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Next-Generation Transit Signal Priority with Advanced Arrival Time Prediction and Custom Traffic Signal Control Logic

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Abstract

Transit signal priority (TSP) is a signal timing strategy to give priority to transit by adjusting the signal operation with the goal of reducing transit delay and improving reliability. While TSP can be a powerful tool, TSP deployments in the U.S. have often resulted in marginal improvements. The primary reasons for limited TSP effectiveness are short detection horizons for TSP requests (e.g., 10 s), near-side bus stops (i.e., located before crossing an intersection) that influence arrival times at the downstream traffic signal, and restrictive signal timing strategies (e.g., lock-out policies that inhibit TSP for a specified amount of time, coordinated control that offers little flexibility for TSP). This paper documents the impacts of a "next-generation" TSP system that couples with custom signal control logic for TSP through a field deployment in Portland, Oregon, U.S., using emerging data sources. The system uses cloud-based, predictive logic for estimating time of arrival, with predictions of bus arrivals available up to 2 min ahead of each intersection and updated continuously every 1 s. The custom signal control logic includes advanced TSP strategies that can take advantage of early prediction. Using data from high-resolution automatic vehicle location, analysis results show the custom signal controller logic with advanced prediction resulted in an average bus delay reduction of 29 s per intersection at major intersections (a reduction of 69% compared with baseline). Analyses using automated traffic signal performance measures and vehicle probe data showed these bus delay improvements were achieved with marginal impacts on motorists and without additional delay to pedestrians and bicycles.

Keywords

traffic signal systems, intersection performance, multimodal, signal priority, public transportation, bus transit systems

Transit signal priority (TSP) is a signal timing technique that has long been recognized as a strategy to reduce transit delay and improve service reliability, making transit more efficient and more attractive. This also helps meet societal objectives by promoting transit use and lowering transit operating costs (*1*). However, in the U.S., conventional TSP deployments have often led to delay reductions of less than 3 s per intersection (*2*). A recently completed Transit Cooperative Research Program (TCRP) synthesis reports that most responding agencies found only marginal improvements in bus travel time resulted from TSP improvements (*3*).

One of the reasons for these meager benefits is a short detection horizon where the average advance detection of approaching buses horizon reported in the TCRP synthesis was only 10 s (*3*). A short prediction horizon means a short limit to green extension, because green extension may not be any longer than the prediction horizon. It also substantially limits the effectiveness of early green, because, in a short time horizon, there is often no chance to end conflicting phases early while meeting pedestrian clearance and minimum green constraints.

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There are two practical reasons for short detection horizons, based on the general principle that priority cannot be requested until a bus has cleared the last upstream bus stop and the last upstream signalized intersection, because stops (especially when buses skip them) and signal delay introduce too much uncertainty in estimated time of arrival (ETA) for buses. The first reason is short stop spacing, which makes travel time between stops often less than 20 s. The second reason is the prevalence of near-side stops (i.e., stops located before crossing an intersection), which reduce the detection horizon to less than 5 s, making it almost impossible for signal control to react before the bus arrives.

Other reasons for limited TSP effectiveness may also be cited. One is restrictive lock-out policies that inhibit TSP for a specified amount of time (e.g., 2 min) or for a specified number of cycles (e.g., next 3 cycles) after a TSP service, reserving time to get the signal back in sync and for traffic to recover from a TSP interruption. Another is conditional TSP with an inordinately high lateness threshold (e.g., allow TSP only if the bus is at least 5 min late) (*4*, *5*). Another is stringent limits—sometimes as little as 5 s—on green extension or red truncation. Another is inaccurate ETA estimation, either because of inappropriate detector location or not accounting for how traffic congestion affects travel speed (*6–9*).

To overcome the challenge of limited prediction range, TSP systems have been both developed and proposed based on longer-range ETA prediction, coined "predictive priority." They give traffic signal controllers time to make dynamic adjustments to the signal cycle to enable a bus to arrive on green and/or to minimize adverse impact on other traffic (*10*).

One of the primary studies for predictive priority was performed by Ekeila et al., where they developed a dynamic TSP control strategy that included a dynamic arrival prediction model (*11*). The dynamic TSP control strategy was compared with the conventional TSP system using simulation at a hypothetical intersection. Simulation results showed that the proposed dynamic TSP control system outperformed the conventional TSP for reducing transit travel time.

Another application for predictive priority involved light rail transit (LRT), whose stops are spaced further apart, are rarely skipped, and have less variable dwell time than buses. Since 2002, Salt Lake City's University Line has used predictive priority in which peer-to-peer communication between traffic signal controllers allows advance notice of an arriving train. ETA prediction uses a fixed travel time. If normal signal operation would have a red signal for the train at its ETA, the controller can extend the green or terminate intervening phases early. Because the cycle is relatively long (120 s), LRT delay is further reduced by inserting additional actuated train service phases into the cycle. Based on a simulation of actual operations, it was determined that TSP with advance prediction lowered average train delay by 14 s per intersection (from 33 s to 19 s) compared with no TSP, while increasing average auto delay by only 1.6 s per intersection (*12*). Houston's light rail has a similar operation; a simulation study done as it was being planned estimated that it would reduce transit travel time by 16 s per intersection (*13*).

Wadjas and Furth proposed and tested, in simulation, a method that predicts arrivals for LRT about 180–270 s (2–3 cycles) in advance (*14*). Prediction intervals typically included one or two transit stops and one or two signalized intersections. ETA regression formulas were estimated for each intersection approach based on historical data, with headway as independent variable (with a longer headway, more passengers will be waiting and therefore dwell time will be greater). To account for uncertainty in arrival time, an arrival time window of ETA + 20 s was established. Signal control logic then either shortens or lengthens intervening cycles as necessary so that the entire arrival time window will fall within a green interval two or three cycles ahead. The strategy of intervening cycles was achieved while respecting minimum and maximum phase lengths (which account for pedestrian crossing needs) and without any coordination constraint. At the last moment, green extension is applied if needed. They found that, with advanced detection and signal cycle length adjustments, 62% of trains arrived on green without any need for a last-moment green extension, and that, with green extension, 82% arrived on green. Average transit delay fell from 21 s to 10 s per intersection, while average vehicle delay increased by only 3 s per intersection. The 95th percentile running time, which is important both for service reliability and for scheduling and, therefore, operating cost, fell by 4.4 min, amounting to 0.55 min per signalized intersection. Islam et al. also developed predictive methods for LRT with good performance (*15*).

Predictive priority for buses is a greater challenge because of shorter stop spacing, the greater likelihood of an upstream stop being skipped, and greater variability in dwell time. No field application has been reported in the literature, but researchers have shown that it is feasible. As early as 2005, Kim and Rilett challenged the idea that priority should not be requested for near-side stops until the bus has begun to pull out of the stop (*16*). Using simulation, they tested the impact of giving priority to buses with near-side stops based on an ETA prediction using a regression model with headway as the independent variable. From regression results, their method determines a 90% ETA prediction window, and then selects the priority action (green extension, early green, phase insertion) that would get all or most of the prediction window within a green interval. Average bus delay for the two near-side stops studied fell from 45 s to 21 s, while average auto delay rose by only 0.5 s.

