Sensitivity Analysis of Transit Signal Priority Impacts on Operation of a Signalized Intersection

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ABSTRACT

The study conducts a systematic simulation evaluation of transit signal priority (TSP) impacts on the operations of a single signalized intersection within a coordinated arterial system. The study demonstrates that, in general, TSP provides benefits to transit vehicles that receive priority. Furthermore, TSP has a marginal system-wide impact for low traffic demands; however, as the demand increases, the system-wide disbenefits of TSP increases. Third, the system-wide impact of TSP is directly proportional to the frequency of transit vehicles. Forth, TSP impacts are sensitive to the demand distribution at a signalized intersection. Specifically, transit vehicle arrivals on heavily congested approaches may result in system-wide benefits if the conflicting approaches are not congested. Alternatively, transit vehicle arrivals on lightly congested approaches may produce significant system-wide disbenefits if the conflicting approaches are heavily congested. Fifth, the system-wide benefits of TSP are dependent on the phase at which the transit vehicles arrive especially if the cycle length is maintained within the priority logic. Sixth, the system-wide benefits of TSP are highly dependent on the optimality of the base signal timings. Finally, transit vehicle dwell times at near-side bus stops can have significant system-wide impacts on the potential benefits of TSP.

Key words: Transit signal priority, traffic modeling, and INTEGRATION model.

INTRODUCTION

While many factors influence the performance of surface transit services in urban areas, it is estimated that the delays introduced by the operation of traffic signals accounts for 10 to 25 percent of the total travel time of transit vehicles

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(Sunkari, 1995). To minimize transit vehicle delay, preferential treatments can be granted to transit vehicles at signalized intersections. These treatments can be provided off-line, by determining signal timing plans that intentionally favor bus movements, or on-line by allowing traffic signals to adjust their timings when a transit vehicle is detected. In the latter case, the signal timings are typically allowed to either hold the green on an approach until the transit vehicle has cleared the intersection, or to advance the start of the green to reduce the delay incurred by a bus in the queue. Other less common options include the implementation of bus-activated exclusive signal phases and the skipping of non-transit service phases.

Several studies have attempted to quantify the impacts of TSP. For example, the Southwest Region University Transportation Center at the University of Texas at Austin conducted an extensive literature review of TSP strategies along urban arterials (Garrow, 1997). The study concluded that TSP can offer significant potential benefits to transit vehicles without seriously compromising competing traffic if the priority system is developed and implemented with the considered needs of the entire transportation network. The study also demonstrated that the success of TSP systems greatly depends on the specific characteristics of the transportation network under consideration.

Dion *et al.* (In press) evaluated the potential benefits of implementing transit signal priority along the Columbia Pike arterial corridor, in Arlington, Virginia. The study used the INTEGRATION microscopic traffic simulation software to evaluate the impact of a number of alternative priority strategies on both the prioritized buses and general traffic during a peak and off-peak period. The transit priority strategies that were considered in the study included providing priority to express buses traveling along the main arterial (Columbia Pike) to both express and regular buses along the arterial and to all buses within the study corridor. The priority logic considered the standard TSP logic, which provides green extensions and green recalls within a fixed-time traffic signal control environment. The simulation results indicated that the buses that were provided with priority would typically incur savings in delay; however, these benefits were typically obtained at the expense of the overall transportation system, particularly when traffic demand was high. The study recommended that a more detailed evaluation be conducted on a single signalized intersection within a corridor in order to identify the critical transit and traffic volume variables that impacted transit priority benefits.

Objectives and Layout of Paper

The objective of this research effort is to isolate the impacts of various traffic, transit, and signal timing factors on the potential benefits of TSP. This objective is achieved by conducting a systematic analysis of TSP at a single intersection within a coordinated arterial corridor. The consideration of a single intersection provides a localized network where a systematic analysis of cause and effect can be conducted. The significance of this research effort lies in the fact that it not only quantifies the potential benefits of TSP for both transit vehicles and the general traffic, but also identifies the critical factors that impact the benefits of TSP.

