Empirical Evaluation of Transit Signal Priority

Fusion of Heterogeneous Transit and Traffic Signal Data and Novel Performance Measures

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Transit signal priority (TSP) can reduce transit delay at signalized intersections by making phasing adjustments. TSP is a relatively inexpensive and easily implemented tool to make transit service faster and more reliable. TSP also sends a signal that a city or region encourages the growth of transit. With the aim of assessing the performance of an existing TSP system, this study had access to a unique set of high-resolution bus and traffic signal data. Novel algorithms and performance measures were proposed. The results indicate that a timely and effective TSP system requires a high degree of sophistication, monitoring, and maintenance. Empirical data suggested that most TSP phase adjustments were granted within the cycle in which buses requested priority but that only a small proportion resulted in reduced delay. In this study, many green extension phases were granted late and were therefore less effective than early signal phases. Despite this situation, the TSP system did not increase delays for passengers and vehicles when side street traffic was considered.

Transit signal priority (TSP) is the process of detecting transit vehicles approaching signalized intersections and adjusting the signal phasing in real time to reduce transit delay (*1*). TSP is relatively inexpensive and easy to implement to improve transit reliability and bus travel speeds (*2*). TSP phase adjustments include green extension and early green (or red truncation). A green extension extends a green phase to speed bus passage through an intersection before the signal turns red. An early green truncates a red phase and begins the green phase early to help transit vehicles begin moving early.

A TSP system typically consists of three components: (*a*) an onboard priority request generator that alerts the intersection traffic control system that the bus requests priority, (*b*) a detection system that receives the priority request and informs the traffic controller where the bus is located, and (*c*) a priority control strategy that determines whether to grant a TSP phase, which TSP phase should be granted, and when the TSP phase should start and end (*2*). Priority control strategies fall into three categories: (*a*) passive, in which priority is granted regardless of the state of the system; (*b*) active, in which priority is granted only when the state of the system meets certain requirements; and (*c*) real-time active. The objective of the TSP may be to minimize total passenger delay, deviations from bus schedules, or other performance measures (*3–10*).

TSP strategies have been evaluated through analytic or simulation models, with significant variations in results. Balke et al. simulated active priority at an isolated intersection with both green extension and early green phases and found significant reductions in bus travel time with minor increases in total intersection delay under moderate traffic levels (*11*). Furth and Muller used simulation to evaluate the passive and active TSP systems in a corridor, with significant improvement in bus schedule adherence (*1*). However, active priority had almost no impact on traffic delay, and passive priority significantly increased traffic delay. Skabardonis evaluated proposed passive and active priority strategies on a corridor with a coordinated signal system and 21 intersections (*12*). The simulation showed that TSP strategies provided modest improvements for buses without adverse effects on auto traffic. Dion et al. used simulation to evaluate active priority strategies on an arterial corridor and showed that buses would benefit from TSP at the expense of increasing overall traffic delays (*13*). Under low traffic flows, the negative impacts were negligible. Byrne et al. used simulation to evaluate a conditional TSP system at a single intersection; the simulation resulted in 11% bus travel time savings at farside stops and a 6% increase in bus travel time at nearside stops (*14*). One study found that TSP was more efficient at farside bus stops because there was less uncertainty in the intersection arrival time (*15*). The prediction of bus arrival times and fast TSP activation and deactivation are key factors that affect the effectiveness of TSP, as shown in a later section.

Unlike previous studies that used simulation to evaluate TSP systems, Lin used analytical models, and found that buses traveling along minor cross streets benefited more than buses traveling on the major arterial (*16*). Skabardonis and Christofa also used analytical models to estimate the potential impact of TSP on an intersection's level of service (*17*). The results showed that TSP had little impact on the intersection level of service under low and moderate traffic flow but could deteriorate the intersection level of service under high traffic flow conditions. In summary, proposed TSP control strategies have been evaluated through analytic or simulation models, and the results have not always been consistent. This inconsistency may be a result of a lack of consistency in controlling for factors such as intersection geometry, signal timing, traffic demand, TSP control strategies and parameters, transit vehicle headways, and the reliability of the detection systems and the TSP request generating system (*18*).

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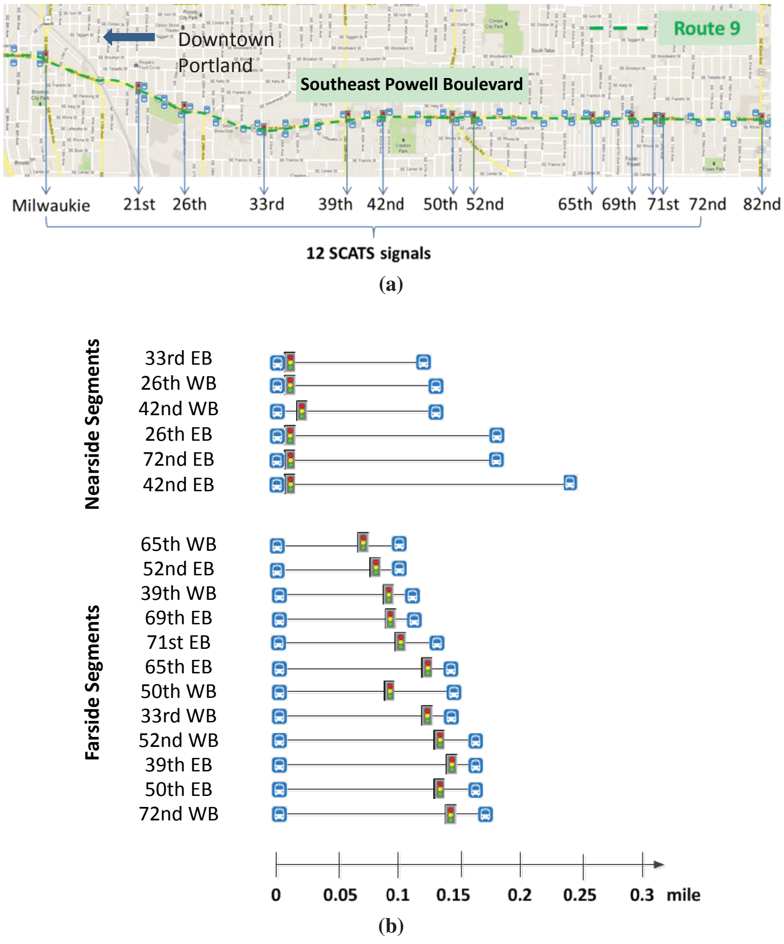
Also, simulation and analytical models have been used for evaluations before TSP installation; this paper focuses on methods that integrate multiple sources of empirical data to evaluate an existing TSP system's performance.

