

Using Hardware-in-the-Loop Simulation to Evaluate Signal Control Strategies for Transit Signal Priority

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The City of Portland, in collaboration with TriMet (Portland's regional transit service provider) and the Oregon Department of Transportation, has implemented transit signal priority (TSP) at more than 240 intersections on seven transit routes as a part of the Streamline program. This study focuses on the simulation of one intersection in Portland by using hardware-in-the-loop simulation to examine the effects of TSP signal control strategies on transit performance. More specifically, near- and far-side bus stops are studied with hardware-in-the-loop traffic simulation to determine the effect of stop location on the effectiveness of the Portland TSP system. This analysis is verified by using a deterministic spreadsheet model to determine the effectiveness of the system and to address whether a green time extension plan should be used if there is passenger activity at a nearside stop.

Transit signal priority (TSP) is an operational strategy that can speed the movement of in-service transit vehicles through traffic signals. By reducing control delay at signalized intersections, it has been shown that TSP can reduce travel time, thus reducing rider travel time and transit operating costs (1). The application of TSP by using conditional priority has secondary benefits, including reduction of transit travel time variability, that actually improve transit service reliability and thereby the quality of the service delivered. These features can make transit service more attractive to choice customers. TSP also has the potential for reducing overall delay at the intersection on a per-person basis. At the same time, TSP attempts to provide these benefits with a minimum of adverse impact on other facility users, including cross traffic and pedestrians (2).

The City of Portland, in collaboration with TriMet (Portland's regional transit service provider) and the Oregon Department of Transportation (ODOT), has implemented TSP at over 240 intersections on seven transit routes as a part of the Streamline program. The Streamline program is a comprehensive transit preferential treatment system that includes TSP, an automatic vehicle location (AVL) system, improved scheduling, and low-cost stop improvement treatments to provide better service to passengers. The pro-

gram has resulted in smart buses that can selectively request priority depending on the status of the bus with respect to its schedule. The purpose of the Streamline program is to offer more efficient service, primarily by reducing run time, on key transit corridors throughout the region.

In Portland, TSP has been put into operation by using conditional priority that is implemented through the transit system's AVL system. The conditional priority system is active if the bus is in service, if it is on route, if the doors are closed, if the infrared emitter is on, and if the bus is 30 s or more behind schedule. The thresholds identified for the priority system have been documented elsewhere (3) but are summarized in Figure 1. It should be noted that during the course of this project the lateness threshold was reduced to improve the responsiveness of the system to lateness.

Several types of priority treatments are given to vehicles in a TSP system. The strategies used for this study are consistent with the signal controller hardware and software that exist on the street in Portland. The traffic signal software used by the city (Wapiti Microsystems Software) provides a range of priority options. Priority can be requested on any of the legs of the intersection and can include red truncation, green extension, or a combination of the two. Priority is implemented by modifying coordination timing plans and adjusting force-offs (green times) for the vehicle movements while coordination remains in effect. This performance is similar to that defined in the National Transportation Communications for ITS Protocol (NTCIP) Standard 1211 for signal control priority.

The maximum green extension is constrained by intersection elements but ranges between 0 and 40 s. The red truncation is heavily dependent on the configuration of the intersection. Table 1 summarizes some of the limitations associated with the signal timing as it relates to bus operations: pedestrian detection, pedestrian timing, multiphase intersections, and cycle lengths.

When the system is in operation, the choice of a particular priority strategy is dependent on the time when the priority request is received. Figure 2 shows the priority strategy implementation plan as implemented by the controller software. Limitations associated with this strategy are discussed later. During the field implementation, red truncation and green extension are used within each intersection's signal timing plan to provide priority. The maintenance of coordination requires that the phase length changes be implemented within the constraints of the overall cycle length; considerations include minimum Walk time, flashing Don't Walk time, and minimum vehicle green time.

