Effect of Transit Preferential Treatments on Vehicle Travel Time

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ABSTRACT

Many agencies around the U.S. are implementing transit preferential treatments, including transit signal priority (TSP), queue jumps, and queue bypass lanes, for transit vehicles operating in mixed traffic on arterials (e.g., bus or streetcar). However, the benefits and disadvantages of these treatments have not yet been quantified using a comprehensive corridor travel time analysis. This paper focuses on a VISSIM study of an existing transit corridor in Fort Lauderdale, Florida and generalizes the results for application to other sites. The assumptions of the study included average transit headways of five minutes, a 100-second signal cycle length, and that transit vehicles would always call for priority (either red truncation or green extension) at intersections with TSP. Each treatment was tested using volume-to-capacity ratios of 0.5, 0.8, and 1.0, and the performance measures included transit vehicle travel time, travel time for all approaching vehicles, and total intersection delay for all vehicles.

The results indicate that transit stop location, volume-to-capacity ratio, and type of treatment each have a significant effect on all three performance measures tested. Some of the principal findings are: a far-side transit stop can reduce transit vehicle travel time by up to five percent over a near-side stop, providing TSP in one direction tends to provide less negative effects to side-street traffic than if TSP is provided in both directions, and queue jumps and queue bypass lanes provide negligible benefits if the volume-to-capacity ratio of an approach is 0.8 or less.

INTRODUCTION

With transportation demand outpacing capacity expansion in many regions, transportation networks and roadways are facing increasing congestion. The provision of transit-supportive strategies to reduce travel time, improve reliability, and provide operational cost savings is becoming increasingly important. Transportation management measures that obtain more capacity out of existing resources must be explored in order to provide financially viable transportation solutions.

Most transit and highway/traffic agencies still have neither formal transit preferential treatment programs nor formal intergovernmental agreements with respect to planning, design, construction, operations/maintenance, and performance monitoring of treatments. Research is needed to determine the benefits of a particular transit preferential treatment strategy so that these agencies can make decisions about implementation.

Detailed Description of Transit Preferential Treatments

Transit preferential treatments include: (1) intersection treatments such as transit signal priority, special signal phasing, queue jump lanes and signals, and queue bypass lanes; and (2) roadway segment treatments such as exclusive or shared transit lanes within the travelled way, exclusive transitways (typically in the median), and corridor signal progression favoring transit operations. This paper focuses on three major intersection treatments and how these can be applied along a transit corridor.

Queue Jump

A queue jump is a phase insertion treatment intended to exclusively serve transit vehicles stopped at a red signal and positioned at a near-side stop in a right-turn lane. During the red phase, passengers may board and alight the transit vehicle. The vehicle is then given a green signal in advance of the adjacent lanes, allowing the vehicle to merge back into a through travel lane ahead of the queued traffic in the adjacent lanes. Typically, the time for this phase is allocated from the parallel general traffic movement and lasts three to four seconds. The treatment is also possible at far-side stop locations, where it would be located in the curb-side through-movement lane. The left-hand images in Figure 1 provide a diagram of the queue jump with a near-side bus stop (*1*).

Queue Bypass Lane

A queue bypass lane is a geometric design treatment in conjunction with a far-side stop. Similar to the queue jump, the transit vehicle approaches the intersection in the curb-side right-turn lane. The bypass lane is aligned directly opposite the right-turn lane, which allows transit vehicles to move into the lane and have passengers board and alight without hindering other mainline through-movement traffic. Unlike the queue jump, the queue bypass lane does not use an exclusive transit signal phase. The right-hand images in Figure 1 display a diagram of a queue bypass lane with a far-side bus stop (*1*).