Several studies have empirically evaluated TSP systems, with varying results. Hunter-Zaworski et al. collected travel time data for buses and other vehicles at four intersections on Powell Boulevard in Portland, Oregon, before and after the implementation of an active TSP system (*19*). Hunter-Zaworski et al. found that after the TSP implementation, bus travel time decreased during peak hours but increased during off-peak hours and that the intersection total person delay increased at certain times of the day. Koonce et al. evaluated a TSP system on Barbur Boulevard, also in Portland, and showed that bus travel time decreased by 0.4 to 3.2 min and that travel time variability decreased by 2.2% to 19.2% at different times of the day and in different travel directions (*20*). No difference was found in bus travel time between late and on-time buses. Kimpel et al. evaluated changes in bus running times, on-time performance, and excess passenger waiting times after TSP implementation on several corridors in Portland and showed that TSP benefits were neither consistent across routes and time periods nor across performance measures (*21*). Slavin et al. used regression models to evaluate TSP on Powell Boulevard and showed significant reductions in corridor travel times for buses that requested TSP (*22*). Albright and Figliozzi used regression models to evaluate TSP on the same corridor and showed that a bus that requested signal priority significantly shortened the headway to its preceding bus and increased the headway to its following bus (*23*). Albright and Figliozzi also found that late bus recovery (the bus schedule delay before and after an intersection) varied but was greater at intersections with less demand on the minor cross streets (*24*). Diab and El-Geneidy used regression models to study an active TSP system on two bus routes in Montreal, Quebec, Canada (*25, 26*). The results indicated that the bus travel times for the two bus routes significantly decreased with TSP and that TSP-equipped buses had shorter travel times than nonequipped buses.

No empirical study has compared the performance and efficiency in delay reduction of the early green and green extension phases. This study fills this gap by integrating data from TSP signal phase logs with automatic vehicle location and automated passenger count data. This study proposes new performance measures for the evaluation of the timeliness, effectiveness, and efficiency of TSP systems and for the comparison of the performance of green extension and early green TSP phases.

STUDY CORRIDOR AND DATA DESCRIPTION

Powell Boulevard is a 4-mi-long major urban arterial corridor in Portland and has two lanes in each direction; downtown Portland is located to the west, as shown in Figure 1*a*. Bus Route 9 is the



(a)

(b)

FIGURE 1 Study corridor and data collection: (*a*) Route 9 on Powell Boulevard and (*b*) stop-to-stop segments (EB = eastbound. WB = westbound).

primary bus route operating along this corridor and runs east–west with an average headway of 15 min during the middle of the day and 6 to 7 min during the morning and evening peak periods. The Sydney Coordinated Adaptive Traffic System (SCATS) is implemented at 12 signalized intersections between Milwaukie Avenue and 72nd Avenue. An active TSP system is programmed to respond to bus priority requests from both the eastbound and westbound directions at each of the 12 intersections. An infrared emitter on a bus is activated and a priority request is sent to downstream traffic signals whenever the following conditions are met: (*a*) the bus is within the city of Portland, (*b*) the bus is on route, (*c*) the doors are closed, and (*d*) the bus is more than 30 s late. At a signalized intersection, an Opticom detector on the traffic signal mast arm receives the priority request and relays the request to the signal controller. Depending on the cycle sequence, either an early green or a green extension can be granted. It is possible for a bus to pass the intersection without the TSP request being cancelled by SCATS.

There are 22 bus stops and 21 stop-to-stop segments (i.e., segments between two consecutive bus stops) in each direction between Milwaukie Avenue and 72nd Avenue. Eighteen stop-to-stop segments include one SCATS signal, and three segments include two signals. This study focuses on the 18 segments with one signal (see Figure 1*b*). Six of these segments are nearside segments (the departure stop of the stop-to-stop segment is a nearside stop), and 12 are farside segments (the arrival stop of the stop-to-stop segment is a farside stop). March 2013 weekday data records were collected and integrated for the 18 stop-to-stop segments.

In the automatic vehicle location and automated passenger count data, each time a bus makes a stop, the following information is recorded: the actual arrival and departure times, the scheduled departure time, the passenger load, and the number of boarding and alighting passengers (*27, 28*). The automatic vehicle location data are only available when buses arrive at bus stops; therefore, no bus location is provided between bus stops. The bus departure time is the time when a bus leaves the location 50 ft downstream of the bus stop; the bus arrival time is the time the bus door opens at a bus stop. If a bus skips a bus stop, the arrival time is the time when the bus is 50 ft upstream of the bus stop. SCATS signal phase data record the start time and end time of each phase, including the regular green phase, the red phase, and the TSP phases (green extension and early green). The SCATS system also provides vehicle count data for each approaching lane of an intersection at 15-min intervals. A more detailed description of the three data sources can be found in Feng (*29*).

ESTIMATION OF BUS INTERSECTION ARRIVAL TIME

A detailed study of TSP performance at the signal phase level requires data on bus intersection arrival times. However, bus trajectories are unknown between bus stops, and the intersection arrival time is therefore also unknown. The bus intersection arrival time is necessary to estimate the bus arrival phase (the signal phase that is active when the bus reaches the intersection). This study has developed algorithms to estimate (*a*) the stop-to-stop travel speed and (*b*) the phase encountered by a bus arriving at an intersection. These algorithms produce probability distributions associated with the travel time and the arrival phase.

Estimation of Bus Travel Speed Distributions

The intersection arrival time is estimated through the use of stop-to-stop travel speed data, excluding trips that experienced signal delay. The inclusion of buses that experienced signal delay would have biased the results by incorrectly lowering the stop-to-intersection travel speeds. The method used to exclude the observations that included signal delay was as follows:

1. Disaggregate the stop-to-stop travel times by the time of day and the stop-to-stop segment.
2. Assume that the total number of bus travel speed observations for a stop-to-stop segment at a certain time of day is N and that the ratio between the median red phase duration and the cycle length of the intersection is R/C ($0 < R/C < 1$), where R is the red phase duration, and C is the cycle length.
3. Place the N bus travel speed observations in order from lowest to highest.
4. Remove the lowest $N \cdot (R/C)$ bus speed observations (round up or down to get an integer).
5. Use the remaining $N \cdot [1 - (R/C)]$ speed observations and 1-mph speed bins to estimate a travel speed probability distribution based on frequency; denote this distribution $f(v)$.
6. Find the minimum and maximum speeds and denote them $v_{\min}$ and $v_{\max}$, respectively.

Four times of day were used: the morning peak (7 to 9 a.m.), the middle of the day (9 a.m. to 4 p.m.), the afternoon peak (4 to 6 p.m.), and the evening (6 p.m. to 7 a.m.). The estimated bus travel speed distribution for the stop-to-stop segment was assumed to apply to both the upstream portion (the departure bus stop to the intersection stop bar) and the downstream portion (the intersection stop bar to the downstream or arrival bus stop). The travel time distributions varied significantly throughout the day (*29*).