The TSP evaluation described here is separated into two parts. The first effort, and the primary focus of this paper, is to examine the impact

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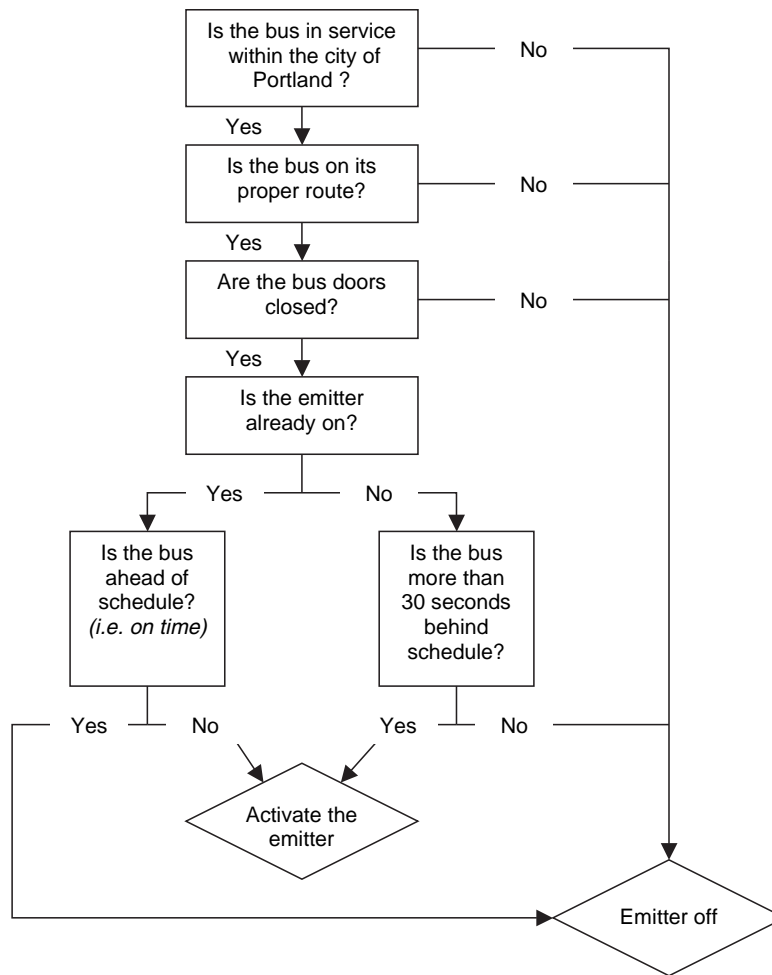


FIGURE 1 Decision framework for emitter activation.

of bus stop location on TSP system performance by using hardware-in-the-loop simulation. This analysis was supplemented with implementation experience and data from AVL system performance to develop a deterministic spreadsheet model for determining benefits. The second portion of the analysis is a review of operating parameters that would improve the system.

AVL SYSTEM

TriMet’s AVL system (installed on all buses in the fleet) uses Global Positioning System technology to monitor the location of transit vehicles in real time. In addition to a data-archiving function, real-time vehicle location coordinates (along with other transit management

TABLE 1 Traffic Signal Timing Considerations for Signal Priority

| Parameter | Limitation | Comment |
|--------------------------|--|--|
| Pedestrian detection | Lack of pedestrian detection (push buttons for actuation) requires the opposing pedestrian phase to time every cycle. | Presence of pedestrian detection increases the potential responsiveness of the intersection to serve transit. |
| Pedestrian timing | Time for flashing Don’t Walk cannot be reduced in any case. | Pedestrian detection reduces the need to recall pedestrian phases each cycle, thereby improving the responsiveness to transit. |
| Multiphase intersections | Phase skipping is not allowed in the state of Oregon, thus minimum vehicle times and clearance times must be considered for all phases (legislative limitation). | Additional phases at intersections increase the amount of required time for service. |
| Cycle lengths | Low cycle lengths reduce the flexibility of the engineer to extend the timing provided to the bus although may provide better responsiveness overall. | The trade-off between flexibility and efficiency at the intersections has been consistently discussed; lower cycle length typically improves bus operations. |

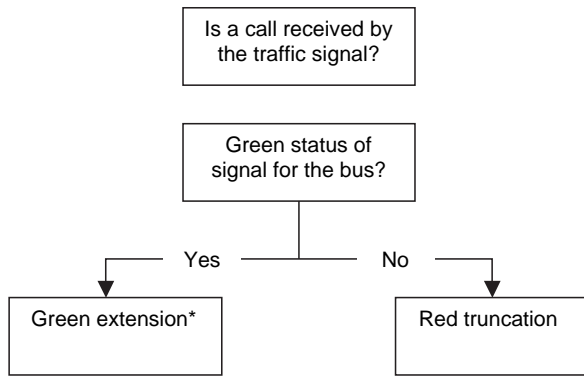


FIGURE 2 Decision framework for TSP strategy to be employed (*green extension may include combination of red truncation for the next cycle).