Moghimidarzi et al. proposed a bus TSP method called "predictive-tentative priority" using an advance prediction horizon that included one intervening stop (*17*). While a bus is serving that intervening stop, ETA is continually updated using expected remaining dwell time, determined from a historical dwell time distribution. When the bus departs the intervening stop, ETA is updated and, if appropriate, the planned priority action is canceled. The underlying traffic signal control was the self-organizing adaptive control logic developed by Cesme and Furth which allows for "self-healing" after a transit priority interruption, enabling aggressive TSP interruptions with little impact to auto traffic (*18*). A simulation study found that average bus delay fell to 5 s per intersection, a 75% reduction over the base case, while increasing auto delay by only 3% (*14*).

Connected vehicle (CV) technology offers a new way to detect buses. Hu et al., proposed a person-based delay optimization method for TSP using CV technology (*19*). They evaluated the proposed method using both analytical and simulation approaches. Simulation results showed that the proposed CV-based TSP logic can reduce bus network delay by approximately 37% compared with the no-TSP scenario (from 58.4 s to 42.4 s). Lee et al., aimed at validating the proposed CV-based TSP algorithm developed by Hu et al. by conducting a field test at the "smart road" of the Virginia Tech Transportation Institute (*19*, *20*). Field evaluations showed that, overall, bus delay was reduced by 57% compared with the no-TSP scenario. While CV-based TSP studies indicated promising findings, in typical applications, vehicle information is first received only about 800–1,000 ft in advance of an intersection, which roughly corresponds to a detection horizon of only 15–20 s, similar to traditional detection, as applied in a field test in Utah (*21*). To overcome this limitation, Zamanipour et al. and Beak et al. have proposed using peer-to-peer intersection communications to send check-in information from a greater distance, with promising results from simulation studies (*22*, *23*).

There remains a need to implement bus TSP with advanced detection and signal control logic that takes advantage of this advanced detection, and to evaluate it in the field. Many TSP implementations are not monitored or evaluated. Where field studies are reported, including several documented in the TCRP Synthesis Report, they often include other priority treatments done as part of the same project, including bus lanes and stop relocation, making it difficult to isolate TSP benefits (*3*). Many TSP evaluation studies consider only bus performance, relying on a transit agency's automatic vehicle location (AVL) data without considering impacts to other modes. While AVL-based studies can yield bus running time results, they can be inadequate for monitoring TSP impacts by intersection because of variability in dwell time at near-side stops and because there can be multiple signalized intersections between time points.

Along with AVL, other big-data sources for a more robust evaluation of TSP have emerged but have been little used for TSP evaluation. One is travel time data from probe vehicles, offered by multiple vendors. Another is traffic signal systems that store high-resolution controller data—from that data one can derive automated traffic signal performance measures (ATSPMs) that can be useful for TSP performance evaluation, as pioneered by Jackson et al. (*24*).

Objectives and Paper Organization

This research investigates a next-generation TSP system implemented on Divison Street in Portland and Gresham, OR, that uses 1) a new method for advanced detection and ETA prediction using machine-learning and artificial intelligence (AI), 2) aggressive and varied bus priority tactics that take advantage of advanced prediction, and 3) priority elements for pedestrian and bicycle service and safety. The main objectives of this research are to describe this next-generation TSP system and to evaluate its impacts to both bus and other traffic. It builds on best practices in TSP evaluation by using AVL, probe vehicle travel time data, and ATSPMs to evaluate the impacts of TSP.

Portland has a long history of TSP. From its inception in 1986, traffic signals on streets with light rail have been timed so that trains get no signal delay between stations following the principle that they may have to wait for a green to depart from station, but then get a green wave to the next station. Portland has also been a leader in TSP for buses; however, its historical bus TSP, based on optical detection, has had limited effectiveness. A recently completed $175 million project refitted 11.5 mi of Division Street in Portland and Gresham with the aim of providing frequent and fast bus service with a next generation TSP system. Colloquially, the project's TSP goal was to aim for the near-zero traffic delay that LRT has long enjoyed.

The sections that follow describe the system used for advanced detection and ETA prediction, the study site, and the signal control logic used for TSP. Next, the study methodology is described, followed by results and conclusions.

Bus Detection and AI-Based ETA Prediction

The Division Street TSP system uses LYT.transit, a cloud-based technology solution for TSP to detect buses

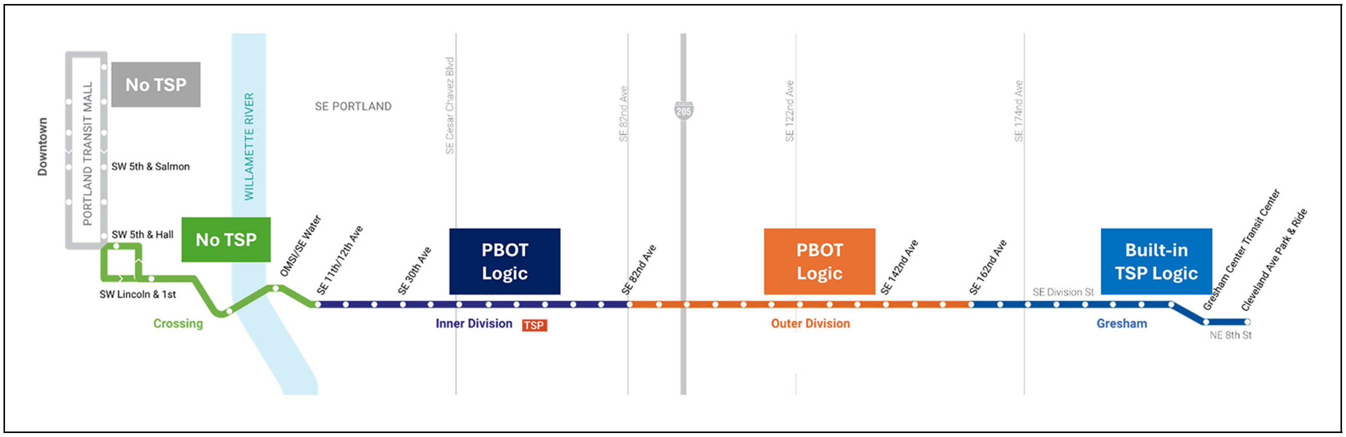

Figure 1. FX-2 division route and segments with no transit signal priority (TSP), with Portland Bureau of Transportation (PBOT) logic, and with built-in TSP logic.

and predict their arrival time. Offline, every few months, LYT applies machine learning to a transit agency's archived AVL data to develop a method for predicting travel time to each intersection from points up to three intersections upstream using an artificial neural network whose inputs are distance, speed, heading, the set of intervening stops, door status (open or closed), and time of day. The prediction horizon often includes one or more bus stops.

In real time, a LYT server in the city's traffic control center, acting as an edge computer, takes in messages as they are received by the transit agency's AVL system, in which buses announce their location, heading, speed, and door status approximately every 5 s. As messages from a given bus are received, LYT applies its prediction method to determine ETA at the next one, two, and three intersections, and sends those updated ETAs to the traffic control center server, which forwards them to the intersection controllers. At each controller, this bus detection information gets routed to the priority request server, which is programmed to generate a priority request (check-in) when ETA falls below 120 s, and to check out (canceling a priority request) when a bus clears the stop line.