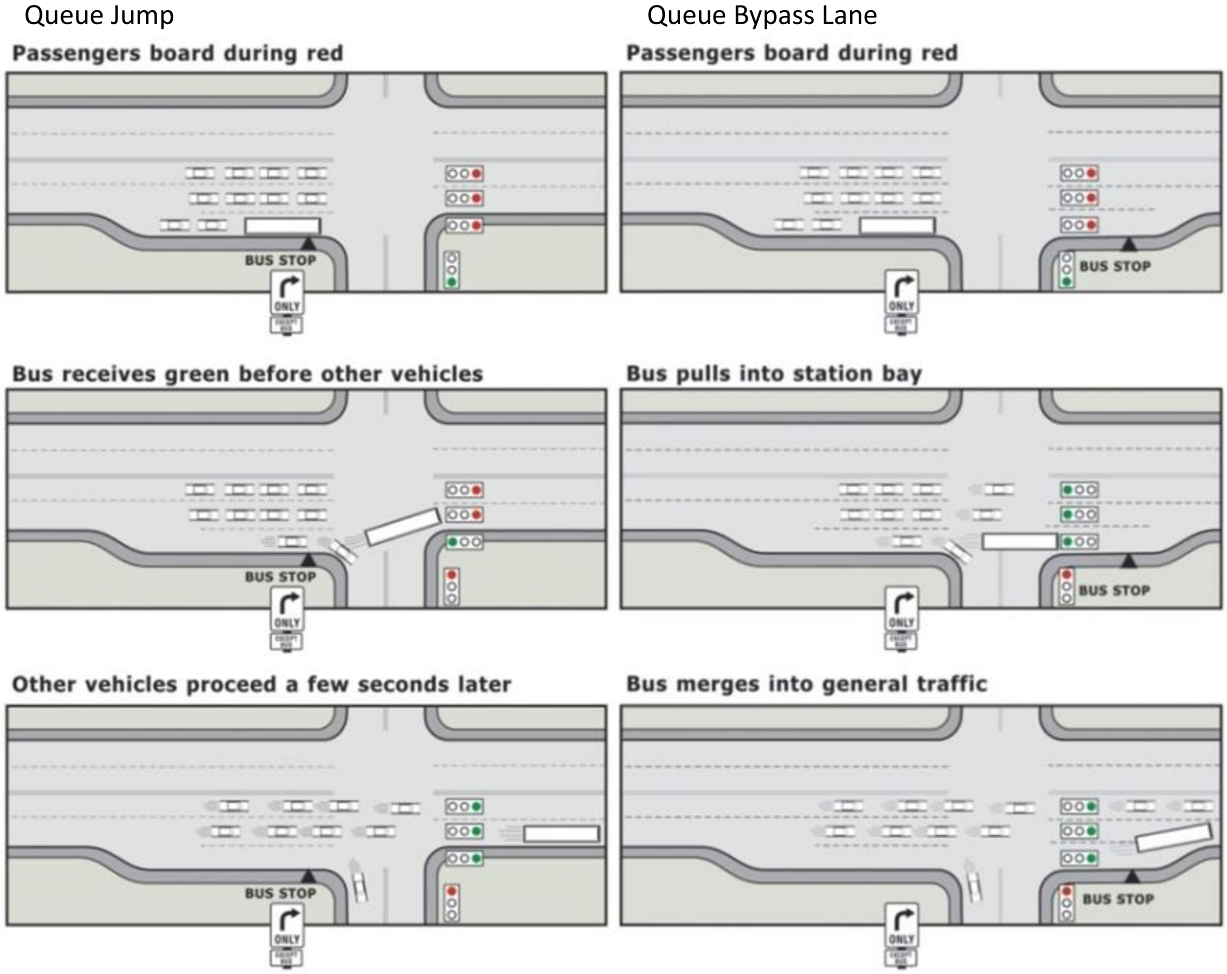

FIGURE 1 Queue Jump and Bypass Lane Illustration. (*1*)

Transit Signal Priority

Transit signal priority (TSP) is a signal timing treatment which prioritizes transit vehicle movement at signalized intersections through two primary functions:

- Green extension, which allows a transit vehicle that is approaching an intersection toward the end of the green phase to extend the green by enough time to pass through the intersection; and
- Early green (also called red truncation), which begins the green phase earlier when a transit vehicle is waiting at a red signal.

Theoretically, TSP can be implemented at any or all legs of a signalized intersection. For purposes of this research, transit signal priority was considered in one or both directions of the mainline street. In practice, TSP may not be used for every transit vehicle—for example, it may only be called when an approaching transit vehicle is running behind schedule—this is known as *conditional* TSP. For purposes of this research, TSP was assumed to be unconditional, i.e., it is called for every transit vehicle.

Research Objective

The following are the objectives of this research:

1. To understand the effect of selected transit preferential treatments on transit and non-transit vehicle travel time, and
2. To develop decision-making guidance for operational planning and functional design of transit preferential treatments on arterials.

Much of the research presented here is called for in comprehensive overviews of transit-supportive roadway strategies such as *TCRP Report 165*, *TCRP Synthesis 83*, and *NCHRP Report 155* (*1, 2, 3*). The reader will be referred to these documents to achieve a more detailed description of the function and design of the transit preferential treatments presented in this paper.

This paper is organized as follows: literature review, methodology, results, conclusion, and references.

Literature Review

To date, no corridor-focused microsimulation studies of transit preferential treatments have been documented. However, a 2014 microsimulation study by Cesme et al. of several transit preferential treatments at an isolated intersection found that far-side stops can reduce transit vehicle delay by 30 seconds compared to near-side stops. The study also found that TSP can substantially reduce transit vehicle delay when the v/c ratio is high, but benefits are minimal when the v/c ratio is low (*4*).

There is much literature on best practices to design and operate transit preferential treatments at intersections and along corridors, and many of these studies have generated a range of travel time savings for transit and non-transit vehicles under a variety of scenarios. *TCRP Synthesis 83: Bus and Rail Preferential Treatments in Mixed Traffic* began the process of obtaining information on the type and extent of recent urban street transit preferential treatment implementation in North America and identified key areas for future research (*2*). It provided a partial update of *NCHRP Report 155: Bus Use of Highways: Planning and Design Guidelines* (*3*).

The Transit Capacity and Quality of Service Manual (TCQSM) provides sections on bus preferential strategies, bus operational strategies (e.g., stop consolidation, turn restrictions), and rail strategies (*1*). Building on *TCRP Synthesis 83*'s discussion of infrastructure strategies, the TCQSM presents warrants and conditions for applying these strategies based on previous studies in the literature, particularly *NCHRP Report 155* (*3*). *TCRP Report 26* and *TCRP Research Results Digest 38* developed analytical tools for evaluating the impact of several different bus lane types (including mixed traffic operations), passive signal priority, and bus stop spacing on bus speeds (*5, 6*). These reports utilized the performance measure *travel time rate* (e.g., minutes per mile) to evaluate the impact of strategies. The U.S. Department of Transportation produced *Transit Signal Priority: A Planning and Implementation Handbook* to provide technical guidance on implementing a successful TSP project (*7*). It reports corridor travel time savings that have been achieved due to TSP (ranging from 9 to 16% in the studied cities), as well as reductions in travel time variability.