information) are transmitted to the transit control center by a wireless communications system. TriMet has implemented these devices on buses as part of their overall management system and to provide riders with more accurate information about when buses will actually arrive at stops, enhancing system efficiency and rider convenience (4). Time-stamped location information is collected for all bus routes at all stops. This makes it possible to determine travel time between all stops as well as to calculate average transit vehicle speeds between stops because distances are known (5). TriMet’s AVL system is integral to the TSP system; AVL integrates information with the TSP system to determine each vehicle’s schedule status (late, on time, or early) according to that vehicle’s schedule. In this research, data from the AVL system were used to verify effects of TSP parameters on transit performance.

HARDWARE-IN-THE-LOOP

Many researchers have studied TSP by using hardware-in-the-loop simulation. Hardware-in-the-loop research uses a combination of simulation software and field signal controller equipment to evaluate traffic conditions in a laboratory setting. This arrangement allows for the exploration of quantifying adapted system performance without disturbing traffic or transit by using live traffic conditions (6).

The implementation of hardware-in-the-loop simulation uses a microscopic simulation program with the city of Portland’s traffic signal control hardware. An interface first developed in the 1990s, known as a controller interface device (CID), is used to provide a real-time link between the simulation program and the traffic controller (7). The CID was developed by FHWA in collaboration with the National Institute for Advanced Transportation Technology (NIATT) and Darcy Bullock, now at Purdue University (8). Hardware-in-the-loop simulation allows researchers to establish traffic conditions by using real signal controllers that provide realistic traffic control with access to all of its features, reporting of a wide range of traffic variables, and no impact on real traffic (9). From an educational standpoint, this arrangement also provides students with hands-on experience working with traffic signal controllers and their timing parameters.

The traffic controllers used in this research are Model 170E (HC11) controllers provided by the city of Portland. The controllers are connected to the CIDs and allow them to communicate with desktop computers. The CIDs are integrated with the microscopic simulation program VISSIM 3.7. Figure 3 shows the setup used in the analysis.

LITERATURE REVIEW

Previous research has used hardware-in-the-loop simulation to evaluate the performance of TSP algorithms. Several previous studies investigated the effectiveness of TSP while varying traffic conditions in a transit simulation environment (10). Throughout the research that was completed and reviewed for this paper, there was a clear preference for the use of farside bus stops for the implementation of TSP because the uncertain passenger loading and unloading times at nearside bus stops would increase the uncertainty in predicting the arrival time of a bus at an intersection (11). It was also believed conceptually that farside bus stops could maximize the efficiency of a signal priority operation since there would be less impact from the dwell time at the bus stop (12).

There is less research that focuses on the effectiveness of TSP and its ability to improve transit system on-time performance by using real data from AVL systems. In fact, recently Kimpel et al. analyzed Portland’s TSP by using AVL data, separating the data on a yearly basis, but they did not isolate the effect of traffic and ridership growth from year to year (13). The research presented here focuses on a

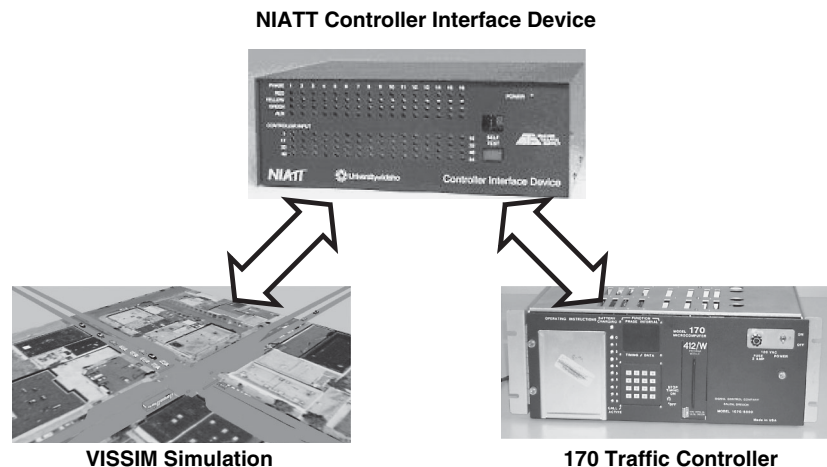


FIGURE 3 Hardware-in-the-loop simulation setup.

particular intersection in order to help guide the implementation of these strategies in the field.