Because the priority request server sometimes fails to generate and cancel priority requests, Portland Bureau of Transportation (PBOT) staff created a script within the controller to check in buses directly if the server has not done so, and another script that checks a bus out 20 s after its ETA has been less than 0.5 s.

Study Site

The study site is the eastern 11.5 mi of TriMet's FX2-Division line, which operates between Gresham and downtown Portland. As illustrated in Figure 1, the study corridor consists of two Portland segments—Inner Division (3.8 mi, with one through lane per direction plus a central turn lane) and Outer Division (4.6 mi, multiple lanes, some short stretches with bus lanes)—and a Gresham segment (2.5 mi with multiple lanes and 0.6 mi with two lanes). At intersections in Portland, signal controllers follow custom TSP logic programmed by PBOT staff (abbreviated as "PBOT logic"), while, in Gresham, controllers use "built-in TSP" logic. Excluded from the study corridor is the western part of the FX2 route, crossing the Willamette River and continuing to downtown Portland, which does not have TSP.

The FX2 line has 12 min headway most of the day. It uses 60 ft articulated buses to increase person-carrying capacity. As part of the Division TSP project, some bus stops were consolidated and, where possible, stops were placed on the far side of signalized intersections; about 25% of the bus stops remain near-side. The project also involved optimizing signal timings. Signal control follows coordinated-actuated logic, with cycle lengths in the range of 60–90 s.

Custom TSP Logic that Takes Advantage of Early Prediction

This section describes the PBOT TSP logic used in Portland to achieve the high level of performance desired and to take advantage of the advance prediction provided by LYT. The goal of PBOT was to deliver a TSP system that eliminates stops at traffic signals, knowing that there are significant challenges within bus operations, especially with near-side stops, that make this difficult to achieve. To meet this goal, the city uses commands that drop coordination with adjacent traffic signals to organize the allocation of green time to minimize the likelihood of stopping based on the bus ETA.

Green Extension and Early Green

PBOT's TSP logic includes both "green extension," which holds a bus phase green until the bus checks out, and "early green," which ends conflicting phases as soon as possible, respecting minimum green and pedestrian clearance, and then holds the bus phase until the bus checks out. Both are triggered when the ETA is less than the "late action threshold" chosen by the PBOT signal engineer, usually set to 40 s where the signal cycle is long and 30 s where it is short. With this 30–40 s prediction horizon, both green extension and early green become far more aggressive than they are in TSP deployments with a short prediction horizon. Green extension will hold the green for up to the entire prediction horizon, that is, up to 30–40 s. And triggering early green 30–40 s before the bus arrives means that multiple phases can be terminated early before the bus arrives, hastening a return to the bus phase. Advancing early green in advance also helps flush the queue that is in front of buses before they arrive at intersections. With green extension reaching 30–40 s into the red interval that normally follows the bus green, and early green curtailing the red interval preceding the bus green, buses should experience far less delay than they would with a short prediction horizon.

Signal controllers all along the corridor have built-in programming for green extension and early green. In Gresham, TSP implementation uses the controller built-in logic.

Early Red with Ped Return

We created the tactic "early red with ped return," a variation of the "early red" tactic described in an earlier report, to both reduce bus delay and improve pedestrian service and safety (*1*). Considering that half the boarding pedestrians on any bus line have to cross the arterial to reach a bus stop, Portland decided that priority for transit should also include priority for crossing pedestrians. This tactic is applied as the bus approaches and based on a calculated interval in the bus ETA, when there is enough time to run the side-street pedestrian crossing before the bus arrives. When activated, the controller will serve subsequent phases as quickly as possible and then return to the side-street pedestrian phase. This gives pedestrians, who may be crossing the street to get to the bus stop, another chance to cross without delaying the bus.

This action is triggered when ETA lies within an "early action window" calculated by PBOT's signal engineer specific to each intersection. The window's range is [*b* to *b + 10*] where:

$$b = C_{\mathrm{min,ped}} + \mathrm{Arterial\_Left\_Minimum\_Split}$$

where

$C_{\mathrm{min,ped}}$ = cycle length if all phases are held to their minimum length while serving all pedestrian phases.

Because the controller is attempting to prioritize the bus phase early, it is usually serving the arterial through phase when the action is triggered. This window gives enough time for the controller to serve the arterial left cycle at reduced split times to the side-street pedestrian phase, and then start the priority phase in the subsequent cycle before the bus arrives. For large intersections, the early action window can be as far out as 90–100 s; for smaller intersections, as close in as 30–40 s.

Early red tactic is deactivated once the side-street phase begins. By then or soon afterwards, ETA will have fallen to be within the "late action window," within which green extension and early green logic may be triggered following the logic described earlier.

The logic for these three tactics (green extension, early green, early red with ped return) is summarized in the following pseudocode, where the controller runs this code every 0.1 s.

User Program 4: Custom TSP Routine

```
IF (ETA is within Early Action Window) AND (side street ped active
more than 2 s) THEN
        SET EarlyActionFlag
        Turn off coordination
        Set forceoff on all phases conflicting with side street ped
ENDIF
IF (EarlyActionFlag = TRUE) AND (side street ped active between 1
and 2 s) THEN
        RESET EarlyActionFlag
        Turn coordination back on
        Lift forceoffs
ENDIF
IF (Bus ETA <= Late Action Threshold) AND (LateActionFlag = FALSE)
THEN
        SET LateActionFlag; START LateActionTimer
        Set forceoff on all phases conflicting with priority phase /* early
        green */
        Set hold on priority phase /*green extention*/
ENDIF
IF (bus checks out) OR (LateActionTimer > 45)
        RESET LateActionFlag; RESET LateActionTimer
        Lift forceoffs and holds
ENDIF
```

One critical feature of this logic is that, for both early and late actions, coordination is turned off when a side-street pedestrian call is registered and until the side-street pedestrian phase is served. Following National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) 1211, the coordinator (a function within the controller) will not allow the coordinated phase (arterial through) to end early and, if the arterial through ends late (putting the cycle out of sync), the coordinator will force minor phases (all except arterial through) to end early to get

Figure 2. Layout and ring diagram for SE division and 148th Street, with three opportunities for bus service per cycle in each direction.

back in sync. To avoid this interference during TSP actions, coordination is turned off until the priority actions are complete.

With this logic, Portland has realigned its priorities on Division Street making arterial progression secondary after transit and pedestrians.

Bus Priority Conflicts

If buses approach an intersection from opposite directions, the bus whose ETA first triggers a priority action takes precedence and action is inhibited for the second bus. However, during the late action window, as ETAs are updated, if the second bus's ETA becomes 8 s earlier than the first bus's, action is taken for the second bus and inhibited for the first.

Extra Bus Phases

At intersections where buses have a conflict with the arterial through movement, the bus phase will typically be short. The key to limiting bus delays in those instances is to avoid long red periods by giving buses multiple phases in the cycle that they can use. This tactic is provided at three intersections by inserting extra bus phases. One of these intersections is SE Division at 148th Avenue (Figure 2). Buses approach in a bus lane shared by right-turning vehicles, and the bus lane does not continue on the departure leg, making it a queue-jump lane. Because right-turning vehicles may be ahead of the bus, any bus phase has to allow right turns as well. The bus phase cannot coincide with mainline through because buses need to merge from the queue jump lane to travel lane, and it cannot coincide with mainline bikes and pedestrians, which conflict with right turns. Nevertheless, there are three places in the cycle where a bus phase in either direction can be inserted, as shown in Figure 2.