Estimation of Bus Arrival Phase

The distribution of bus intersection arrival times is a function of the travel speed, the time of departure from the upstream stop, the arrival time at the downstream stops, and the signal phase start and end times. The notation is presented below.

$\boldsymbol{I}$ is defined as the set of bus trips for a stop-to-stop segment that contains one signalized intersection, and i is defined as the index for the ith bus trip, $i \in \boldsymbol{I}$. $\boldsymbol{J}$ is defined as the set of cycles for the signalized intersection in the stop-to-stop segment, and j is defined as the index for the jth cycle, $j \in \boldsymbol{J}$; in the following algorithm, a cycle is defined as the time interval between two consecutive red phase end times $[R_j^e, R_{j+1}^e]$. The inputs are

d_1 and d_2 = distance between upstream bus stop and intersection stop bar and distance between intersection stop bar and downstream bus stop, respectively;
dt_i and at_i = departure time from upstream stop and arrival time at downstream stop, respectively, for bus trip i;
load_i = number of onboard passengers during trip i;
R_j^s and R_j^e = red phase start time and end time, respectively, for cycle j;

GE_j^s and GE_j^e = green extension phase start time and end time, respectively, for cycle *j*; and

EG_j^s and EG_j^e = early green phase start time and end time, respectively, for cycle *j*.

The outputs are

$\mathrm{prob\_}R_i$ = intersection arrival probability during cycle *j* red phase for bus trip *i*;

$\mathrm{prob\_}G_i$ = intersection arrival probability during cycle *j* green phase for bus trip *i*;

$\mathrm{prob\_GE}_i$ = intersection arrival probability during cycle *j* green extension phase for bus trip *i*;

$\mathrm{prob\_EG}_i$ = intersection arrival probability during cycle *j* early green phase for bus trip *i*;

$\mathrm{BTS\_GE}_i$ and $\mathrm{PTS\_GE}_i$ = expected bus and passenger time savings, respectively, attributable to green extension phase for bus trip *i*; and

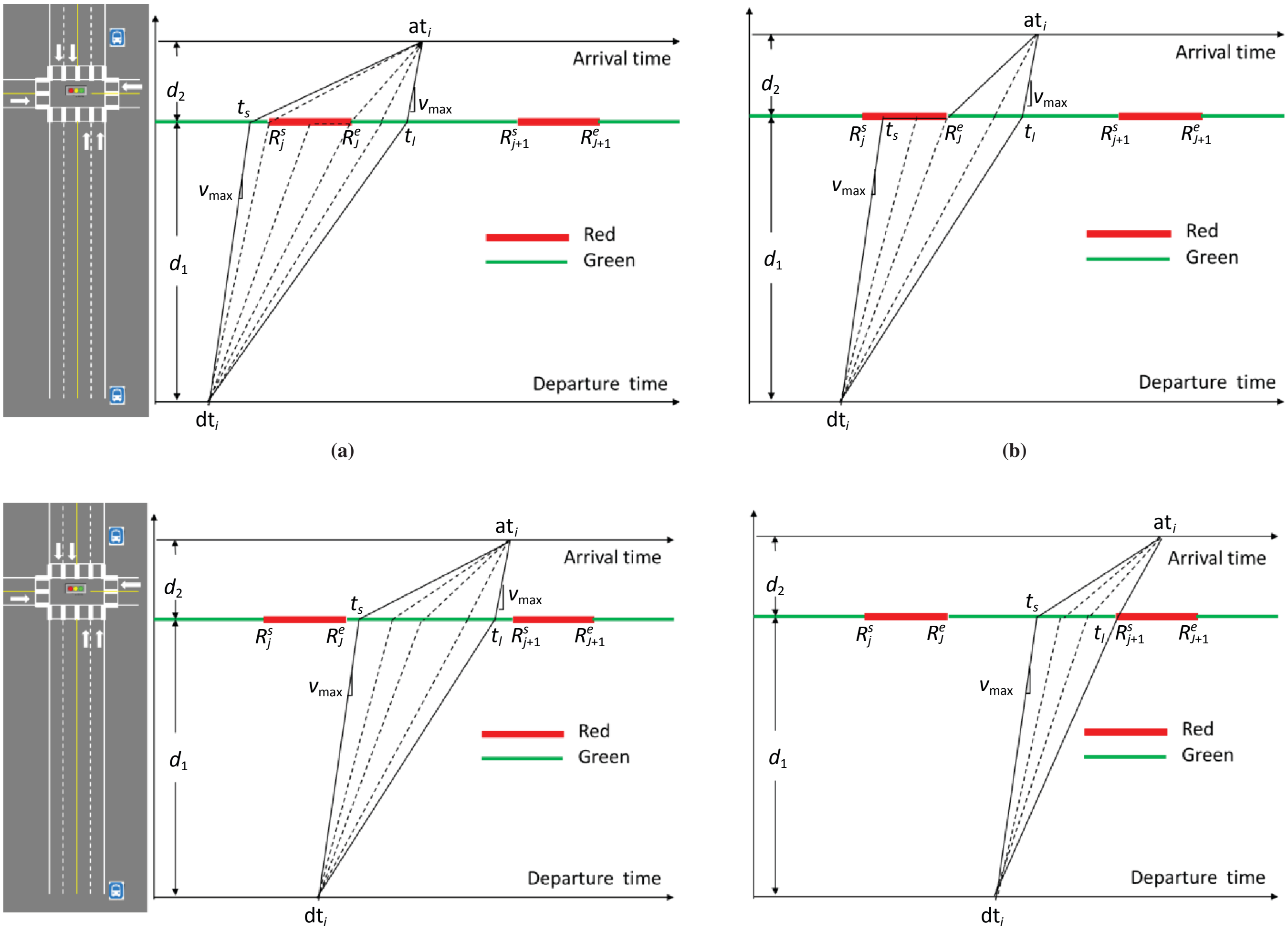
$\mathrm{BTS\_EG}_i$ and $\mathrm{PTS\_EG}_i$ = expected bus and passenger time savings, respectively, attributable to early green phase for bus trip *i*.