STUDY DESIGN

Simulation scenarios were designed and tested within the hardware-in-the-loop simulation. The study design encompassed four scenarios: (a) nearside stops without TSP, (b) nearside stops with TSP, (c) farside stops without TSP, and (d) farside stops with TSP. With the ability to activate TSP, the four scenarios can be further broken down into two categories, green extension and red truncation plans. The traffic signal control software is able to request either a red truncation or a green extension, as described previously. The basic geometry of the simulated intersection is representative of the intersection of North Albina Avenue and North Killingsworth Street in Portland, which is a four-leg intersection with nonactuated pedestrian movements controlled by a two-phase timing plan. TriMet’s bus Route 4 operates on Killingsworth Street, running north- and southbound.

Actual signal timing from the field was used. The cycle length is 70 s, and each movement receives a split of 31 s of green, 3 s of yellow, and 1 s of red clearance with existing traffic conditions. The TSP strategies were implemented as follows: for the green extension, the bus received a 12-s extension by reducing the following (opposing side-street) phase accordingly. For the red truncation, this plan truncates the side-street (opposing) green light from 31 to 19 s, depending on when the TSP call is received, allowing for the green phase to return early in order to serve the transit vehicle sooner. At this intersection, there is a minimum green time (Walk and flashing Don’t Walk) of 19 s to allow pedestrians to safely cross the intersection. The time allocations for the normal and TSP plans are summarized in Figure 4.

In the simulation a left-turn lane was added to all legs because it was believed that added delay for turning movements would affect the traffic flow on the through- and right-turning movements. In the model, TSP detection was established 500 ft from the stop bar of the intersection. The speed limit at the site is 35 mph and free-flow travel time for the priority range setting (500 ft) is 9.7 s. Thus, the extension of 12 s set in the controller provides slightly more time than is necessary to serve a bus at 35 mph through the intersection.

The delays introduced by the bus stop and dwell times are included in the analysis within the reported travel time in the results. Dwell times were assumed to be within the range of 20 to 40 s (since this is a heavily used bus stop near several schools). Other inputs from actual field conditions were used where possible.

The hardware-in-the-loop simulation is run in real (clock) time. Therefore, each test was run for 25 h and resulted in 24-hourly data sets for each of the four scenarios. The simulation was set to run each scenario for 25 h (90,600 s), including 300 s of warm-up time to allow for the system to reach equilibrium before collection of data. Input values for traffic volumes are noted in Table 2, along with the modeled traffic characteristics taken from the study location during the peak hour for 15-min durations. During the simulation runs a few assumptions were made: the bus is always behind schedule, and the bus always serves the bus stop, which, although not true under actual operating conditions, allows an increase in the number of potential priority requests in the simulation study.

Data were compiled for delay and travel times for each of the four scenarios for each hour the simulation was run. For this analysis, a

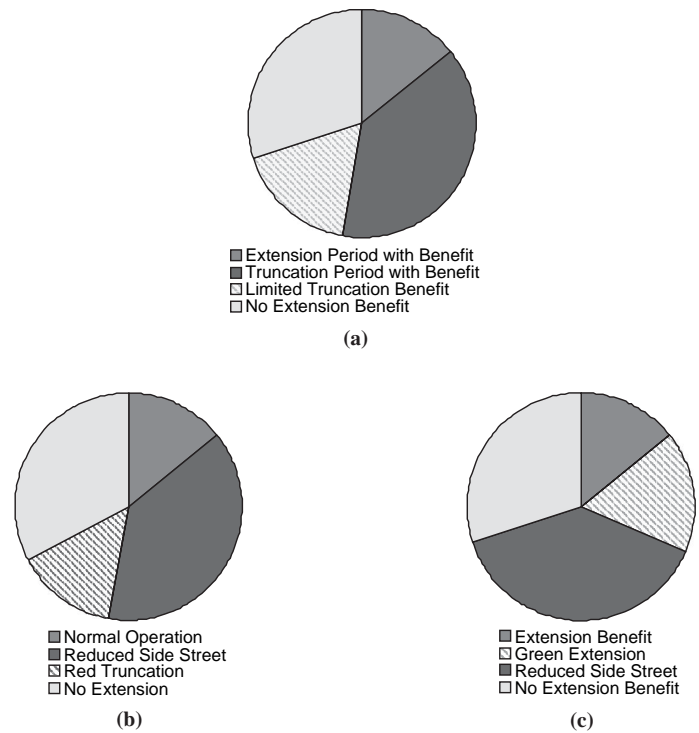


FIGURE 4 Signal timing scenarios for TSP operations: (a) normal, (b) red truncation, and (c) green extension.

one-way headway of 12 min between buses, resulting in a total of 10 buses per hour, will be used when performance measures are summarized. Some variability was introduced into the headway to ensure randomness between scenarios by using VISSIM’s random seed generator.

