop, the results indicate that longer travel times between stops (directly correlated with longer distances) allow for more recoveries. A segment with several stops might hide this recovery by averaging the time recovered with TSP with the time lost because of long stay times and intersection delay. However, a bus is more likely to recover as the length of its run without stopping increases if TSP is also provided along the way.

The two major intersections (SE 39th and SE 82nd Avenues) show the lowest number of recoveries. Both SE 39th and SE 82nd Avenues are five-lane arterial corridors with two through lanes in each direction and dedicated left-turn lanes. The northbound movement on SE 39th Avenue has an additional right-turn-only lane on the south side of the intersection with SE Powell. Low recoveries at these intersections may be caused by long queues and cycle failure or by high numbers of lift usage and passenger movement that are attributable to more transfer activity between bus routes. The greatest numbers of recoveries are found at the intersections immediately before or after major intersections. This phenomenon indicates that buses become late after crossing the major arterials and recover during subsequent stops. Even though TSP is not operational at 82nd Avenue, that intersection follows a pattern similar to the one at 39th. These results may suggest that TSP has little or no impact at 39th Avenue.

Regression Analysis of TSP and Additional Factors

Effective TSP should have a significant impact on late buses. To explore this trait, a regression analysis with total corridor travel time as the dependent variable is run. The following independent variables are used:

1. Stops, the total number of open-door stops a bus makes along the corridor;
2. Lifts, the total number of times the lift was operated;
3. Ons, the total number of passengers boarding;
4. Offs, the total number of passengers alighting;
5. Priority, a binary variable equal to 1 if the bus does use priority consistently throughout the corridor and 0 otherwise;
6. Very late, a binary variable equal to 1 if bus lateness is >5 min and 0 otherwise;
7. p.m. (afternoon) peak, a binary variable equal to 1 if the time the bus entered the corridor was between 4 and 6 p.m. and 0 otherwise; and
8. a.m. (morning) peak, a binary variable equal to 1 if the time the bus entered the corridor was between 7 and 9 a.m. and 0 otherwise.

Priority and nonpriority trips were classified as follows: priority trips had initial (at the start of the study segment) lateness of 90 s or more. Trips with initial lateness between −30 and +30 s were classified as the nonpriority control group. Using 90 s as the priority threshold gives some assurance that the buses will not catch up immediately, and the TSP Opticom emitter is turned off for the rest of the trip.

A regression analysis was completed for each direction of travel. Table 6 shows the final regression models after removal of the correlated and insignificant variables. In the table, dashes denote variables that are excluded or not significant. The results show intuitive signs and coefficients; for example, the major peak period for each direction (westbound to downtown in the a.m. peak and eastbound to the freeway in the p.m. peak) is highly significant, as expected. Each peak period adds 125 to 250 s on average to total travel times. As expected from previous studies, in all segments, the number of stops and passenger boardings (ons) are significant variables. Alightings (offs) are only significant for eastbound movements in which the number of alighting passengers is significantly higher than the number of boarding passengers. The models have good R^2 values and similar adjusted R^2 values, which indicate adequate fit and no collinearity.

At the corridor level, TSP is found to be significant in both the eastbound and westbound directions. At the segment level, TSP is significant in both eastbound segments from the bridge to 39th and

Westbound Trips					
Model 4. 82nd to Kelly and Corbett		Model 5. 82nd to 39th		Model 6. 39th to Kelly and Corbett	
Coefficient	*P*-Value	Coefficient	*P*-Value	Coefficient	*P*-Value
868.0	.000	291.5	.000	404.4	.000
16.1	.000	22.2	.000	15.6	.000
58.7	.032	—	—	—	—
6.0	.000	2.6	.008	4.2	.000
—	—	—	—	—	—
−94.1	.000	—	—	−52.1	.000
—	—	—	—	—	—
—	—	—	—	—	—
125.8	.001	—	—	147.8	.000
—	—	—	—	—	—
	.603		.514		.580
	.590		.508		.569

from 39th to 82nd; TSP is significant only in the westbound segment from 39th to the Kelly and Corbett westbound segment. This can be explained by the values contained in Table 2, which shows that, in the eastbound direction, (*a*) direction average and median lateness tend to be higher and (*b*) more significant recoveries (larger than 30 s) occur. Therefore, the results of the regression and Table 2 seem to indicate that TSP is more effective in bus routes that have more severe lateness.

The significance of TSP is related to what intersections are used to define the segment. The results in Table 4 show a significant reduction in lateness after 39th (westbound) but not between 82nd and 39th. Therefore, TSP effectiveness measured between two intersections with high lateness will tend to be poor; in this case, all the recoveries may have been lost or evened out. In contrast, if TSP effectiveness is analyzed between an intersection or stop with high lateness and an intersection or stop with low or negative lateness, the effectiveness will tend to be high and significant.

CONCLUSIONS

In this study, AVL and APC data from the TriMet system were used to locate late buses and determine their recovery at each bus stop. Lateness and recovery were defined as performance measures to estimate the effectiveness of TSP along SE Powell Boulevard in Portland. Along this corridor, average lateness was shown to be high, and a large percentage of unique trips were shown to be late at some point on the corridor. A stop-level analysis was performed on stops near traffic signals with TSP to determine whether recoveries were likely to occur because of the influence of TSP. A regression analysis was also performed to gain an understanding of the statistical significance of TSP.

The results indicate that lateness, schedule recovery, and TSP effectiveness tend to be fairly localized; the degree of variability among stops is high, even between stops that are located closely. Therefore, the significance of TSP is related to which intersections are used to define the segment under study. The results seem to indicate that TSP is more effective for bus routes that have more severe lateness. As expected, lower values of dwell times, passenger movements, and bus loads are associated with higher percentages of recoveries; the results also suggest that lift usage precludes any recovery at the stop level.

Regression analysis shows TSP to be a significant factor in determining travel time for the corridor. The stop- and intersection-level analyses show that TSP effectiveness can be hidden or evened out when effectiveness at a route level is analyzed.

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