Many studies of the quantitative benefits of transit preferential treatments have concerned implementation in specific cities. TriMet and the City of Portland, Oregon implemented a package of transit preferential strategies—TSP, stop consolidation, and bus pullout removal—to

12 “streamlined” bus routes. Comparing route performance in 2005 to 2000 (*8*), the streamlined routes were 0.8 minute faster, while nine similar non-streamlined routes were 1.3 minutes slower. Albright and Figiliozzi studied the effect of TSP performance on a congested arterial corridor in Portland, Oregon, focusing on conditional TSP (*9*). The paper concluded that TSP seems to be more effective in bus routes with severe lateness and at intersections with lower volumes and without significant queuing. Additionally, the research showed that TSP effectiveness (evident at the stop and intersection level) can be “hidden or evened out when analyzing effectiveness at a route level.” It is therefore important to evaluate TSP on both a corridor level and intersection level. Rephlo and Haas describe TSP implementation along a 9.8-mile segment of an arterial in Sacramento, California that experiences traffic volumes exceeding 100,000 vehicles per day in some sections (*10*). Bus travel time decreased by 4% along the corridor and bus reliability improved during one-third of the time periods studied. Mobility increased along the corridor but decreased for cross-street movements, although the authors advise interpreting those results with caution due to data collection issues. Narrigan et al. studied a series of improvements, including TSP implementation and rerouting, on one of the busiest bus routes in Springfield, Massachusetts (*11*). The combination of improvements reduced travel times from 45 minutes to 30 minutes, but the paper did not isolate the proportion of the time savings attributable to TSP.

An International Association of Public Transport (UITP) working group reviewed TSP in 29 cities around the world (*12*). Each of the cities surveyed gave a positive review of their system, and a wide range of benefits were reported; for example, travel time savings of between 2 and 24% were reported. A Federal Transit Administration (FTA) report on implementing TSP includes two case study corridors in the San Francisco Bay Area (*13*). The study showed the benefit of TSP was highest at intersections where buses were stopped for 30% of more of the traffic signal cycle length and decreased as the percentage of stopped time decreased. On-time performance improved by four to six percentage points, and average schedule deviation at the route end decreased by one to two minutes. Impacts to major and minor street delay were statistically or practically insignificant when the volume-to-saturation (v/s) ratio (the proportion of green time required to serve vehicular demand) was 0.7 or less. At higher v/s ratios, major street delay was reduced 9–27%, while minor street delay increased an average of 8%.

METHODOLOGY

The following sections describe the methodology used to develop the travel time models, including data collection, model development, and scenario development.

Data Collection and Extraction

At least two methods were available to develop a model framework for travel time through various transit preferential treatments:

- Empirically, through the use of field data from transit vehicles. This would rely on collecting travel time information from transit vehicles at various intersections with a range of preferential treatments (or none at all) in order to test all random variables. However, the number of intersections with some transit preferential treatments, especially transit signal priority, is limited, and conducting a fully controlled experiment with field data would likely be time-consuming and expensive.

- Using data from microsimulation, through the use of a microsimulation model. The research team chose this method because it allows for all variables to be tested without requiring a large amount of field data for calibration.

Site Selection

A 1.3-mile segment of Broward Boulevard in Fort Lauderdale, Florida was chosen as a testing ground for model scenario development (Figure 2). This site was chosen for its arterial nature and because it includes both congested and uncongested signalized intersections. While this corridor was selected as a testbed, the fully-developed model was not intended to simulate the existing or potential operations of Broward Boulevard—adjustments to volumes, driveways, and lane configurations were made in order to create the necessary environment for the experiment. All transit vehicles were modeled as buses and will be referred to as such for the remainder of this paper.

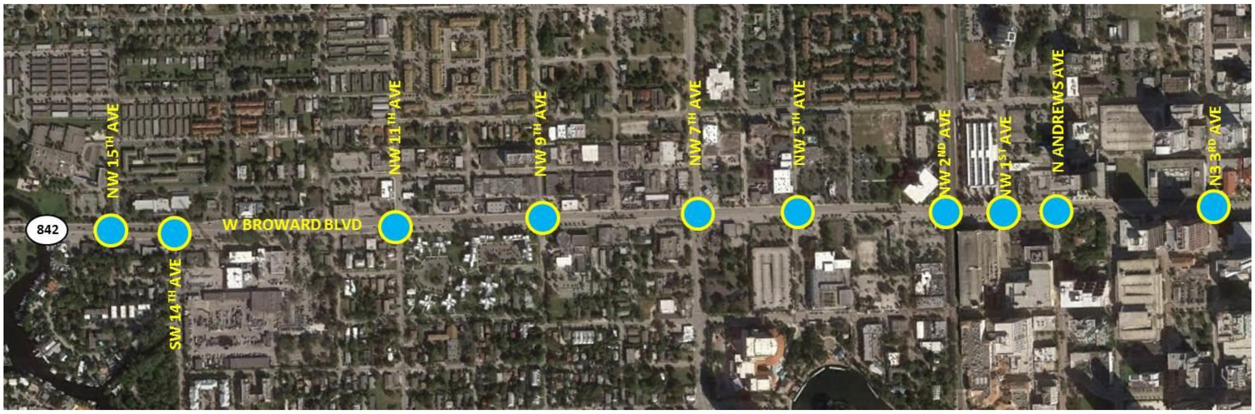

FIGURE 2 Model Corridor on Broward Boulevard. (*14*)

Scenario Development

This section describes the development of various scenarios to be tested in VISSIM, including the transit preferential treatments, traffic volume levels, transit headways, and performance measures.