For the project, delay and trip time are the measures of effectiveness. Secondary measures including bus travel time variability are measured as well as the trip time of other vehicles passing through the intersection.

ANALYSIS

The traffic signal delays were simulated by using the traffic controller software as part of the hardware-in-the loop simulation. Average travel times for the four scenarios were as follows:

TABLE 2 Traffic Volumes and Turning Movement Percentages for Traffic Simulation Modeling

| Phase | Traffic Volume | | | |
|-------|----------------|---------|-------|------|
| | Volume (veh/h) | Through | Right | Left |
| 2 NB | 500 | 70% | 15% | 15% |
| 4 EB | 500 | 85% | 5% | 10% |
| 6 SB | 500 | 50% | 20% | 30% |
| 8 WB | 500 | 80% | 15% | 5% |

NB = northbound, EB = eastbound, SB = southbound, WB = westbound.

TABLE 3 Simulation Results for Delay per Bus

| Bus | Nearside | | | Farside | | |
|--------------------|-----------|--------|---------------------------|-----------|--------|---------------------------|
| | Delay (s) | | Overall Delay Savings (s) | Delay (s) | | Overall Delay Savings (s) |
| | W/O TSP | W/ TSP | | W/O TSP | W/ TSP | |
| Average (NB/SB) | 27.6 | 32.5 | -4.9 | 25.2 | 16.7 | + 8.5 |
| Standard deviation | 5.34 | 5.56 | | 5.18 | 2.05 | |

| Scenario | Average Bus Travel Time (s) |
|-------------|-----------------------------|
| Without TSP | |
| Nearside | 79.1 |
| Farside | 76.8 |
| With TSP | |
| Nearside | 84.1 |
| Farside | 68.3 |

Further comparison of the signal delay for the scenarios is provided in Table 3. By comparing the control delay, it is clear that the two scenarios without TSP yield similar results when compared with the standard deviation for each scenario. It was observed that the difference may be related to the fact that occasionally the presence of a queue adjacent to the bus stop results in the bus's being blocked from reentering the traffic stream.

Close inspection of the results indicates that a nearside stop with TSP has the potential to negatively affect the arrival at the signal by extending the green unnecessarily when the bus is not going to effectively use the extension plan. The nearside transit stop case with TSP results in inefficient use of the green time and in some cases increases delay for buses slightly. This delay increase occurs when a priority request is implemented 500 ft upstream (9.7 s in advance) of the intersection. In the event that an extension is requested before passengers are served (a given condition in the nearside TSP case here), a green extension for a nearside stop will most likely run out while passengers are being served. This case is less likely to happen in a red truncation scenario, but it is dependent on the dwell time and several other factors. The simulation results indicate that this is the case, since the travel time for transit vehicles is reduced by 8.5 s in the farside TSP case. When priority is given to a bus, it is usually expected that the time savings will come from side-street traffic (eastbound and westbound traffic).

The effects of TSP on side-street vehicle delay are summarized in Table 4. The increase of side-street delay with both nearside and farside transit stops is experienced but is minimal for this intersection

because of the short cycle length, modest volume-to-capacity ratio tested (well below 1.0), the relative infrequent cycles per hour that are affected (12 of 51), and the amount of priority provided (as much as 10 s). Reducing the time provided to the bus phase to meet the agency's signal timing policy can mitigate this problem.

The secondary measure of effectiveness used in the evaluation was the standard deviation of the signal delay (also reported in Table 3). The impact of travel time variability is important to on-time performance and thus of critical importance to scheduling run times for buses throughout the TriMet system. Table 3 shows that farside TSP implementation reduces the standard deviation considerably and thus reduces the potential for buses to fall behind schedule.