It should be noted that the study does not consider the potential for drivers to alter routes as a result of changes in signal timings caused by TSP. However, it is recommended that further studies be conducted to study TSP impacts considering the potential diversion effects.

BACKGROUND

The study utilizes the INTEGRATION 2.30d model to conduct the study (M. Van Aerde & Assoc., 2002). Prior to describing the test network and scenarios that were considered in the evaluation of TSP, the INTEGRATION software and its TSP logic are briefly described.

The INTEGRATION model was selected as the tool of choice to conduct the study for a number of reasons. First, given that the model was conceived in the mid-1980's, it has been extensively validated and tested by various independent private and public transportation agencies (Rakha, 1989; Rilett, 1991; Rakha et al., 1998). Second, the software is capable of modeling the standard TSP procedures in addition to adaptive and actuated signal control. It should be noted that this study does not consider the diversion effects associated with TSP because of the size of the network (single intersection).

Among the unique features of INTEGRATION is the use of the same traffic flow logic to represent both freeway and signalized links. Simulation with the model involves the tracking of individual vehicle movements from a vehicle's origin to its final destination at a maximum update rate of 1/10 of a second. This microscopic approach permits the detailed analysis of many traffic phenomena, such as shock waves, gap acceptance, and weaving behavior. It also permits considerable flexibility in representing spatial variations in traffic conditions. The dynamic approach adopted by the model further allows it to consider virtually continuous time-varying demands, routings, link capacities, and traffic controls without the need to pre-define an explicit common time-slice duration. Finally, the INTEGRATION model can be used not only to estimate stops (Rakha et al., 2001) and delay (Dion et al., In press), but also to estimate vehicle fuel consumption and emissions within a simulated network (Rakha et al., 2000; Ahn et al., 2001; Rakha et al., 2003). Embedded in the model are routines that compute the fuel consumption and emissions of hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) of each simulated vehicle on a second-by-second basis based on the vehicle's instantaneous speed and acceleration levels.

The TSP logic that is embedded in INTEGRATION detects transit vehicles that are within 100 m of the traffic signal to provide either a green extension or an early green recall (red truncation) to accommodate the approaching transit vehicle, subject to the need to maintain a common network cycle length. The logic is used to determine whether signal changes are required at an intersection to accommodate an approaching transit vehicle. The operation of this logic is best described through an example. In this example, traffic signals A and B are neighboring each other, and signal B is located to the east of signal A. If it is assumed that the traffic signals A and B operate on a two-phase mode with a common cycle length, the detection of a transit vehicle traveling eastbound while traffic on the east/west travel direction is being served may result in a number of possible outcomes depending on when the detected transit vehicle is projected to arrive at intersection A within the signal cycle:

- If the transit vehicle is projected to arrive early in the green interval so that it can proceed uninterrupted through the intersection, no alterations are made to the signal timings.
- Alternatively, if the transit vehicle is projected to arrive after the end of the green interval, the interval is extended at user-specified increments (set at 5 seconds for this study) until the transit vehicle is served or the maximum green interval duration is reached. The maximum green interval can be set by the user; however, for purposes of this study, it was set to equal the cycle length, minus the summation of the intergreen times of all the phases defined in the signal cycle and the summation of a 5-second minimum green for each phase defined within the signal cycle. It should be noted that the TSP logic is checked each second to identify what changes, if any, should be made to the signal timings.

- If, on the other hand, the traffic signal at intersection A serves the north/south approaches as the transit vehicle arrives, the priority logic truncates the north/south phase after providing the minimum green duration and the required amber interval.
- Finally, if transit vehicles are detected on two conflicting approaches, the TSP logic makes no changes to the signal timings, as the priority calls from both approaches to be equally weighed.