Treatments

The following scenarios were developed in the VISSIM model to maximize the applicability of the results:

- Near-side versus far-side stop locations: to compare the effect of stop location (either near-side or far-side) at the subject intersection.
- Queue jump: to compare the effect of adding a queue jump and the accompanying transit signal phase at the subject intersection. The queue jump can be implemented at a location with either a near-side or far-side stop, so both of these scenarios were developed.
- Queue bypass lane: to compare the effect of adding a queue bypass lane at the subject intersection. A queue bypass lane can only be implemented at a location with a far-side stop.
- Transit signal priority: to compare the effect of adding TSP to the major street through-movements at the subject intersection. Scenarios with either one-way or two-way TSP were developed.

Queue jumps and bypass lanes were only tested for the intersection-level analysis because they tend to be less-frequently implemented on a corridor-level basis due to geometric constraints and isolated benefits. Alternatively, the main focus of the corridor-level analysis was to test different forms of TSP implementation, including direction, number of intersections, and general level of congestion at the intersections where it is implemented.

Volumes

It is useful to understand the effect of various treatments at varying levels of congestion, as certain benefits could be lost or gained during peak or off-peak travel periods. To model different levels of congestion, turning movement volumes were scaled proportionally to achieve the following volume-to-capacity (v/c) ratios at different intersections along the corridor:

- v/c = 0.50
- v/c = 0.80
- v/c = 1.00

In each case, the v/c ratio shown is the weighted average of all intersection approaches. Testing the scenarios at this range of v/c ratios is intended to simulate a range of intersections or travel periods, e.g. the v/c = 0.50 case is intended to represent a minor intersection or off-peak period, while the v/c = 1.00 case is intended to represent a major intersection during peak travel times.

Transit Headways

Some of the treatments tested affect the signal timing and phasing of the intersection. Therefore, the frequency at which those treatments are activated becomes a contributing factor to operational performance. When the authors originally experimented with the VISSIM model, bus headways of 5, 10, and 15 minutes were used. However, headways larger than 5 minutes tend to take a very long simulation period to achieve an acceptable sample size. Therefore, only the results for 5-minute headways (i.e., 12 buses per direction per hour) are reported in this paper.

Intersection-level Method

At the intersection level, transit preferential treatments are only applied to a single intersection to identify effects at a point location. To simulate the effect of upstream and downstream signals within a corridor, three intersections were simulated:

- W Broward Boulevard / 9th Avenue
- W Broward Boulevard / 7th Avenue
- W Broward Boulevard / 5th Avenue

For all intersection-level scenarios, the central intersection (W Broward Boulevard / 7th Avenue) served as the subject intersection where all transit preferential treatments were tested, while the two adjacent intersections served to help meter traffic volume so that operations could be realistically modeled at the central intersection.

Corridor-level Method

Unlike the intersection-level analysis, the overall corridor was not modeled at various levels of v/c ratio. Instead, the various intersections and their respective v/c ratios were used to provide the cross-section of effects that congestion plays with respect to intersection performance under TSP implementation. The following scenarios were developed for the corridor-level analysis:

- *Existing* –no TSP implementation.

- *Major Ints* –TSP implemented at two major intersections (both with $v/c \geq 0.9$);
- *Mod Ints* –TSP implemented at three moderately-congested intersections (with v/c between 0.6 and 0.9);
- *Minor Ints* –TSP implemented at two minor intersections (both with $v/c \leq 0.6$);
- *ALL* –TSP implemented at all seven signalized intersections; and
- *2-min HW* – same simulation as *ALL* but bus headways are reduced to 2 minutes in order to represent an "overload" condition where there is a perpetual signal demand to provide bus priority.

Table 1 shows the intersections where TSP was implemented by scenario. It also indicates whether each intersection contains an upstream or downstream stop in either direction.

TABLE 1 TSP Intersection Implementation by Scenario and Stop Location

Signalized Intersection	Corridor Scenario						EB Stop Location		WB Stop Location	
	Existing	Major Ints	Mod Ints	Minor Ints	ALL	2-min HW	Near-side	Far-Side	Near-side	Far-side
15th Ave								X[1,2]		X
14th Ave		X			X	X			X[1]	
11th Ave			X		X	X		X		X[1]
9th Ave			X		X	X	X		X	
7th Ave		X			X	X	X		X	
5th Ave				X	X	X	X		X	
1st Ave				X	X	X				
Andrews Ave			X		X	X		X		
3rd Ave							X			X[2]

[1] Stop has a bus pull-out bay.

[2] Stop is modeled with a large mean dwell time and standard deviation to provide variability of bus arrival during the cycle downstream.

Model Development

Some of the treatments tested required unique calibration of the VISSIM ring barrier controller (RBC). This section describes the methods used to develop the microsimulation model.

Queue Jump

Programming a queue jump in the RBC controller requires adjusting the ring-barrier diagram to include the "bus phase." Figure 3 below shows the ring-barrier diagrams for an intersection with and without the queue jump.

FIGURE 3 Ring-barrier diagram showing typical cycle (top) and queue jump programmed cycle (bottom).

These bus phases (Φ9 and Φ10) are placed before their parallel green movements and are only activated if a bus is stopped at the intersection in the right-turn lane. The bus phases do not activate concurrently but rather serve a first-in/first out programming. Thus, when these phases are served, all other phases are red, and only buses (i.e. no right-turning cars) are permitted. Considering the purpose of the bus phase is intended to allow the bus to pull ahead of the traffic platoon, the duration of the phase can be minimal. For the purposes of this effort, a four-second phase of green time followed by three-second yellow clearance was used for Φ9 and Φ10.