DETERMINISTIC MODELING EXERCISE

A deterministic modeling exercise was completed to verify the results of the simulation analysis and to determine the relative effects of the various parameters associated with the results. A spreadsheet was used to develop an estimated benefit for the bus by using signal priority with the assumption that the bus was not stopping. This spreadsheet was completed to determine the effect of the first assumption in the simulation modeling, which was that the bus was always going to serve passengers in the cases studied. In reality, the nearside TSP case would remain effective when the bus passes the stop without serving passengers; that is, signal delay would be reduced much as it is in the farside TSP scenario.

The spreadsheet was used to assess the effect of a bus arrival during each second of the cycle. The spreadsheet for the study intersection is shown in Tables 5 and 6. The estimated benefit of TSP is a comparison of what portion of the cycle the bus would arrive on with and without priority. For example, in the 45th second of the cycle, the green begins for the bus phase and arrival of the bus is expected 10 s later (during the 55th second in the cycle). The bus phase would normally

TABLE 4 Simulation Results for Delay per Vehicle on Side Streets

| Side Street | Nearside Delay (s) | | Overall Delay Change (s) | Farside Delay (s) | | Overall Delay Change (s) |
|-------------|--------------------|--------|--------------------------|-------------------|--------|--------------------------|
| | W/O TSP | W/ TSP | | W/O TSP | W/ TSP | |
| EB | 17.8 | 21.1 | -3.3 | 17.1 | 19.6 | -2.5 |
| WB | 16.2 | 18.4 | -2.2 | 16.6 | 18.6 | -2.0 |
| Average | 17.0 | 19.7 | -2.7 | 16.8 | 19.1 | -2.3 |

TABLE 5 Deterministic Spreadsheet Model for Evaluation of TSP: Cycle Seconds 0 to 34

| Detection Time in Cycle | Signal at Time of Detection | Time at Arrival | Priority Plan Activated | Estimated Signal Color at Arrival (normal) | Estimated Signal Color at Arrival (TSP) | Stopped Delay Under Normal (s) | Stopped Delay Under TSP (s) | Estimated Benefit (s) | Was There a Benefit? |
|-------------------------|-----------------------------|-----------------|-------------------------|--|---|--------------------------------|-----------------------------|-----------------------|----------------------|
| 0 | G | 10 | E | G | G | 0 | 0 | 0 | No |
| 1 | G | 11 | E | Non-G | G | 38 | 0 | 38 | Yes |
| 2 | G | 12 | E | Non-G | G | 37 | 0 | 37 | Yes |
| 3 | G | 13 | E | Non-G | G | 36 | 0 | 36 | Yes |
| 4 | G | 14 | E | Non-G | G | 35 | 0 | 35 | Yes |
| 5 | G | 15 | E | Non-G | G | 34 | 0 | 34 | Yes |
| 6 | G | 16 | E | Non-G | G | 33 | 0 | 33 | Yes |
| 7 | G | 17 | E | Non-G | G | 32 | 0 | 32 | Yes |
| 8 | G | 18 | E | Non-G | G | 31 | 0 | 31 | Yes |
| 9 | G | 19 | E | Non-G | G | 30 | 0 | 30 | Yes |
| 10 | G | 20 | E | Non-G | G | 29 | 0 | 29 | Yes |
| 11 | Non-G | 21 | T | Non-G | Non-G | 28 | 16 | 12 | Yes |
| 12 | Non-G | 22 | T | Non-G | Non-G | 27 | 15 | 12 | Yes |
| 13 | Non-G | 23 | T | Non-G | Non-G | 26 | 14 | 12 | Yes |
| 14 | Non-G | 24 | T | Non-G | Non-G | 25 | 13 | 12 | Yes |
| 15 | Non-G | 25 | T | Non-G | Non-G | 24 | 12 | 12 | Yes |
| 16 | Non-G | 26 | T | Non-G | Non-G | 23 | 11 | 12 | Yes |
| 17 | Non-G | 27 | T | Non-G | Non-G | 22 | 10 | 12 | Yes |
| 18 | Non-G | 28 | T | Non-G | Non-G | 21 | 9 | 12 | Yes |
| 19 | Non-G | 29 | T | Non-G | Non-G | 20 | 8 | 12 | Yes |
| 20 | Non-G | 30 | T | Non-G | Non-G | 19 | 7 | 12 | Yes |
| 21 | Non-G | 31 | T | Non-G | Non-G | 18 | 6 | 12 | Yes |
| 22 | Non-G | 32 | T | Non-G | Non-G | 17 | 5 | 12 | Yes |
| 23 | Non-G | 33 | T | Non-G | Non-G | 16 | 4 | 12 | Yes |
| 24 | Non-G | 34 | T | Non-G | Non-G | 15 | 3 | 12 | Yes |
| 25 | Non-G | 35 | T | Non-G | Non-G | 14 | 2 | 12 | Yes |
| 26 | Non-G | 36 | T | Non-G | Non-G | 13 | 1 | 12 | Yes |
| 27 | Non-G | 37 | T | Non-G | G | 12 | 0 | 12 | Yes |
| 28 | Non-G | 38 | T | Non-G | G | 11 | 0 | 11 | Yes |
| 29 | Non-G | 39 | T | Non-G | G | 10 | 0 | 10 | Yes |
| 30 | Non-G | 40 | T | Non-G | G | 9 | 0 | 9 | Yes |
| 31 | Non-G | 41 | T | Non-G | G | 8 | 0 | 8 | Yes |
| 32 | Non-G | 42 | T | Non-G | G | 7 | 0 | 7 | Yes |
| 33 | Non-G | 43 | T | Non-G | G | 6 | 0 | 6 | Yes |
| 34 | Non-G | 44 | T | Non-G | G | 5 | 0 | 5 | Yes |