Pedestrian Priority When There is No Bus

In a corridor with arterial coordination, minor intersections can be forced to have a cycle considerably longer than needed for capacity, which can lead to side-street pedestrians waiting through a long mainline phase with long idle periods. To reduce pedestrian delay, when there is no bus call, PBOT logic will end the arterial phase after it has run for a specified minimum (called *gMin2*), and force any other intervening phases to end early in order expedite the side-street ped phase. PBOT usually sets *gMin2* equal to 5 s longer than the arterial phase's programmed green. Pseudocode for this routine is as follows:

User Program 3: non-TSP Ped Priority Routine

```
IF (no TSP call) AND (side street Ped call) AND (Arterial green > gMin2) THEN
    SET PedPriorityFlag
    Force off all phases conflicting with side street ped
ENDIF
IF (PedPriorityFlag = TRUE) AND (side street ped is active) THEN
    RESET PedPriorityFlag
    Lift forceoffs
ENDIF
```

Phase Rotation for Preventing Buses from Blocking Left Turns and for Early Green

Where buses stop in-line at a far-side stop (i.e., stops located after crossing an intersection) and the departure leg has only one travel lane, a stopped bus will block the departure leg. If it becomes time to start a side-street left turn whose departure leg is thus blocked, PBOT logic will apply that left-turn demand to a lagging left turn, as illustrated in Figure 3. With this tactic, phase 3 can be omitted and phase 11 activated, and similarly, phase 7 can be omitted and phase 12 activated. Additionally, when a bus is expected to arrive during high demand leading mainline left-turn phases (i.e., phases 1 and 5), a similar action is taken by the controller by applying left-turn demand to both leading and lagging phases. This is meant to clear any left-turn queue spillback onto the mainline with the goal of reducing bus delay. Note that this action is rare, since the advanced prediction in conjunction with custom TSP logic ensures that buses are served during the regular mainline through phase (i.e., phases 2 and 6) in most cycles. Furthermore, it is only activated when a left-turn queue is detected by the advanced detection for the left-turn lane indicating the risk that a long left-turn queue may be blocking the mainline through phase.

Study Methodology

Treatment Cases

For the analysis of the developed TSP strategies, a base case and two TSP treatment cases were operated. Table 1 provides a summary of these TSP treatment cases along with TSP business rules and the test periods that they operated for data collection.

The built-in TSP case has green extension and early green logic as provided in the controllers. LYT ETA messages were treated as bus priority requests when ETA reached the late action threshold (30–40 s). While this case uses standard TSP tactics, it is an aggressive version of TSP by American standards, with green extension that can last up to 30–40 s and with detection early to terminate multiple conflicting phases early.

For safety reasons, certain aspects of TSP were retained in all three cases. Phasing plans were not changed, including those that provide multiple inserted phases for buses that have to merge into through lanes (i.e., queue jumps). At seven large intersections, early red with return to ped was maintained because it was considered important to pedestrian safety. With these safety precautions, operations at the three intersections with queue jumps and inserted phases were essentially the same in all three cases, and so those intersections were omitted from the intersection-level performance analysis.

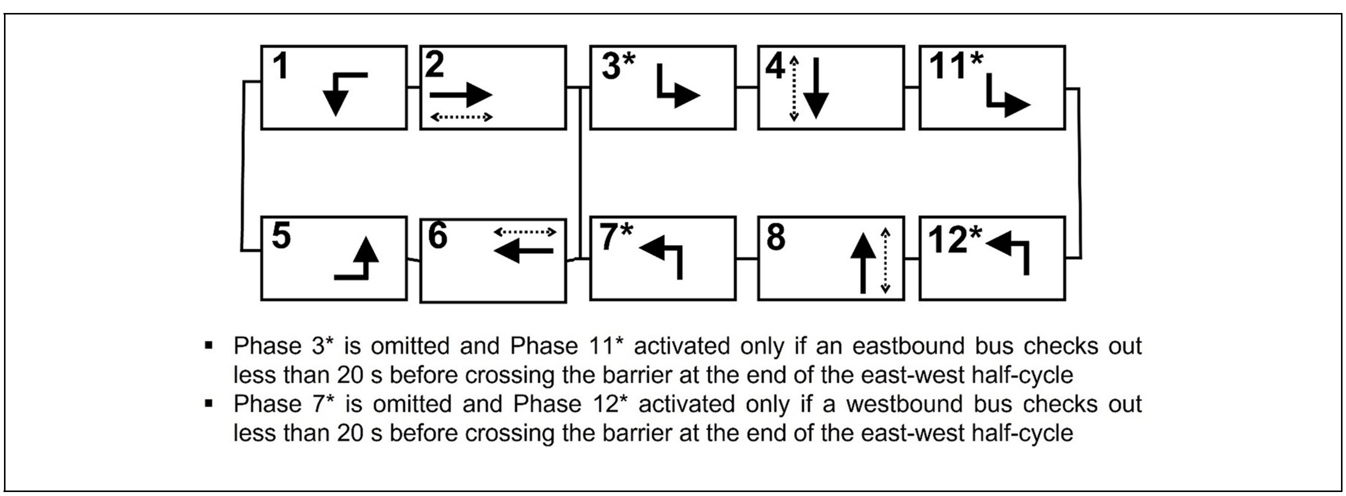

Figure 3. Ring diagram with extra phases 11 and 12 that switch the side-street's left-turn demand to the lagging phase when its departure leg is blocked by bus at a far-side stop (second half-cycle).

Table 1. Summary of Transit Signal Priority (TSP) Treatment Cases, Business Rules, and Periods They Operated

Treatment case	Description	TSP strategy	Conditionality for TSP	Test period
No TSP	No TSP except for custom logic at queue jump intersections.	Not applicable	Not applicable	May 16–19, 2023
Built-in TSP	Controller's built-in TSP logic for Portland and Gresham intersections. No custom logic except at queue jump intersections.	• Aggressive green extension • Early green (up to 30–40 s)	Unconditional	May 22–24, 2023
PBOT TSP	Custom logic (PBOT TSP) at Portland intersections, including all queue-jump intersections. Controller's built-in TSP logic at Gresham intersections.	• Aggressive green extension • Early green (up to 30–40 s) • Early red and other custom TSP strategies	Unconditional	May 25–June 2, 2023

Note: PBOT = Portland Bureau of Transportation.

In advance of the study, bus operators were instructed not to hold at timepoints if early so that running time impacts would not be masked, and the public was warned that there would be temporary signal timing changes that could affect pedestrian phases. Analysis focused on the weekday AM peak (7–9 a.m.) and PM peak (4–6 p.m.) periods.

Data Collected

The data used for evalulation all come from automatically collected big-data sources: the transit agency's AVL system, high-resolution controller data from the traffic signal system, and travel time data from INRIX probe vehicles.