An extensive study conducted by the Advanced Traffic Management Systems Committee and Advanced Public Transportation Systems Committee of the Intelligent Transportation Society of America (ITS America) identified the green extension and red truncation transit priority logic, which is embedded in the INTEGRATION software, as the standard state-of-practice procedure for implementing transit priority (Baker et al., 2002). Specifically, the study identified green extension and red truncation as the most commonly used TSP application with phase skipping being implemented in some rare instances (Baker et al., 2002). Consequently, the logic that is considered in this paper represents the current state-of-practice in TSP modeling. It should be noted, however, that enhancements to the INTEGRATION TSP logic are being considered in order to provide priority that is weighed by the occupancy of the transit vehicles and also considers the level of congestion on conflicting approaches in granting priority to transit vehicles.

TEST NETWORK AND SCENARIO DESCRIPTION

This section describes the test network and test scenarios that were considered in the analysis prior to discussing the study results in the subsequent section.

Test Network Description

The test network that was analyzed consisted of four approaches to a signalized intersection of length 250 meters. Two traffic signal phasing schemes were considered in the analysis, namely, a 2-phase (→←, ↓↑) and a 4-phase scheme (→, ←, ↓, ↑). For the base 2-phase scheme an equal demand of 600 veh/h was loaded in the eastbound and northbound directions, respectively. Alternatively, for the base four-phase scheme, an equal demand of 254 veh/h was loaded on all approaches in order to maintain the same volume-to-capacity ratio for both phasing schemes.

An optimum cycle length of 60 seconds with a 50:50 phase split for the 2-phase scheme and a 25:25:25:25 phase split for the four-phase scheme was implemented. The traffic signal offset was set at 0 seconds, and the demand was loaded for a total of 5 minutes with an additional 15 minutes to clear the network of any vehicles traveling at the conclusion of the demand.

In order to ensure that increases in vehicle delay were only caused by the traffic signal operations rather than differences in traffic demand, the speed-at-capacity was set approximately equal to the free-speed (59.9 and 60.0 km/h, respectively). The unopposed saturation flow rate was set at 1800 veh/h (headway of 2 seconds). The jam density of 100 veh/km results in a vehicle spacing of 10 meters when vehicles are fully stopped.

Test Scenario Description

In order to provide a systematic evaluation of TSP, a sensitivity analysis was conducted using nine variables, including the time of departure of a transit vehicle, the signal phasing scheme, the total traffic demand approaching the intersection, the demand distribution across various approaches, the signal cycle length, the signal phase split, the approach on which the transit vehicle arrived, the dwell time at the bus stop, and the frequency of buses, as summarized in Table 1.

A number of hypotheses were developed and tested in this paper. The first hypothesis was that the impacts of TSP are affected by the arrival time of transit vehicles within the traffic signal cycle. In addressing this hypothesis, eight transit vehicle departure times (variable A) were considered. In addition, overall average benefits were estimated by averaging over the eight potential transit vehicle arrival times.

The second hypothesis was that the network-wide impacts of TSP are sensitive to the number of signalized phases. Consequently, two phasing schemes were considered: a 2-phase scheme and a 4-phase scheme (variable B). As was mentioned earlier, in both schemes the volume-to-capacity ratio was held constant at the signalized approaches. For example, for a 2-phase signal plan operating at a 60-second cycle length with a 4-second intergreen interval, the approach operates at a capacity of 780 veh/h (1800×26/60). Alternatively, an approach to a 4-phase traffic signal operating at the same 60-second cycle length and an identical 4-second intergreen interval operates at a capacity of 330 veh/h (1800×11/60). Consequently, the total traffic demand was altered in the 4-phase scheme in order to ensure consistency in the volume-to-capacity ratios for the two phasing schemes ranging from 0.5 to 1.0.

The third hypothesis that was identified was that the network-wide impacts of TSP increase with increased levels of congestion. In addressing this hypothesis, five traffic demand levels were considered that resulted in approach volume-to-capacity ratios that ranged from 0.5 to 1.0.