Transit Signal Priority

TSP adjusts the length of green times within the cycle to provide benefit to transit. This is done to simulate the two mechanisms of TSP (green extension and early green). The authors implemented a check-in/check-out detection method in VISSIM, described as follows:

- Green Extension: Green extension is a function developed for buses arriving at the signal towards the end of the green time. The extension provides the extra time needed to help the bus clear the intersection. The RBC controller codes for green extension by establishing an “Extend Limit,” which is the maximum number of seconds the green time will extend beyond the yield point before terminating the phase, given a bus checks in a TSP call. All scenarios were coded for a maximum of 10-second extensions.
- Early Green: Early green is a function developed for buses arriving at the signal on red. The TSP request is intended to shorten phases as needed and, if possible, give an early green phase to the bus. The RBC controller will produce an early green by truncating (no phases are omitted) to the extent needed without violating minimum phase time (both vehicle and pedestrian). The “Priority Min Green” table can set additional minimum phase times that exceed the global and plan minimums; this table is useful for certain phases that may require more green time than the minimum timing would permit (e.g., a heavy protected left turn movement). Without establishing priority min green times, side street operations can become substantially degraded.
- Detector Plan: Setting up the detector plan for the check-in/check-out configuration is dependent upon whether stops are located near-side or far-side. The basic premise for this configuration is as follows:

1. The bus triggers a TSP call by traveling over the “check-in” detectors upstream of the intersection, which requests TSP service on a particular approach.
2. The signal controller works to service the TSP call until the bus reaches the “check-out” detectors located past the stop bars of the approach.
3. Once a bus passes the “check out” detectors, the TSP call is dropped, and the signal recovers back into coordination.

For near-side stops, the detector plan is shown in the VISSIM screenshot on the top of Figure 4. The “check-in” detectors are located at the end of the bus stop and are only activated when the bus is departing the stop (i.e., the detector is not triggered during boarding/alighting).

For far-side stops, the detector plan is shown in the VISSIM screenshot on the bottom of Figure 4. The “check-in” detectors are located upstream of the intersection, since the bus will not stop for boarding/alighting near-side. The distance upstream is determined by approximating the distance the average bus will travel during the “Extend Limit” programmed. This distance was estimated from the average travel speed of buses and the ten-second extend limit. The results would be the same if a presence (continuous call) detection technology was used.

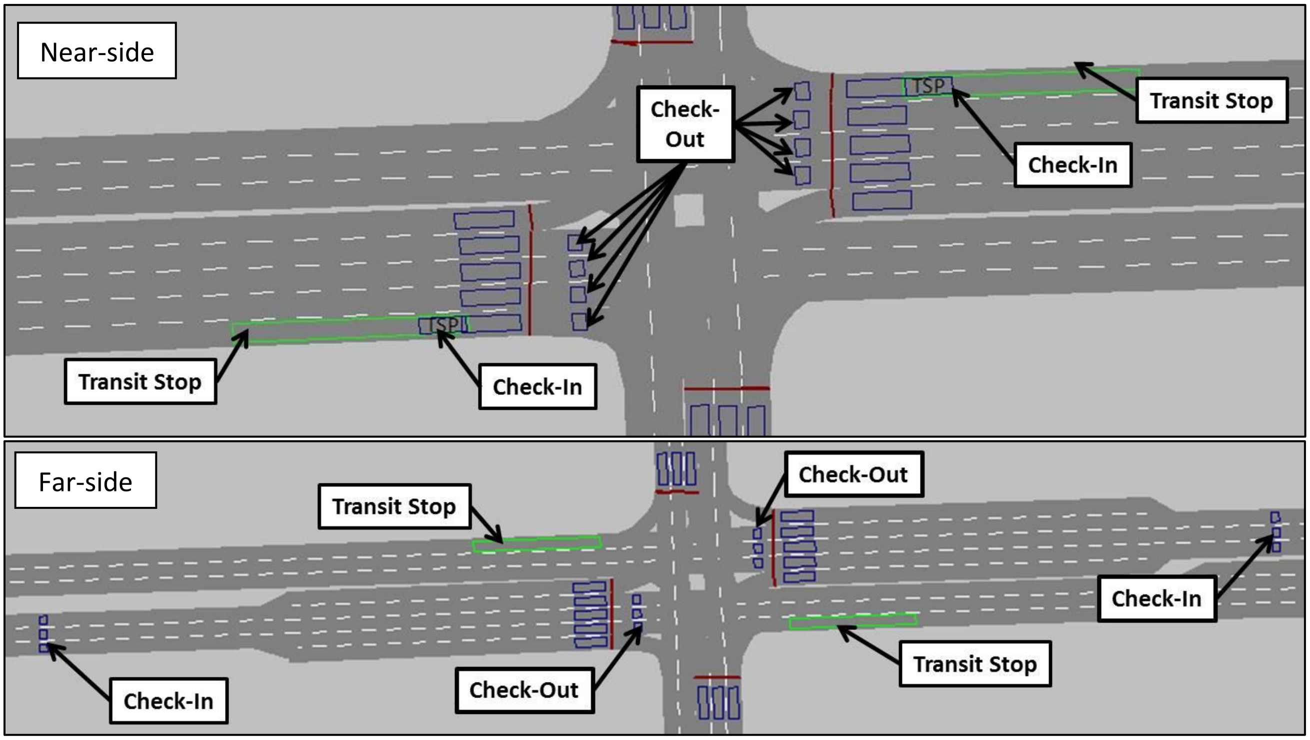

FIGURE 4 Far-side bus stop TSP detector layout.

Simulation Process

Each scenario was simulated in VISSIM for 30 runs using unique traffic seeding to produce a statistical distribution of results. An individual scenario “run” is a total of 90 simulated minutes, which is broken into the following periods:

1. 15-minute “warm-up” period – this allows the model to be fully populated with traffic and for traffic signals to start up and run the expected timings.