G = green; E = (green) extension; T = (red) truncation.

be green during the 50th second of the cycle and thus there is no benefit with TSP.

The benefits are summarized in Table 7. As shown, the benefits associated with the farside TSP case are modeled as 8.6 s per bus. This is a gross estimate for stopped delay due to all of the assumptions included within the calculations. From close inspection, one can surmise that the average stopped delay under these calculations without TSP is 10.6 s.

There are notable oversimplifications within the spreadsheet presented (the effect of traffic congestion, buses traveling slower than free-flow speed, other delays to the bus, etc.), but it does provide a

framework from which to estimate potential reduction in delays for transit vehicles in uncongested settings.

By using the deterministic model for evaluation of the intersection, it is possible to compare and contrast different occurrences that affect the performance of the TSP algorithm. For instance, if the arrival of the bus at the intersection is delayed by passenger dwell time, there is a substantial effect on the intersection and the operation of the signal. This delay results in a condition that would result in the introduction of delays during the green extension periods. Depending on the dwell time at the stop, the truncation may have mixed results. Certainly providing more green time to the bus phase would reduce overall

TABLE 6 Deterministic Spreadsheet Model for Evaluation of TSP: Cycle Seconds 35 to 69

| Detection Time in Cycle | Signal at Time of Detection | Time at Arrival | Priority Plan Activated | Estimated Signal Color at Arrival (normal) | Estimated Signal Color at Arrival (TSP) | Stopped Delay Under Normal (s) | Stopped Delay Under TSP (s) | Estimated Benefit (s) | Was There a Benefit? |
|-------------------------|-----------------------------|-----------------|-------------------------|--|---|--------------------------------|-----------------------------|-----------------------|----------------------|
| 35 | Non-G | 45 | T | Non-G | G | 4 | 0 | 4 | Yes |
| 36 | Non-G | 46 | T | Non-G | G | 3 | 0 | 3 | Yes |
| 37 | Non-G | 47 | T | Non-G | G | 2 | 0 | 2 | Yes |
| 38 | Non-G | 48 | T | Non-G | G | 1 | 0 | 1 | Yes |
| 39 | Non-G | 49 | T | G | G | 0 | 0 | 0 | No |
| 40 | Non-G | 50 | T | G | G | 0 | 0 | 0 | No |
| 41 | Non-G | 51 | T | G | G | 0 | 0 | 0 | No |
| 42 | Non-G | 52 | T | G | G | 0 | 0 | 0 | No |
| 43 | Non-G | 53 | T | G | G | 0 | 0 | 0 | No |
| 44 | Non-G | 54 | T | G | G | 0 | 0 | 0 | No |
| 45 | G | 55 | E | G | G | 0 | 0 | 0 | No |
| 46 | G | 56 | E | G | G | 0 | 0 | 0 | No |
| 47 | G | 57 | E | G | G | 0 | 0 | 0 | No |
| 48 | G | 58 | E | G | G | 0 | 0 | 0 | No |
| 49 | G | 59 | E | G | G | 0 | 0 | 0 | No |
| 50 | G | 60 | E | G | G | 0 | 0 | 0 | No |
| 51 | G | 61 | E | G | G | 0 | 0 | 0 | No |
| 52 | G | 62 | E | G | G | 0 | 0 | 0 | No |
| 53 | G | 63 | E | G | G | 0 | 0 | 0 | No |
| 54 | G | 64 | E | G | G | 0 | 0 | 0 | No |
| 55 | G | 65 | E | G | G | 0 | 0 | 0 | No |
| 56 | G | 66 | E | G | G | 0 | 0 | 0 | No |
| 57 | G | 67 | E | G | G | 0 | 0 | 0 | No |
| 58 | G | 68 | E | G | G | 0 | 0 | 0 | No |
| 59 | G | 69 | E | G | G | 0 | 0 | 0 | No |
| 60 | G | 0 | E | G | G | 0 | 0 | 0 | No |
| 61 | G | 1 | E | G | G | 0 | 0 | 0 | No |
| 62 | G | 2 | E | G | G | 0 | 0 | 0 | No |
| 63 | G | 3 | E | G | G | 0 | 0 | 0 | No |
| 64 | G | 4 | E | G | G | 0 | 0 | 0 | No |
| 65 | G | 5 | E | G | G | 0 | 0 | 0 | No |
| 66 | G | 6 | E | G | G | 0 | 0 | 0 | No |
| 67 | G | 7 | E | G | G | 0 | 0 | 0 | No |
| 68 | G | 8 | E | G | G | 0 | 0 | 0 | No |
| 69 | G | 9 | E | G | G | 0 | 0 | 0 | No |