Because the bus trajectory is unknown, it is useful to define the bus trajectory boundaries: ts_i is the soonest possible intersection arrival time for trip *i,* and tl_i is the latest possible intersection arrival time for trip *i.* The boundaries t_s and t_l are defined by the following equations:

$$\mathrm{ts}_i = \max\left\{\mathrm{dt}_i + \frac{d_1}{v_{\max}},\ \mathrm{at}_i - \frac{d_2}{v_{\min}}\right\} \tag{1}$$

$$\mathrm{tl}_i = \min\left\{\mathrm{dt}_i + \frac{d_1}{v_{\min}},\ \mathrm{at}_i - \frac{d_2}{v_{\max}},\ R_{j+1}^s\right\} \tag{2}$$

Figure 2 shows four bus trajectory boundaries as a function of four departure times for trip *i* (dt_i); all other parameters are held constant. For the sake of clarity, Figure 2 shows only the feasible bus trajectory boundaries determined by the maximum speeds. The minimum speeds are usually not a constraint; if they are a constraint, they are taken into account by Equations 1 and 2. In addition, a feasible boundary may span two or fewer cycles; as a reference, the distance between a bus stop and an intersection is always less than 0.15 mi (see Figure 1), and a bus traveling at 7.5 mph (less than the minimum speed observed)



(a) (b)

(c) (d)

FIGURE 2 Example of feasible stop-to-stop trip trajectories with four departure times.

requires 72 s (which is less than the typical cycle of 120 s) to travel that distance.

Then

$$\text{prob\_}G_i \equiv 1 - \text{prob\_}R_i \qquad \forall i \in \boldsymbol{I}$$

where the yellow time is assumed to be used as green time and there is no TSP phase. When there is an early green (EG) TSP phase in cycle *j*, the probability of arriving at the intersection during the EG phase can be estimated as follows (see the Figure 3*a*):

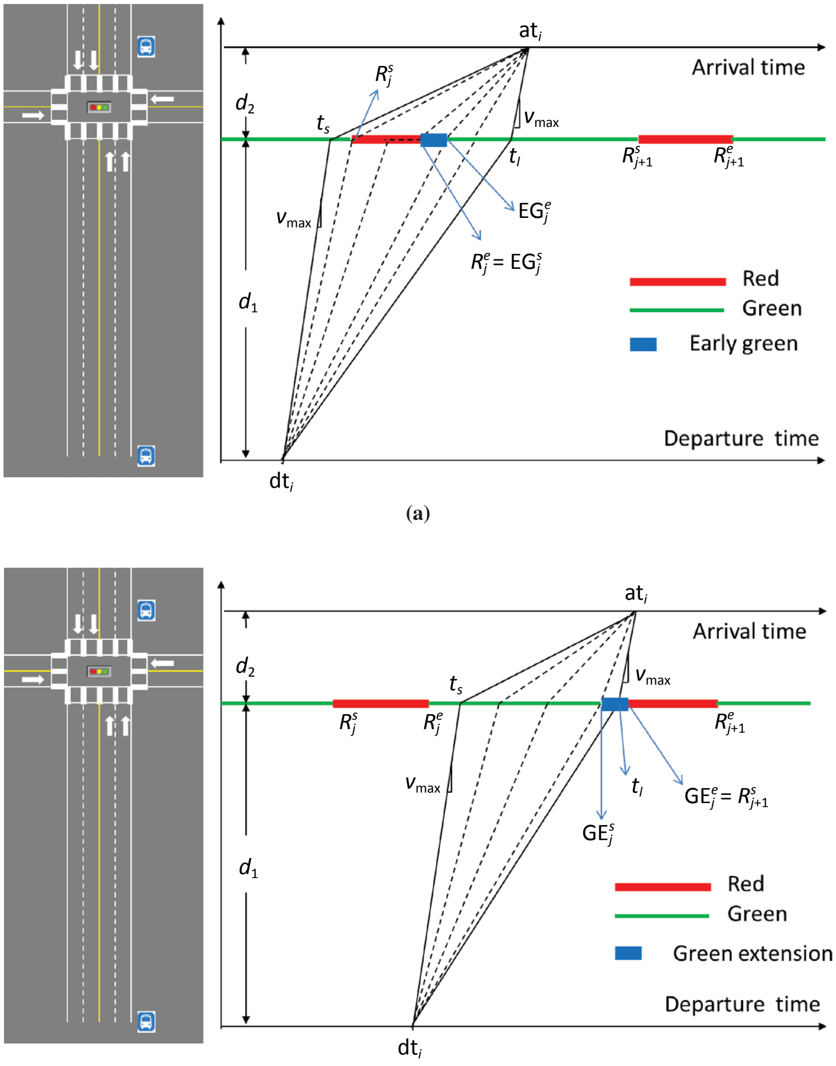
$$\text{prob\_EG}_i = \sum_{j \in J} \frac{\text{prob}\left[\dfrac{d_1}{\min\{\text{EG}_j^e, \text{tl}_i\} - \text{dt}_i} \le v < \dfrac{d_1}{\max\{\text{EG}_j^s, \text{ts}_i\} - \text{dt}_i}\right]}{\text{prob}\left[\dfrac{d_1}{\text{tl}_i - \text{dt}_i} \le v < \dfrac{d_1}{\text{ts}_i - \text{dt}_i}\right]} \qquad (3)$$

If there is a green extension (GE) phase in cycle *j*, the probability of arriving at the intersection during a GE phase can be estimated as follows (see Figure 3*b*):

$$\text{prob\_GE}_i = \sum_{j \in J} \frac{\text{prob}\left[\dfrac{d_1}{\min\{\text{GE}_j^e, \text{tl}_i\} - \text{dt}_i} \le v < \dfrac{d_1}{\max\{\text{GE}_j^s, \text{ts}_i\} - \text{dt}_i}\right]}{\text{prob}\left[\dfrac{d_1}{\text{tl}_i - \text{dt}_i} \le v < \dfrac{d_1}{\text{ts}_i - \text{dt}_i}\right]} \qquad (4)$$

RESULTS OF TSP PERFORMANCE EVALUATION

TSP performance can be evaluated along multiple dimensions. A novel contribution of this research is to define four dimensions for the evaluation of TSP performance: (*a*) frequency, (*b*) responsiveness, (*c*) timeliness, and (*d*) effectiveness.