2. 60-minute data collection period – this is the time period where all performance measures are captured.
3. 15-minute stabilization period – this time ensures that traffic is present continuously until the end of the data collection period.

After runs were completed, performance metrics were analyzed for traffic during the 60-minute data collection period for all traffic, non-bus traffic, and buses individually. The chief performance metrics extracted from the simulation were control delay, broken down by approach, vehicle class (i.e. bus or non-bus), and total intersection delay.

Statistical Analysis

A t-test for independent means was used to compare the mean travel times or intersection delays over the 30 runs for each treatment with the base scenario (no treatment). A significance level of $\alpha=0.05$ was used to test the null hypothesis that the mean travel time (or intersection delay) was unchanged after the addition of each treatment.

RESULTS

This section explains the results of the model development, including the intersection- and corridor-level results.

Intersection-level

For the intersection-level analysis, Table 2 shows the percent change in travel time, for all arterial vehicles and for buses only, after each treatment is added in isolation, as well as the percent change in intersection delay for all vehicles. While the effect of these treatments on bus and non-bus travel time is the main focus of this paper, the intersection delay metric provides a picture of how each treatment may affect side-street vehicles. The following treatments were tested on an individual intersection level:

- Moving the stop to the far side
- Adding TSP in both directions
- Adding TSP in one direction
- Adding a queue jump
- Moving the stop to the far side and adding a queue bypass
- Moving the stop to the far side and adding TSP in both directions
- Moving the stop to the far side and adding TSP in one direction

Each scenario was tested at three levels of v/c ratio (0.5, 0.8, and 1.0).

TABLE 2 Results (Base Case is Near-side Stop with No Treatment)

Treatment (V/C = 0.5)	%Change in Travel Time		%Change in Intersection Delay
	All Arterial Vehicles	Buses	
Move stop to far-side	-1.5	-1.3	-2.4
Add TSP (both directions)	-1.4	-1.5	+1.6
Add TSP (one direction)	-1.1	-1.5	+1.2
Add queue jump	+2.8	NS*	+2.0
Move stop to far-side and add queue bypass	-1.8	-1.4	-2.9
Move stop to far-side and add TSP (both directions)	-2.3	-3.1	-0.8
Move stop to far-side and add TSP (one direction)	-3.3	-3.3	-1.6

Treatment (V/C = 0.8)	%Change in Travel Time		%Change in Intersection Delay
	All Arterial Vehicles	Buses	
Move stop to far-side	-1.3	-1.8	-3.8
Add TSP (both directions)	-1.4	-1.5	+3.8
Add TSP (one direction)	-2.7	-1.7	-1.9
Add queue jump	+4.9	-0.8	NS
Move stop to far-side and add queue bypass	-2.2	-2.5	-4.4
Move stop to far-side and add TSP (both directions)	-2.3	-4.1	-0.6
Move stop to far-side and add TSP (one direction)	-3.9	-4.2	-5.0

Treatment (V/C = 1.0)	%Change in Travel Time		%Change in Intersection Delay
	All Arterial Vehicles	Buses	
Move stop to far-side	NS	-4.6	-6.6
Add TSP (both directions)	-2.6	-4.0	NS
Add TSP (one direction)	-4.3	-5.2	NS
Add queue jump	+5.5	-3.4	+2.6
Move stop to far-side and add queue bypass	-2.2	-5.3	-8.0
Move stop to far-side and add TSP (both directions)	-2.6	-7.4	-5.8
Move stop to far-side and add TSP (one direction)	-5.5	-7.4	-5.3

*NS = not a statistically significant effect (alpha=0.05)

The table indicates that the greatest benefit to the travel time of all arterial vehicles was to move the stop to the far-side and add TSP in one direction; the same holds if only buses are considered. Adding a queue jump tended to result in a slight increase in travel time when all vehicles were averaged, and it did not have a significant effect on travel time or intersection delay unless the v/c ratio was equal to 1.0. When total intersection delay (including side-street delay) was considered, the greatest benefit (regardless of v/c ratio) occurred when the near-side stop was moved to the far-side and TSP was added in one direction.

Moving the stop to the far-side resulted in a significant decrease in travel time for buses and non-buses for all levels of v/c ratio; the travel time decrease was compounded when a treatment such as queue bypass or TSP was added. Adding TSP to a near-side stop resulted in an increase in overall intersection delay, but the increase was less significant as v/c ratio increased. When the v/c ratio was equal to 1.0, all treatments resulted in a statistically significant decrease in bus travel time (ranging from 3.4 to 7.4 percent), but only one treatment (adding a queue jump) resulted in an increase in intersection delay. This is consistent with some results presented in Cesme et al. (*4*), but the results are not as dependent upon v/c ratio as those presented in Cesme et al.

Compared with TSP in both directions, adding TSP in one direction resulted in more pronounced travel time benefits and had a greater effect on non-bus travel time than bus travel time. Additionally, when the stop was moved to the far-side and TSP was added, adding TSP in one direction tended to equalize the travel time benefit to buses and non-buses.

When the stop was moved to the far-side, adding TSP tended to result in a decrease in overall intersection delay, and adding a queue bypass also tended to decrease overall intersection delay. When westbound TSP was eliminated, the travel time benefit of TSP became more pronounced—this is similar to the results presented by Cesme et al. (*4*). Removing the westbound TSP had a greater effect on non-bus travel time than bus travel time. For the treatment of moving the stop to the far-side and adding TSP, eliminating westbound TSP tended to equalize the travel time benefit to buses and non-buses.