The AVL system provided data on travel time, on-time performance (OTP), and headway regularity. Bus travel time was evaluated not only for the route as a whole, but also, to determine bus delay by signalized intersection approach, for an influence area extending from 400 ft upstream of a stopline to 75 ft downstream. Where the influence area includes a stop, time spent at the stop was omitted using an AVL data attribute that marks when buses are at a stop. (This travel time adjustment method could underestimate travel time, since a portion of the time at stop could be because of signal delay; however, the authors believe that this had little influence on results because the same methodology was used for all treatments, and only about 10% of intersections with TSP had near-side stops.) Figure 4 shows an example of AVL records for a bus traveling eastbound at 162nd Avenue, where there is a near-side stop.

INRIX vehicle probe data provided travel time measures for general traffic. Average travel time by 15 min period was obtained by INRIX XD segment (average segment length = 0.24 mi) all along the study corridor. To analyze delay to cross-street traffic, XD segment data were obtained on cross-street approaches to five intersections.

High-resolution controller data from 16 intersections in the City of Portland were used to determine four standard performance measures using Utah DOT's open-source software for ATSPMs: "frequency of overflow," "mainline arrivals on green," "first pedestrian delay" (time from pedestrian actuation to service), and "first bicycle delay" (time from first bike detection to service). "Overflow" is defined in this paper as when the green phase ends before the queue clears. It is sometimes called "split failure;" however, if TSP includes early green, overflow is not a failure but rather a feature (and it becomes a failure only if its frequency far exceeds the expected number of early green activations, in which case it would indicate that queues formed because of a TSP interruption are not being cleared in subsequent cycles).

The chosen intersections all have TSP and encompass a range of conditions incuding minor intersections (two-phase only intersections) as well as major left turns with leading and lagging phases, intersections with signal-separated pedestrian and bike crossings, and intersections with special bus phases for queue jumps. Custom coding was used to obtain two additional ATSPMs—green ratio by movement and frequency of bus phase activation—at two other intersections with queue jumps and inserted bus phases.

Results and Discussion

Bus Delay

Figures 5 and 6 show reduction in bus delay by intersection for the two treatment cases, combining both directions and both AM and PM peak periods. Intersections are categorized as major if the cross street has a protected

Figure 4. Bus automatic vehicle location (AVL) records in the influence area of an intersection approach with a near-side bus stop.

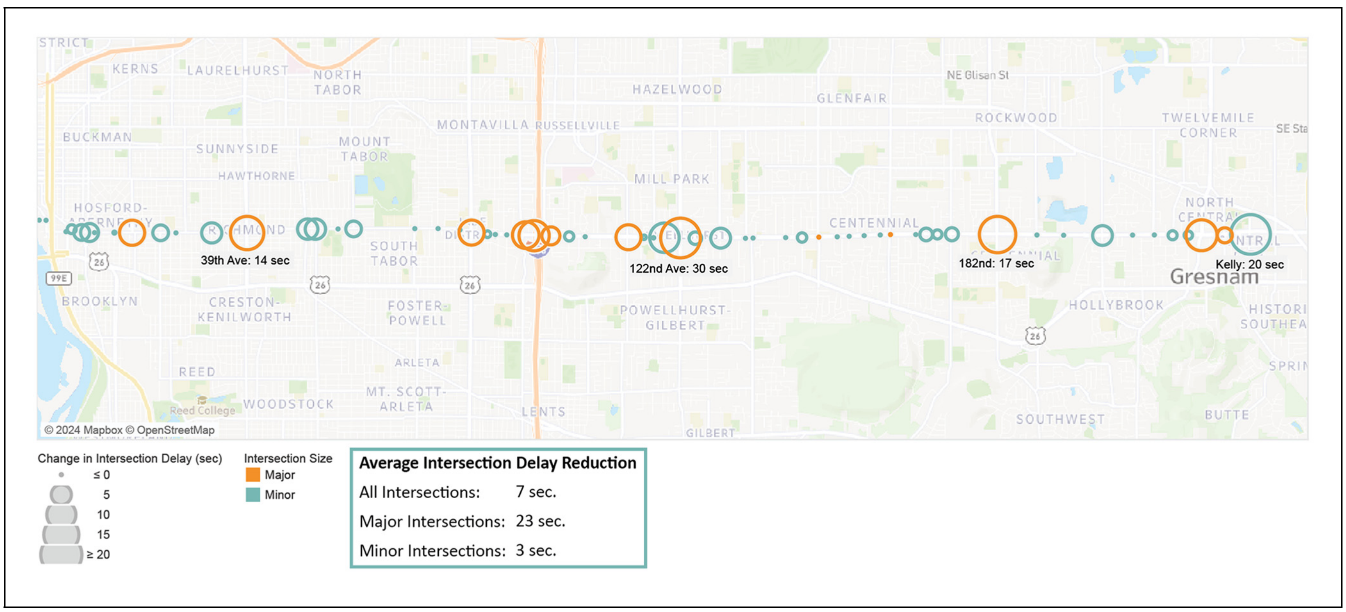

Figure 5. Reduction in bus delay with built-in transit signal priority (TSP).

left turn as well as through phases, and minor otherwise; one can observe that most of the large delay reductions occur at major intersections. (Indeed, 70% of the total intersection delay reduction comes from only 10 intersections.) Figure 7 summarizes results for the two categories of intersection. With PBOT TSP logic, average bus delay fell to 13 s for major intersections and 11 s for minor intersections. For major intersections, that is a reduction of 29 s per intersection—a reduction of 69% of base case delay. For minor intersections, base case delay was low already, and so the reduction was small. Combined, average delay reduction was 9 s per interection or 45% for the PBOT TSP case, and two-thirds as big for the built-in TSP case. Note that average bus delay at the three intersections whose operation was unchanged (and are omitted from the results just presented) differed by less than 1 s between the three treatment cases, which helps rule out background effects as a cause.

While these delay reductions still fall short of the goal of near-zero bus delay, they are much greater than those

Figure 6. Reduction in bus delay with Portland Bureau of Transportation (PBOT) transit signal priority (TSP).

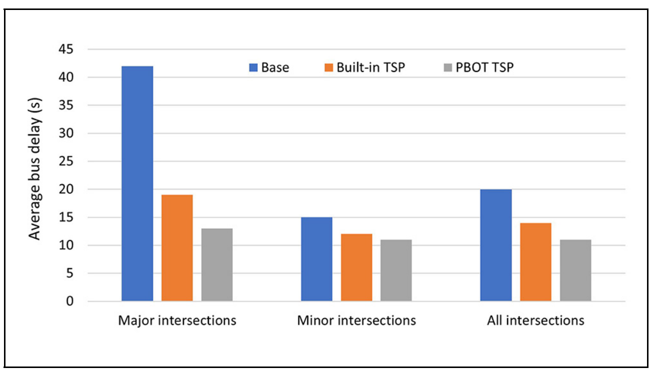

Figure 7. Average bus delay by intersection type (s).
Note: PBOT = Portland Bureau of Transportation; TSP = transit signal priority.

reported in previous studies, showing the value of advanced detection ETA prediction combined with control logic that takes advantage of advanced bus arrival prediction with the flexibility of leaving coordination (*3*). The large delay reductions at major intersections show that, with advanced prediction and flexibility in control, buses can be served with very little delay even while also serving substantial conflicting traffic flows and accommodating long pedestrian crossings.

Results for the Built-in TSP case—particularly the 23 s (55%) bus delay reduction for major intersections—shows that, with advanced detection in the 30–40 s range and aggressive green extension settings, traditional TSP can reduce bus delay far more than is customary in the U.S.