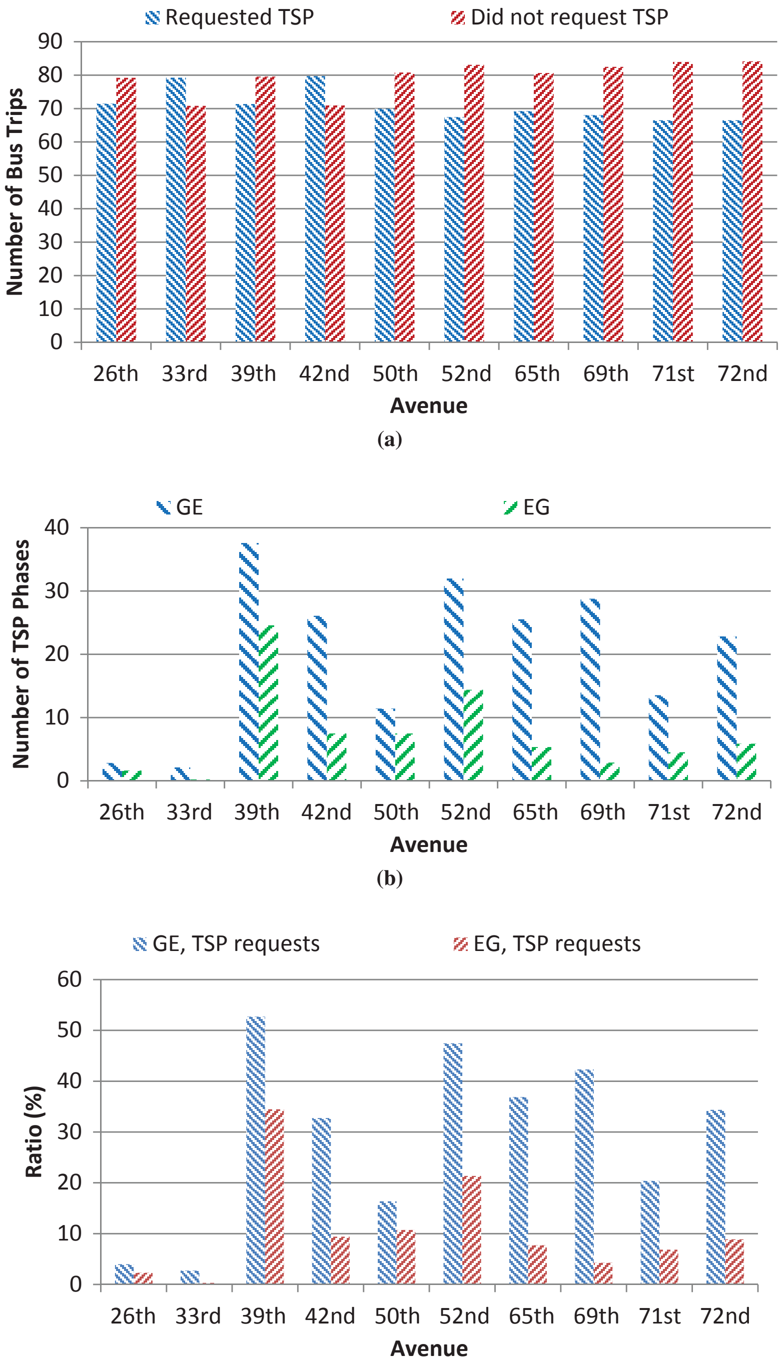
(a)

(b)

FIGURE 3 Example of stop-to-stop trip trajectories with an (*a*) EG and (*b*) GE TSP phase.

TSP Frequency

TSP systems can be deployed, but few phases may actually be granted, as shown in Figure 4. There is no correlation between the number of trips and the number of EG and GE TSP phases granted, even though this corridor has almost the same bus frequency in both directions. The ratio of TSP phases and requests shows that very few TSP phases were granted at the intersections of 26th Avenue and 33rd Avenue; the low frequency indicates a potential TSP setting problem. A TSP configuration problem was later confirmed by the City of Portland; this identification of this problem indicates the usefulness of TSP frequency in the initial detection of TSP performance. In the rest of this section, the results for the 26th Avenue and 33rd Avenue intersections are omitted.

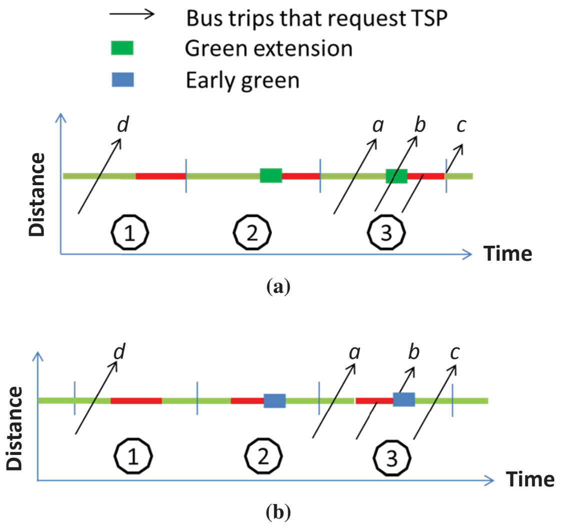


(a)

(b)

(c)

FIGURE 4 TSP frequency (*a*) average number of bus trips per day, (*b*) average number of TSP phases per day, and (*c*) percentage of TSP phases to TSP requests.



(a)

(b)

FIGURE 5 TSP timeliness and effectiveness: (*a*) GE and (*b*) EG (1, 2, and 3 = cycles; *a*, *b*, *c*, and *d* = buses).

TSP Responsiveness

Responsiveness aims to measure whether TSP phases are granted to buses that (*a*) request priority and (*b*) arrive at the intersection during the cycle in which the TSP phase was granted. The cycles are defined around GE and EG phases. As shown in Figure 5, for a GE phase, a cycle is defined as the time interval between two consecutive green phase start times; a cycle is only labeled "responsive" if a bus that has requested TSP arrives at the intersection during this cycle (e.g., Cycle 3 in Figure 5*a*). For an EG phase, a cycle is defined as the time interval between the middle of two consecutive green phases; a cycle is responsive if a bus that has requested TSP arrives at the intersection during this cycle (e.g., Cycle 3 in Figure 5*b*). In Figure 5, *a* and *b*, bus *d* arrives at the intersection in Cycle 1 and triggers a TSP phase in Cycle 2; therefore, the TSP phase in Cycle 2 is not responsive to any bus. Bus *a*, *b*, or *c* arrives at the intersection in Cycle 3 and triggers a TSP phase granted in the same cycle; therefore, bus *a*, *b*, or *c* triggers a responsive TSP phase. Because bus travel time distributions are known, for each TSP phase it is possible to estimate the probability that at least one bus arrived in an EG or GE phase.

After a bus requests priority, there are four potential outcomes:

1. Arrival at the intersection during a cycle with a GE phase,
2. Arrival at the intersection during a cycle with an EG phase,
3. Arrival at the intersection during a cycle with both GE and EG phases, and
4. Arrival at the intersection during a cycle with neither a GE nor an EG phase.

The fourth outcome means that a bus requested TSP but no GE or EG phase was granted within the same cycle. Figure 6 shows the breakdown of the four outcomes for TSP requests at each intersection from both directions. There are no results for the intersections at 69th and 71st Avenues in the westbound direction because there are two signalized intersections in this stop-to-stop segment, and the algorithm presented in the previous section does not estimate bus arrival times at both of the intersections. The results vary significantly across the intersections and by direction. For example, very few TSP requests resulted in the responsive granting of a TSP phase at 42nd Avenue in the eastbound direction or at 50th Avenue in either direction. Overall, the results show that more than half of the TSP requests did not result in the granting of any responsive TSP phase. Also, TSP requests resulted in more GE phases than EG phases, and there is no clear difference in the results between nearside segments and farside segments.