Corridor-level

This section describes the results of the corridor-level analysis, including the effect of each corridor treatment on average intersection delay, side-street delay, and travel time for both buses and non-buses.

Average Intersection Delay

Figure 5 displays the results of the corridor-level analysis in terms of average intersection delay (including side-street delay). In terms of all traffic, the only scenario that resulted in a decrease in average intersection delay relative to *Existing* was *Mod Ints*, indicating that TSP is most effective when implemented at moderately congested intersections along a corridor. It is further noted that treating just the *Mod Ints* intersections with TSP resulted in slightly lower bus delay as the scenario with all intersections being treated with TSP. Additionally, the average intersection delay for *2-min HW* was 11% greater than that of the *Existing* scenario, indicating that frequent calls for TSP (nearly every cycle) may disrupt traffic operations and not provide any benefit for buses.

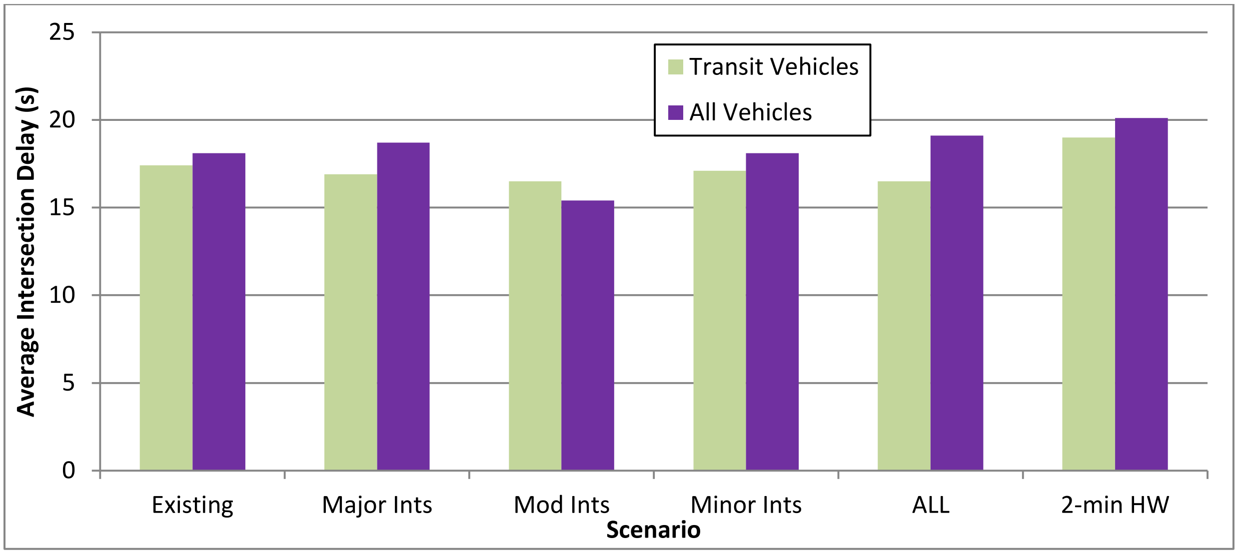

FIGURE 5 Average Intersection Delay for Corridor Results.

Intersection delay only slightly fluctuated between scenarios when all traffic was considered, except at 7th Avenue. This is likely because 7th Avenue has the heaviest cross-street volumes of the treated intersections, and that intersection tended to drive the overall results.

Travel Time

Figure 6 displays the change in arterial travel time (compared to the *Existing* scenario) associated with each treatment.

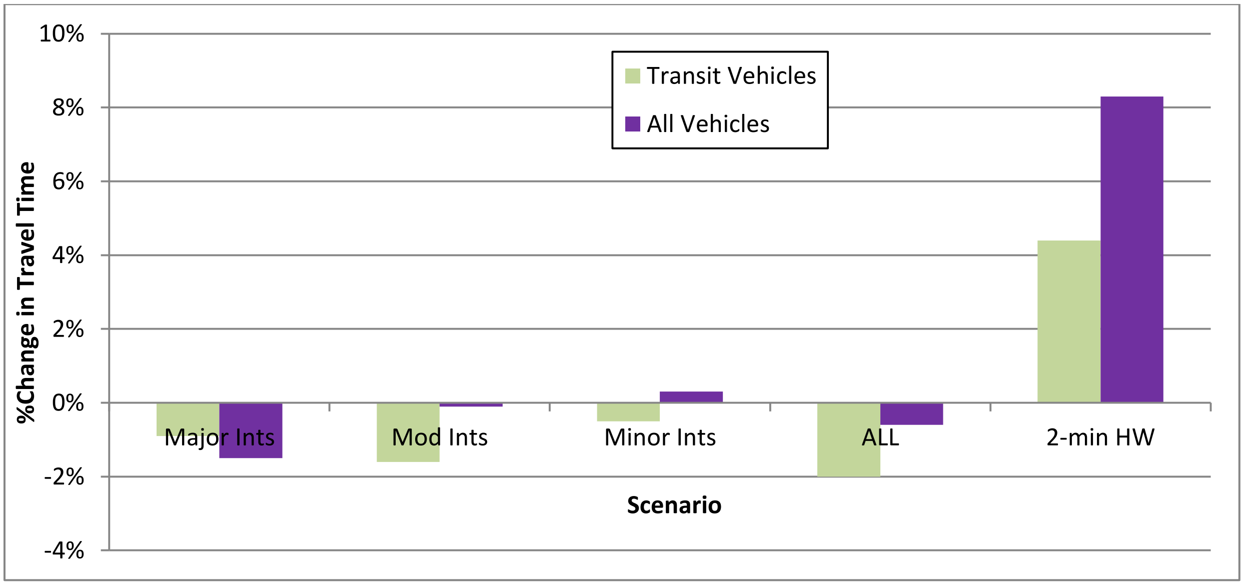

FIGURE 6 Change in Average Corridor Travel Time (Both Directions).