The literature indicates that the system-wide negative impacts of TSP result when the approaches not receiving priority operate at high volume-to-capacity ratios (v/c greater than 90 percent). In order to investigate this hypothesis, the 2-phase scheme was loaded with six demand distribution scenarios, as summarized in Table 2. In these scenarios, the v/c ratio ranged from 0.13 to 1.41 by loading traffic demands that exceeded the capacity of the signalized intersection approaches. The approach at which the transit vehicle arrived was also varied in order to vary the level of congestion on the approach receiving priority.

Another hypothesis that was proposed was that the base signal timing plan impacts the system-wide benefits of TSP. Consequently, sub-optimal signal timings are introduced in order to test the proposed hypothesis. Specifically, the impact of sub-optimal cycle lengths and sub-optimal phase splits were considered in the analysis, as summarized in Table 1 (variables D and F).

Finally, the study investigates the impact of dwell time at a nearside bus stop that is located within the detection range of the traffic signal. The hypothesis that is proposed is that the system-wide disbenefits of TSP increase as the transit vehicle dwell time increases because the TSP logic grants the transit vehicle priority while passengers are ascending and/or descending from the bus.

SIMULATION RESULTS

As mentioned earlier, a number of hypotheses were identified as part of this study. The objective of the study was to establish the appropriateness of these hypotheses. Importantly, because the network was composed of a single intersection, the phrase “system-wide” refers to “intersection-wide” impacts.

Impact of Traffic Demand

In order to quantify the impact of traffic demand on the potential benefits of TSP, a total of 80 simulation runs were executed. These 80 runs included 8 bus departure times, 2 phasing schemes, and 5 levels of total traffic demand (variables A, B, and C in Table 1). Figure 1 illustrates the variation in the various measures of effectiveness (MOEs) for transit vehicles, passenger cars, and all vehicles as a function of the level of congestion at the signalized intersection for a transit demand of 12 veh/h and a 2-phase scheme. The figure demonstrates that as the traffic demand increases, the average delay, average vehicle stops, and average fuel consumption of transit vehicles also increases in the 2-phase scheme. Furthermore, regardless of the v/c ratio, TSP can decrease the average delay, stops, and fuel consumption of transit vehicles when compared with the base no-TSP scenario. Specifically, for the 2-phase scheme, the average delay of transit vehicles decreases by 28.7 percent. Interestingly, the figure indicates that the benefits to transit vehicles that results from TSP increases as the level of congestion increases. The reason for this finding will be described later in this section.

Figure 1 demonstrates that as the traffic demand approaching the intersection increases, the average transit vehicle delay, stops, and fuel consumption increases. Furthermore, the results demonstrate that providing TSP to transit vehicles has a marginal effect on the average passenger car delay (a 0.09 percent decrease), stops, and fuel consumption. Figure 1 also illustrates the average system-wide impacts of TSP (impacts on transit and non-transit vehicles). The figure demonstrates that as the traffic demand increases, the system-wide average delay, vehicle stops, and fuel consumption increases. Furthermore, providing TSP to transit vehicles has a marginal system-wide effect on the average delay, vehicle stops, and fuel consumption.

Figure 2 illustrates the variation in the maximum potential benefits associated with a single transit vehicle traveling in the eastbound direction for a 2-phase traffic signal plan. The transit vehicle departs 15 seconds into the cycle and requires 15 seconds to travel the length of the link (traveling at 60 km/h over a distance of 0.25 km). In the case of no priority, the transit vehicle would have to come to a complete stop at the intersection since it arrives during the amber interval at the conclusion of the first phase green interval. Alternatively, when TSP is allocated to the bus, the first phase is extended to allow the bus to proceed through the intersection without having to stop. The difference in the priority and no-priority delay curves is constant and is equal to the duration of the second phase given that the vehicle arrives just as the second phase starts.