TSP Timeliness

TSP can be responsive at some intersections but not necessarily timely (i.e., occurring at suitable times). In Figure 5, buses *a*, *b*, and *c* would all trigger a TSP phase granted in the same cycle; however, only bus *b* would benefit from the TSP phase, which means that bus *b* saved time as a result of the TSP phase. Buses *a* and *c* would trigger the TSP phase, but the TSP phase would be late and early for buses *a* and *c*, respectively. Therefore, the TSP phase in Cycle 3 is defined as timely (on time) for a bus that requests priority. [A TSP request benefits from a timely (on time) TSP phase.]

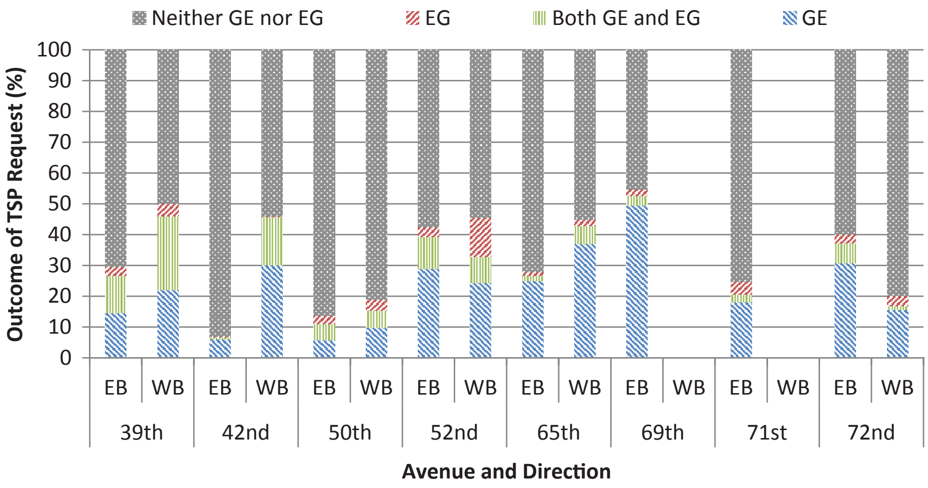


FIGURE 6 Breakdown of TSP request outcomes.

The probability that a TSP request triggered an early, on time, late, or out of cycle TSP phase can be calculated with the formulas presented in the previous section. The results are shown in Figure 7, *a* and *b*, for GE and EG phases, respectively. Figure 7, *a* and *b*, shows that bus TSP requests have only a 0% to 5% probability of benefiting from a GE phase and a 0% to 15% probability of benefiting from an EG phase. On average, across intersections, a bus has a 25% probability of triggering a late green extension phase. The results may indicate a problem with the TSP control strategies (e.g., a GE phase may be granted irrespective of whether a TSP request is received in the beginning of a regular green phase or at the end of a regular green phase). The results may also indicate a problem with the TSP request deactivation. For example, a TSP call in the signal controller may not have been canceled even if a bus had already passed the intersection. It is also possible that there is a lag in how SCATS is processing the priority requests, because EG phases are happening on time much more frequently than green extension phases.

TSP Effectiveness

The goal of TSP systems is to reduce transit travel times and their variability. This final performance measure aims to measure the effectiveness of TSP systems in the reduction of trip and passenger travel times. A more complete measure of effectiveness includes time savings for other vehicles on the major street and vehicle delays on minor streets. Because the average durations of the GE and EG phases are different across intersections and phases, the time savings and delays per second of the TSP phase are used in the comparisons.

For each stop-to-stop segment, the average bus passenger time savings per second of the TSP phase can be estimated by

$$\frac{\sum_{i\in I}\text{PTS\_GE}_i}{\sum_{j\in J}\text{GE}_j^e-\text{GE}_j^s}$$

$$\frac{\sum_{i\in I}\text{PTS\_EG}_i}{\sum_{j\in J}\text{EG}_j^e-\text{EG}_j^s}\qquad(5)$$

The formulas that were used to estimate the bus and passenger time savings can be found in Feng (*29*). Figure 8, *a* and *b*, shows that the estimated total passenger time savings per second of the GE phase is much lower than for the EG phase. The EG phases are relatively more effective than the GE phases at most intersections. This finding may be because too many GE phases are not utilized