As shown, when TSP is implemented at major and moderate intersections, travel time improves for all traffic. The *2-min HW* scenario shows an 8.3% increase in average bi-directional travel time, likely due to high bus volume increasing the blockage of curb-side lanes and relatively slower speeds compared to the rest of the traffic stream.

For buses, travel time (average of both directions) was lowest for the *ALL* scenario and highest for the *2-min HW* scenario. As expected, implementing TSP at all intersections resulted in the lowest bus travel time, but implementing TSP only at the moderate intersections resulted in nearly the same reduction in bus travel time, suggesting a more cost-effective strategy.

CONCLUSIONS

The modeling efforts described in this paper indicate that a system of transit preferential treatments can be successfully modeled within the VISSIM microsimulation program and produce statistically significant results.

The intersection-level modeling efforts support the conclusion that in terms of decreasing travel time for buses, using a far-side stop with TSP in one direction was the most effective transit preferential treatment. This treatment reduced bus travel time by 3 to 7 percent while also reducing travel time for non-buses on the same approach without causing substantial delay to side street vehicles. The queue bypass lane was also an effective treatment and tended to reduce bus travel time by 1 to 5 percent. The queue jump was not as effective and tended to increase side street delay due to the phase insertion.

The corridor-level results suggest that TSP is most effective as a corridor treatment when it is only implemented at moderately congested intersections (with v/c ratios of 0.6 to 0.9). This scenario resulted in similar bus travel times and intersection delays as when TSP was implemented at all intersections (regardless of v/c ratio), which indicates that targeted TSP implementation at moderately congested intersections is a cost-effective strategy. Consistent with the literature, TSP provides less travel time benefits to buses at less-congested intersections, but the findings here indicate that TSP may also not be beneficial at highly congested intersections (with v/c ratios greater than 0.9) because it can strongly degrade side street traffic operations.

The corridor-level results also indicate that when TSP is requested nearly every cycle (as simulated by 2-minute headways), it is disruptive to traffic operations of all vehicles, including buses. The authors recommend that future research efforts incorporate a more detailed study of the effect of transit headways on traffic operations at intersections and corridors with TSP.

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REFERENCES

1. Kittelson & Associates, Inc.; Parsons Brinckerhoff, Inc.; KFH Group, Inc.; Texas A&M Transportation Institute; and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd Edition. Transportation Research Board of the National Academies, Washington, D.C., 2013.

2. Danaher, A.R. *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic.* Transportation Research Board of the National Academies, Washington, D.C., 2010.

3. Levinson, H.S., C.L. Adams, and W.F. Hoey. *NCHRP Report 155: Bus Use of Highways—Planning and Design Guidelines.* Transportation Research Board, National Research Council, Washington, D.C., 1975.

4. Cesme, B., S. Altun, and B. Lane. "Queue Jump Lane, Transit Signal Priority, and Stop Location: Evaluation of Transit Preferential Treatments using Microsimulation." Presented at 94th Annual TRB Meeting. Transportation Research Board, National Research Council: Washington, DC, 2014. In press.

5. St. Jacques, K. and H.S. Levinson. *TCRP Report 26: Operational Analysis of Bus Lanes.* Transportation Research Board, National Research Council, Washington, D.C., 1997.

6. St. Jacques, K. and H. S. Levinson. *TCRP Research Results Digest 38: Operational Analysis of Bus Lanes on Arterials: Application and Refinement.* Transportation Research Board, National Research Council, Washington, D.C., 2000.

7. Smith, H.R., B. Hemily, and M. Ivanovic. *Transit Signal Priority (TSP): A Planning and Implementation Handbook.* ITS America, Washington, D.C., May 2005.

8. Koonce, P., P. Ryus, D. Zagel, Y. Park, and J. Parks. An Evaluation of Comprehensive Transit Improvements—TriMet's Streamline Program. In *Journal of Public Transportation,* Vol. 9, No. 3, 2006, pp. 103–115.

9. Albright, E. and M. Figliozzi. Factors Influencing Effectiveness of Transit Signal Priority and Late-Bus Recovery at Signalized-Intersection Level. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2311. Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 186–194.

10. Rephlo, J. and R. Haas. *Sacramento–Watt Avenue Transit Priority and Mobility Enhancement Demonstration Project: Phase III Evaluation Report.* US Department of Transportation, Washington, D.C., April 14, 2006.

11. Narrigan, T.R, J.R. Herr, M.J. Chase, and T. Doherty. *The Successful Deployment of a Transit Signal Priority System: Sumner Avenue, Springfield, Massachusetts.* Presented at the APTA Bus and Paratransit Conference, Nashville, Tenn., May 2007.

12. Gardner, K., C. D'Souza, N. Hounsell, B. Shrestha, and D. Bretherton. *Review of Bus Priority at Traffic Signals around the World.* UITP Bus Committee, Brussels, April 2009.

13. Li, Y., P. Koonce, M. Li, K. Zhou, Y. Li, S. Beaird, W. Zhang, L. Hegen, K. Hu, A. Skabardonis, and Z.S. Sun. *Transit Signal Priority Research Tools.* Report FTA-CA-26-7049-2008.1. Federal Transit Administration, Washington, D.C., May 2008.

14. Google Maps. <http://maps.google.com>. Accessed 5-24-2015.