Bus Service Reliability

The first bus service reliability metric analyzed is OTP, shown in Figure 8, in which measurements by timepoint were aggregated by segments. Recall that the Gresham segment does not have PBOT TSP logic, and so a change in performance was not expected in the Gresham segment between the two TSP treatment cases.

Because bus operators were instructed not to hold if early, the relevant finding is the fraction of late departures. Reductions in late departures are dramatic in the PBOT TSP case—they nearly disappear for buses headed toward downtown Portland, and fall from roughly 50% to 21% for the other direction. Reductions for the built-in TSP case are about 75% as large.

The other bus service reliability measure is “good headway adherence,” the fraction of buses on the FX2 line having a headway of 12 ± 3 min. It rose from 53% in the base case to 64% in the built-in TSP case and 67% in the PBOT TSP case. Headway adherence in the two TSP cases may have been better still if operators had not been allowed to depart timepoints early.

Bus Running Time

Reductions in interection delay with PBOT TSP logic aggregate to 8.2 min per round trip on the FX2 line (daily average). Compared with scheduled running time within the study corridor, this is a running time reduction of 11%; compared with scheduled running time for the entire line, a reduction of 7%. If these faster running

Figure 8. On-time performance by segment (AM and PM peak periods combined).
Note: PBOT = Portland Bureau of Transportation; TSP = transit signal priority.

times were carried into the schedule, the number of needed revenue-hours per weekday would fall by 13 on the FX2 line, and by 18 if other routes that operate for short stretches along the corridor are included. Applying TriMet's operating cost per vehicle-hour of $143, that represents annual savings of $650,000 for weekday service (*25*). Reductions in recovery time reflecting the improvements in service reliability could trigger additional operating cost savings.

Traffic Signal Performance Measures

Table 2 shows changes in the ATSPMs averaged over 16 selected Portland intersections. Overflow frequency is a sum over both directions within a 2 h peak. Overflows are rather frequent in the base case; for example, 13.3 mainline left-turn overflows in the 2 h AM peak period, and 16.6 in the PM peak.

With TSP, the increase in overflows observed in the PM peak seems consistent with proper TSP operation. With 20 bus arrivals per hour in each 2 h period and early green triggered when the bus signal is red when ETA reaches the late action threshold of 30–40 s, one would expect 5–10 instances in which the mainline left-turn phase is forced off, resulting in overflow unless demand was low enough to be served during minimum green. The observed increase in overflows in the PM peak—5.6 with built-in TSP and 4.1 with PBOT TSP—seems consistent with expectations. The absence of a large increase in overflows indicating that queues formed because of TSP interruptions did not endure for multiple cycles afterwards.

There was almost no increase in overflows in the AM peak, which raises the question of whether early green is functioning as it should in the AM peak. The difference cannot be explained by lower demand, since both peak periods show large base levels of overflow.

Overall, PBOT TSP logic resulted in fewer overflows than built-in TSP logic. This may reflect the early red function of PBOT logic, in which the mainline phase can be forced off early, resulting in more time for minor phases. Mainline arrivals on green barely changed, indicating that, in spite of the aggressive TSP logic used, arterial progression was essentially unaffected.

In the PM peak, there is a 6.6 s reduction in pedestrian delay with PBOT TSP, but less than 1 s reduction in the AM peak. PBOT logic should lower pedestrian delay during both peak periods, because of both the early red and non-TSP pedestrian priority tactics, and it is not clear why the effect can be observed in the PM but not the AM peak. With built-in TSP, the increase in pedestrian delay was less than 1 s on average. Bike delay fell by 2–4 s with PBOT TSP, and is essentially unchanged with built-in TSP.

Figure 9 displays green ratios for the eight standard vehicular movements at two of the intersections that had queue jumps and inserted bus phases—the 148th Avenue intersection (shown in Figure 2) and a similar intersection at 122nd Avenue. Green ratios are remarkably constant

Table 2. Change in Traffic Signal Performance Metrics for the Peak Periods (2 h period)

Metric	Built-in TSP logic	PBOT TSP logic
AM peak period (7–9 a.m.)		
Overflows, side-street through (base = 13.8 total number of overflows)	−1.3	0.1
Overflows, side-street left (base = 7.9 total number of overflows)	4.1	1.4
Overflows, mainline left (base = 13.3 total number of overflows)	0.4	−1.1
% arrivals on green, mainline average	1.18	0.03
First pedestrian average delay crossing Division Street (s)	0.95	0.07
First bike average delay, mainline (s)	−8.6	−5.9
First bike average delay, side street (s)	1.4	−3.9
PM peak period (4–6 p.m.)		
Overflows, side-street through (base = 19.2 total number of overflows)	6.4	2.9
Overflows, side-street left (base = 10.4 total number of overflow)	2.5	−0.3
Overflows, mainline left (base = 16.7 total number of overflow)	5.6	4.1
% arrivals on green, mainline average	−1.11	−0.05
First pedestrian average delay crossing Division Street (s)	0.55	−6.59
First bike average delay, mainline (s)	−1.4	−2.7
First bike average delay, side street (s)	−0.4	−1.9

Note: PBOT = Portland Bureau of Transportation; TSP = transit signal priority.