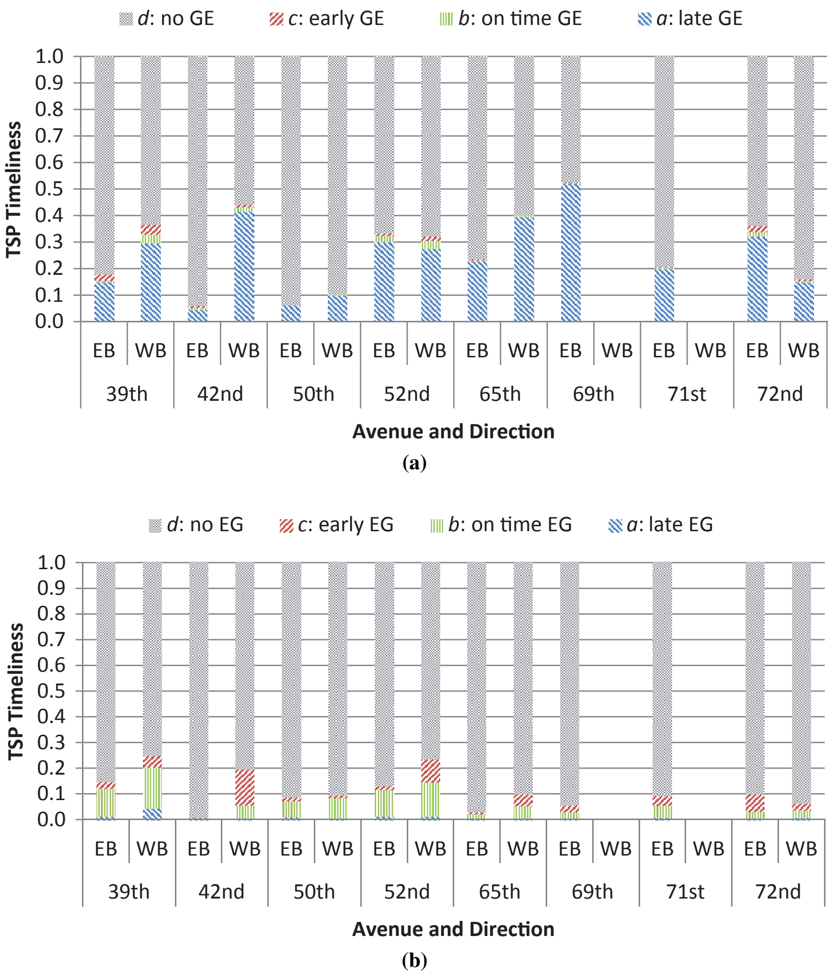
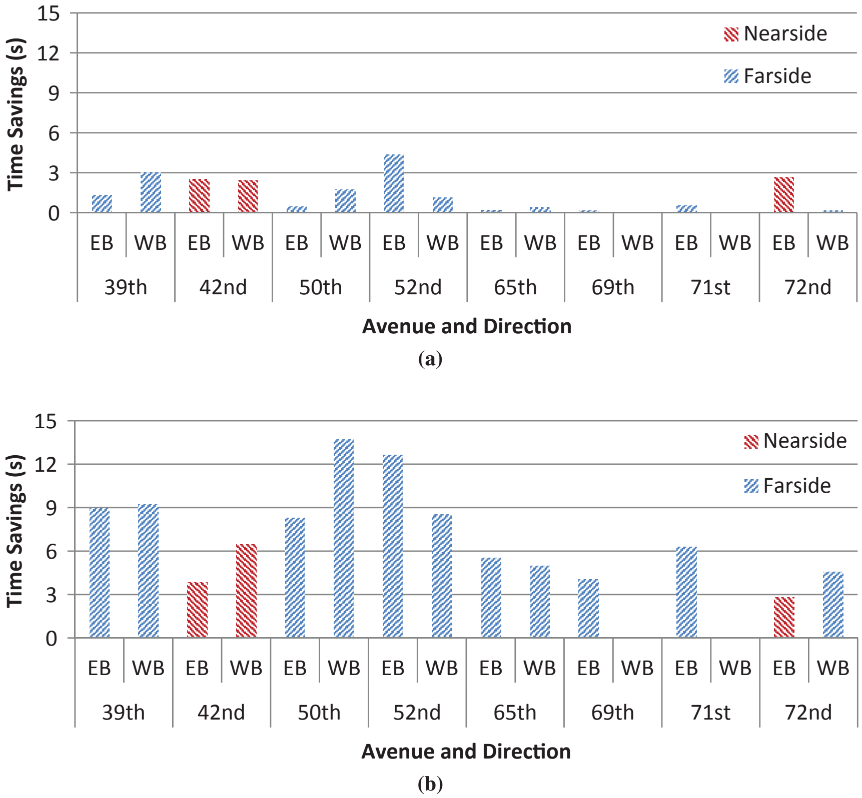


FIGURE 7 TSP timeliness for requested (*a*) GE and (*b*) EG phases.



(a)

(b)

FIGURE 8 Estimated total passenger time savings per second of TSP phase: (*a*) GE and (*b*) EG.

by buses. Therefore, this finding might not be true if both GE and EG phases were working correctly. According to Smith et al., TSP should be more effective at farside stops because bus arrival time prediction is more reliable at farside stops (*2*). However, Figure 8, *a* and *b,* does not show clear differences between nearside and farside stops, but this finding is not conclusive because of the small sample size (only six nearside and 12 farside segments).

Under the assumptions that vehicle arrival rates at intersections are uniform (vehicle platooning arrival patterns were not considered), traffic conditions are unsaturated at all four approaches, and regular green phase and red phase durations will not change if a GE or EG phase is granted, the total time savings (TTS) for nonbus vehicles on the major street and the total delay (TD) for vehicles on the side street can be estimated by the following:

$$\text{TTS} = \frac{q_1 \cdot q_2}{2(q_2 - q_1)}\left(2 \cdot \text{red} \cdot \text{TSP} - \text{TSP}^2\right) \tag{6}$$

$$\text{TD} = \frac{q_1 \cdot q_2}{2(q_2 - q_1)}\left(2 \cdot \text{red} \cdot \text{TSP} + \text{TSP}^2\right) \tag{7}$$

where

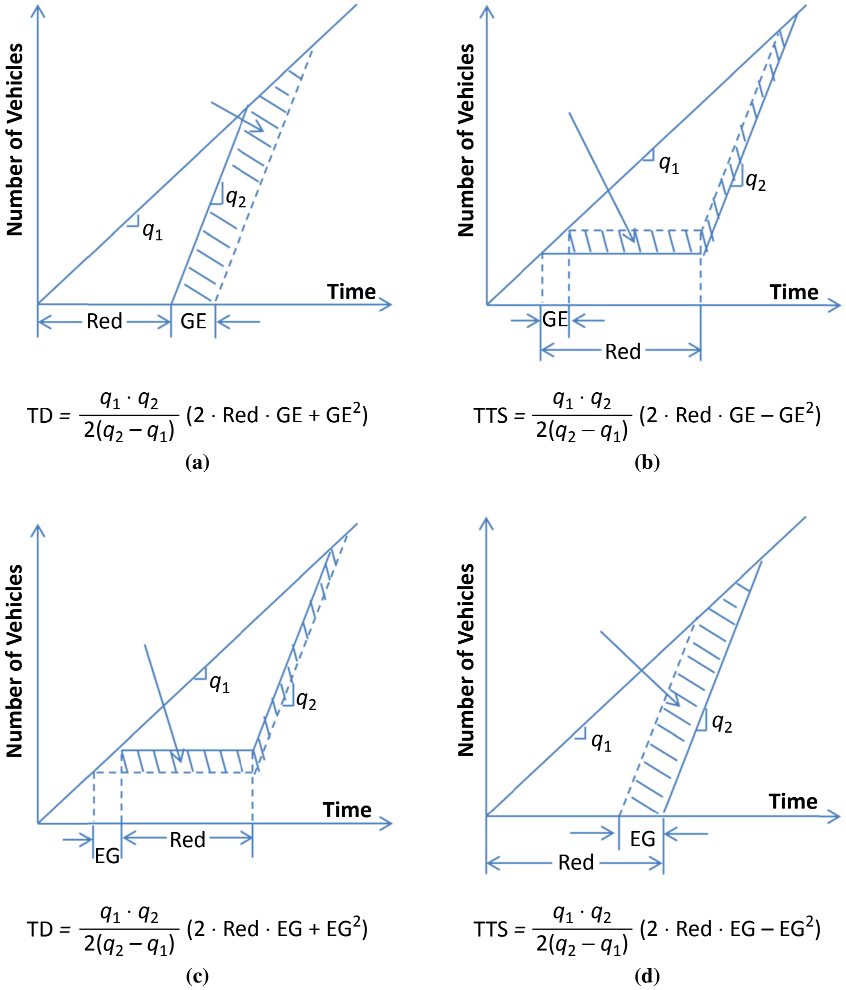
q_2 = discharge flow (assumed to be 1,800 vehicles per hour per lane),
q_1 = vehicle arrival flow from an approach of an intersection, estimated by the intersection vehicle count data,
red = regular red phase duration for an approach to an intersection, and
TSP = median TSP phase duration (either green extension or early green) for an intersection.