TABLE 7 Summary of Deterministic Model

| Priority Plan | % of Cycle | Average Reduction in Stopped Delay | Weighted Average Benefit |
|--------------------|------------|------------------------------------|--------------------------|
| Shorten | 48.6 | 7.9 | 3.9 |
| Lengthen | 51.4 | 9.3 | 4.8 |
| Effective shorten | 40.0 | 9.6 | |
| Effective lengthen | 14.3 | 33.5 | |
| Total | 54.3 | | 8.6 |

delay on the approach and reduce congestion that may affect bus delay through the intersection.

A conditional system that is truly intelligent would include monitoring of the bus stop request bell to eliminate unnecessary TSP requests and other issues.

DISCUSSION OF RESULTS

This study used a stochastic simulation model and a deterministic spreadsheet model to examine the effectiveness of TSP strategies related to transit stop placement. Insights were provided on the changes

in bus performance from the perspective of signal operations by analyzing transit with hardware-in-the-loop simulation.

One of the most important findings is that the nearside bus stop results in high passenger service time, leading to poor performance of the TSP algorithm because there is limited intelligence at each intersection to make decisions once the call has been received and will no longer be used. There are certainly improvements that can be made to the system, including the following:

1. Integration of the on-board stop request with the priority request relay. This action would require modification of the hardware on board the bus but would eliminate a portion of the ineffective plans that occur when passengers are alighting.
2. Detection of passengers at the nearside stops. Although this action is impractical for the purposes of the Portland implementation at 240 intersections, it is likely that bus rapid transit systems with more-limited coverage throughout the country could provide passenger amenities that would include lighting for the stops that could be activated by passengers at the station. This lighting would likely not be effective in every case, especially for those passengers who are just reaching the bus stop or station.
3. Eliminate extension plans from the signal control strategy with a nearside stop. This strategy is likely what will be done in the Portland case, where stop percentages are significant enough to reduce the disbenefit associated with the nearside stop. An alternative strategy is to change the priority range setting to a point after the nearside bus stop, thus eliminating the potential benefit in the event that the bus does not stop at the nearside location.

CONCLUSION

It is demonstrated that bus stop location is important to the success of an unconditional priority system. The benefits of TSP are a function of the free-flow speed of the street segment, the actual bus operating speed on the corridor, and the signal priority settings (distance setting for priority activation and the signal priority strategy used). The specific comparison completed for this research yielded a reduction in signal delay of 33% in the farside TSP case and an increase in the nearside TSP case (in both cases it is assumed that buses stop on each run). The farside reduction translated into a reduction in average travel time of up to 12% in the farside TSP case. Control delay increased for the opposing side-street traffic. With a longer study or lower free-flow travel speed, the benefits realized would be more limited.

Advancements to control the bus priority request would include connecting the bus-stop-requested indication with the emitter power relay to reduce the likelihood that the traffic signal will accept calls that will not be effective for bus operations.

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