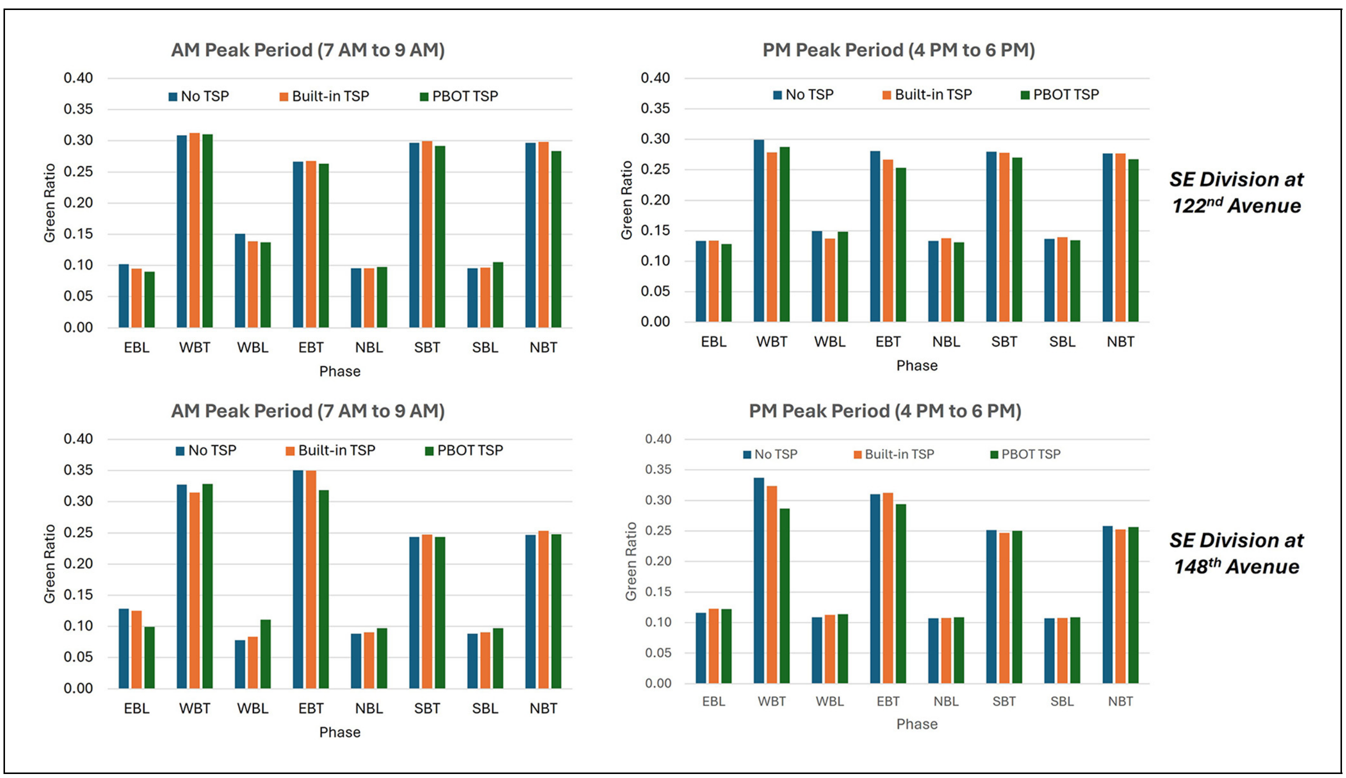

Figure 9. Phase green ratios for vehicle movements at two protected intersections with complex phasing under various transit signal priority (TSP) scenarios. Top left = AM peak period at SE Division and 122nd Avenue intersection; Top right = PM peak period at SE Division and 122nd Avenue intersection; Bottom left = AM peak period at SE Division and 148th Avenue intersection; Bottom right = PM peak period at SE Division and 148th Avenue intersection.
Note: PBOT = Portland Bureau of Transportation.

over the three cases and, where there are small differences, they do not appear to be systematic. This is not surprising because, while the phasing strategy strongly favors bus movements, it should not be harmful to other traffic since bus phases are short and occur when a bus passes through.

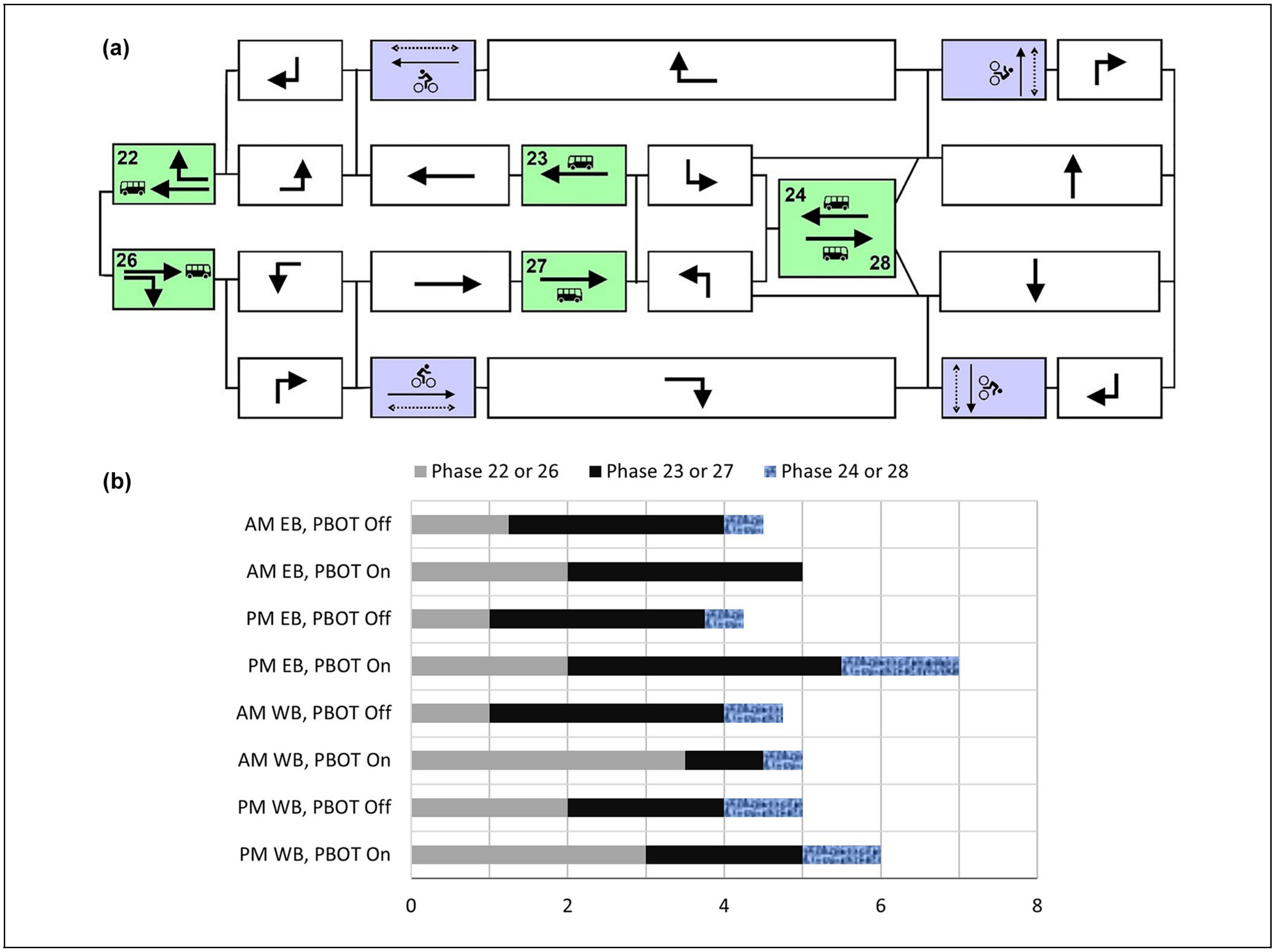

Figure 10. Ring diagram and the number of times per hour inserted bus phases are served (SE division at 148th Street): (*a*) ring diagram with bus phases at the intersection of SE division and 148th Street and (*b*) number of bus phases inserted.
Note: PBOT = Portland Bureau of Transportation.

Figure 10 shows the number of times per hour the various inserted bus phases are served during the AM and PM peak periods for the TSP scenarios at the 148th Street intersection (results are similar at 122nd Avenue). The ring diagram at the 148th Street intersection, along with the bus phases, are also shown. The total number of bus phases observed is between four and six for all except one of the eight direction/period/case combinations examined, consistent with a service frequency of five buses per hour. One can see that all three phases were called, showing the value of inserting multiple bus phases to account for the different times in the cycle a bus might arrive. The third bus phase (24 and 28) is called the least; this is not suprising, since it separated from the second bus phase by only the side-street left-turn phase, which is usually short. The first phase (22 and 26) is called more frequently under PBOT logic versus built-in TSP logic, perhaps because the early red with return to ped tactic favors serving the bus in the first phase following the side-street through.

Travel Time and Delay for General Traffic

Travel time changes for general traffic both along the arterial and across the arterial were found to be negligible. Average travel time over the study corridor, about 32 min in the base case, fell by 1.1% (0.35 min, or 21 s) with PBOT TSP, and by 0.2% (about 5 s) with built-in TSP. There were no significant changes for any period, direction, or segment.