The derivations of these equations are illustrated in Figure 9. Under the assumption that all nonbus vehicles are single occupancy vehicles, the results are shown in Figure 10. The results show that the total time savings and delays for nonbus vehicles per second of the GE phase and per second of the EG phase are very similar (less than a 2-s difference); this finding means that the nonlinear effect of TSP phase duration on time savings and delays for nonbus vehicles is negligible. For each second of the EG phase, the bus passenger time savings are slightly less than the total vehicle delay on the side street for intersections west of 52nd Avenue, but the sum of the bus passenger time savings and the total vehicle time savings on Powell Boulevard is higher than the side street vehicle delay at all intersections. For each second of the GE phase, the sum of the bus passenger time savings and the nonbus vehicle time savings on the major street is almost equal to the vehicle delay on the side street.

CONCLUSIONS

TSP systems are relatively low cost and easy to implement systems that can improve transit running times and reliability. This research shows that TSP systems can be challenging to implement to create a system that is both timely and effective. TSP systems require not only maintenance but also continuous monitoring to promptly detect problems and intersections with low TSP performance.

This study developed a novel method to integrate traffic signal and automatic vehicle location and automated passenger count data for the estimation of bus arrival times and phase probability distributions at intersections, as well as bus travel time savings. Four novel TSP performance measures were proposed: frequency, responsiveness, timeliness, and effectiveness. TSP, by definition, is a partnership between



$$\text{TD} = \frac{q_1 \cdot q_2}{2(q_2 - q_1)}\,(2 \cdot \text{Red} \cdot \text{GE} + \text{GE}^2)$$

(a)

$$\text{TTS} = \frac{q_1 \cdot q_2}{2(q_2 - q_1)}\,(2 \cdot \text{Red} \cdot \text{GE} - \text{GE}^2)$$

(b)

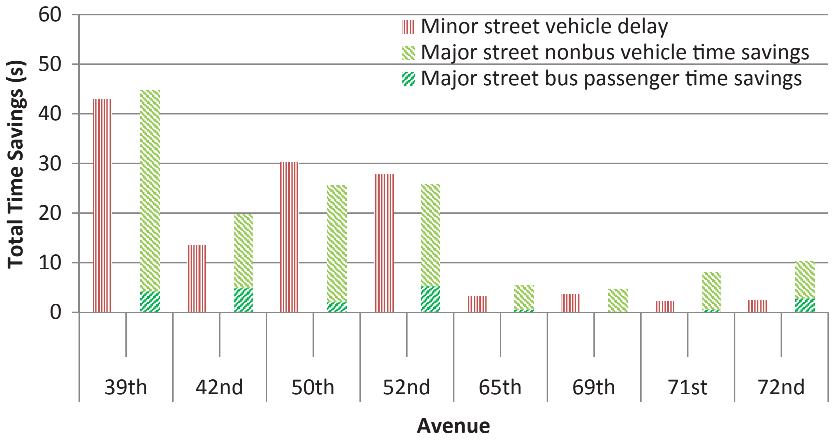
$$\text{TD} = \frac{q_1 \cdot q_2}{2(q_2 - q_1)}\,(2 \cdot \text{Red} \cdot \text{EG} + \text{EG}^2)$$

(c)

$$\text{TTS} = \frac{q_1 \cdot q_2}{2(q_2 - q_1)}\,(2 \cdot \text{Red} \cdot \text{EG} - \text{EG}^2)$$

(d)

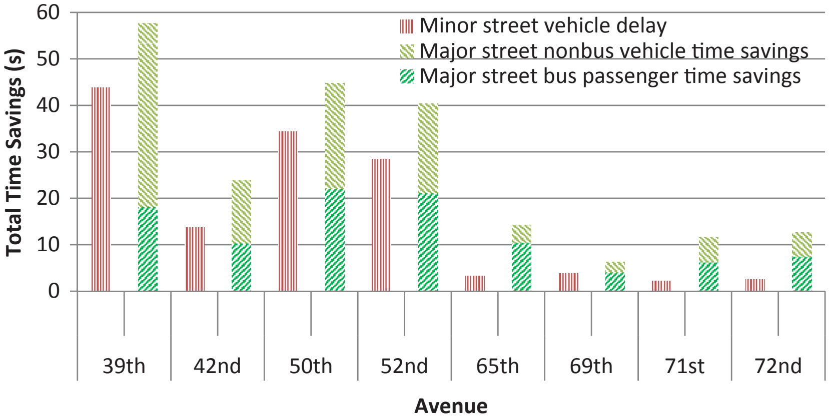
FIGURE 9 Side street delay (*left*) and main street time savings (*right*): (*a* and *b*) GE and (*c* and *d*) EG.



(a)

FIGURE 10 Total passenger time savings and vehicle delays per second of TSP phase: (*a*) GE.

(continued on next page)



(b)

FIGURE 10 *(continued)* **Total passenger time savings and vehicle delays per second of TSP phase: (*b*) EG.**

the transit agencies that operate the bus systems and the cities that manage the traffic signal systems. Proactive TSP performance analysis can help transit agencies and cities to better understand the existing TSP system performance, as well as identify potential problems and improvement opportunities. Future research should examine TSP detector health and performance in other settings and corridors.

For this study, the results indicated that more than 80% of the TSP phases were granted within the cycle in which a bus arrived at the intersection. However, the TSP timeliness was relatively low during the study period, and a gap remained between the ideal TSP effectiveness and the actual TSP performance. EG phases were better than GE phases, because too many GE phases were granted late or lost. This finding may indicate potential problems with the TSP control strategies, the reliability of the activation and deactivation of bus emitter priority requests, or the reliability of priority request detection. The results also showed that EG phases were more efficient than GE phases. The estimated nonbus vehicle time savings and the delay per second of the TSP phase were similar. The total passenger time savings and the delays per second of the GE phase were almost equal to each other, but the total passenger time savings per second of the EG phase was much higher than the total nonbus vehicle delay.

The TSP performance evaluation results provided worthwhile information for the city and the transit agency to identify potential problems and improvement opportunities for the TSP system. The algorithms and performance measures are general and can be applied to other corridors on which TSP is implemented. However, the specific values for GE and EG timeliness and effectiveness are site specific.

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