Travel time on cross-street segments also experienced little change. In the AM peak, none of the 10 cross-street segments (obtained from five intersections as noted above) examined saw their average travel time change by

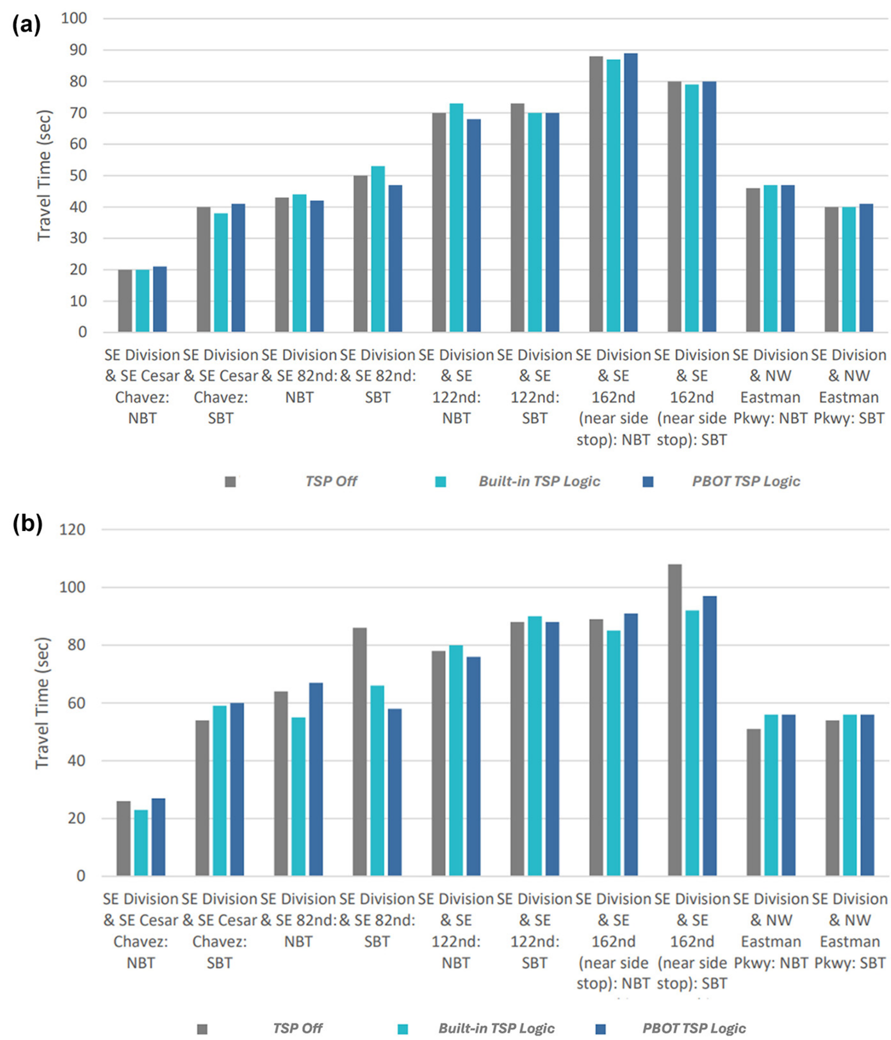

Figure 11. Travel time on cross-street segments during AM and PM peak period: (*a*) AM peak period cross-street travel time and (*b*) PM peak period cross-street travel time.
Note: PBOT = Portland Bureau of Transportation; TSP = transit signal priority; NBT = northbound through; SBT = southbound through.

more than 3 s with either TSP treatments (see Figure 11*a*). Changes were a little larger in the PM peak (as shown in Figure 11*b*), but do not show a systematic increase. The largest increase in average travel time was 6 s, and two segments experienced travel time reductions between 16 and 22 s. Note that the length of the travel time segments for each cross-street approach varied because of the INRIX XD segmentation. Overall, the cross-street segments did not include upstream signalized intersections and the length of segments varied between 1,000 and 3,000 ft with a median length of roughly 1,800 ft.

In summary, no overall adverse impact on either through traffic or cross-street traffic was observed for either TSP treatment.

Conclusions

This research analyzed the effects of a "next-generation" TSP system that uses advanced detection for bus arrivals and custom signal control logic that can take advantage of this advanced detection. Based on a comprehensive analysis of a case study in Portland, Oregon, a multimodal evaluation of a next-generation TSP system was conducted using emerging data sources. The deployed next-generation TSP system uses machine learning and predictive cloud-based capabilities for bus arrival time calculations. The predictions for bus arrival time start up to 2 min in advance of each signalized intersection (and therefore includes dwell times at stops as well as expected delay caused by adjacent signals) and are continuously updated (every second) based on historical and current traffic and transit data. To leverage the advanced prediction and achieve the high-level performance desired for transit, custom signal controller programming logic was also developed. To better isolate the effect of the TSP, the study team designed a field experiment in which the TSP was "turned off" and then "turned on" over the span of 2 weeks.

Analysis results show that the deployed next-generation TSP system holds promise in significantly improving transit service with relatively little capital investment or impact on other modes. Results obtained from the high-resolution bus AVL data found that, with the custom signal control logic developed (i.e., PBOT TSP) along with advanced prediction, bus delay was reduced by 29 s per intersection at major intersections, corresponding to a 69% reduction of base case delay. Results for the built-in TSP scenario (i.e., controllers' built-in TSP logic) also resulted in substantial improvements; 23 s bus delay reduction (corresponding to a 55% decrease) at major intersections. This result shows that, with advanced detection in the 30–40 s range and aggressive green extension settings, traditional TSP can reduce bus delay far more than is typical in the U.S. When all intersections were considered (i.e., both major and minor), the average intersection bus delay reduction was 7 s with the built-in TSP scenario and 9 s with the PBOT TSP. These results suggest that focusing on major intersections and fine tuning the controller logic to work well at those individual locations should increase the benefit/cost of next-generation TSP even further.

When intersection delay improvements are aggregated, the PBOT TSP logic was able to reduce bus running times by 8.2 min per round trip on the FX2 line (daily average). Compared with the scheduled running time within the study corridor, this corresponds to a run time reduction of 11%.

Analysis using the ATSPMs (i.e., high-resolution signal controller data) and vehicle probe data using INRIX XD data showed that the deployed TSP system overall has marginal impacts on motorists and no impacts for pedestrians and bicyclists.

This case study also demonstrates that care should be taken to avoid poor OTP (especially early departures) toward the end of the route, especially for unconditional TSP systems. To counter this, agencies might adjust schedules to account for TSP travel time savings. Alternatively, agencies might consider implementing conditional priority based on lateness, which requires carefully designed schedules to take advantage of conditional priority or reserve this strategy for high-frequency routes that aim for headway adherence rather than meeting schedules at pre-defined timepoints (*26*).

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: B. Cesme., J. Barrios, P. Koonce, M. Haines; data collection: B. Cesme, J. Barrios, P. Koonce, M. Haines, C. Bame, N. Dobrota; analysis and interpretation of results: B. Cesme, J. Barrios, C. Bame, N. Dobrota, P. Furth; draft manuscript preparation: B. Cesme, J. Barrios, P. Koonce, M. Haines, P.Furth, C. Bame, N. Dobrota. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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