Figure 2 also illustrates the variation in the various measures of effectiveness for a transit vehicle that departs 7.5 seconds into the cycle. In this case the bus arrives at the signalized intersection 22.5 seconds into the cycle and thus can proceed through the intersection without having to stop. However, as the demand increases longer queues are formed upstream the intersection causing the transit vehicle to be delayed and thus missing the first phase green interval, which concludes 26 seconds into the cycle. Alternatively, in the case of TSP although the bus is delayed by the queue formation upstream of the traffic signal, the green interval is extended to allow the transit vehicle to proceed without having to wait for the duration of the entire second phase. This finding explains why larger benefits were experienced by the transit vehicles for the higher demands in Figure 1.

The impacts of TSP in the case of a 4-phase traffic signal plan were found to be very similar to the for 2-phase scenario. In summary, the analysis demonstrates that, in general, TSP provides benefits to transit vehicles that receive priority and these benefits are highly dependent on the time of arrival of the transit vehicle within the cycle length. In this case, minor negative impacts were incurred on the general automobile traffic.

Impact of Transit Demand

The previous analysis indicated that while TSP provided benefits to the transit vehicles, no disbenefits were incurred on the general traffic. In order to ascertain that these findings were not caused by the transit vehicle demand being low, the next step of the analysis was to investigate the system-wide impacts of TSP for a larger transit demand. Specifically, a transit vehicle headway of 2 minutes (30 veh/h) and 1 minute (60 veh/h) were considered.

Simulation results show that the higher transit vehicle demands of both 30 veh/h and 60 veh/h while providing benefits to the transit vehicles did not result in negative system-wide impacts for levels of congestion ranging from a v/c ratio of 0.5 to 1.0 for both the 2-phase and 4-phase scenarios.

During the study, larger reductions in transit vehicle delay were observed for the 4-phase scheme than for the 2-phase scheme. The higher benefits of TSP for the 4-phase scheme are attributed to there being less of a percentage of green time allocated to a specific approach is less for the 4-phase scheme compared to the 2-phase scheme. Consequently, the transit vehicles are more likely to arrive when the traffic signal indication is red in the case of no priority, thus providing more opportunities to reduce transit vehicle delays by extending the green interval.

The study also indicates two reasons for why the benefits of TSP to the vehicles receiving priority increases as the level of congestion increases. The first reason is because the base case involves higher delay to transit vehicles as the approach demand increases. The second reason is because the transit vehicle may be queued upstream the intersection within the detection range, causing a longer temporal opportunity for the vehicle to be detected.

Impact of Demand Distribution and Phase Requesting Priority

Given that the TSP logic that was tested provided vehicle priority within traffic signal coordination (i.e., maintained a constant cycle length), it was important to investigate the sensitivity of the results to the phase requesting priority. Specifically, two batches of simulation runs were conducted in which transit vehicles traveled along the eastbound direction (arrivals during phase 1) and a series of runs in which transit vehicles traveled in the northbound direction (arrivals during phase 2). In addition, six demand distribution levels and two signal timing schemes were considered. In the first scheme, the signal timings were held fixed at a 50:50 phase split while in the second scheme the signal timings were optimized to reflect the different demand distributions. Specifically, the phase lengths were set proportional to the critical volume-to-capacity ratios for each phase. It should be noted, that the volume-to-capacity ratio varied considerably for the 50:50 phase split scheme, as demonstrated in Table 2.

The objectives of this analysis are two-fold. First, the analysis attempts to investigate the sensitivity of results to the phase requesting priority. Second, the analysis attempts to investigate the impact of different demand distributions at the approaches to a signalized intersection on the benefits of TSP.

Figure 3 demonstrates the variation in the average system-wide delay for a 50:50 phase split with a transit demand of 12 veh/h versus a transit demand of 60 veh/h and an optimised phase split with a transit demand of 12 veh/h versus a transit demand of 60 veh/h. The graphs to the left consider an eastbound transit demand while the figures to the right consider a northbound transit demand.

In the case of the two-phase 50:50 phase split scenario with a transit demand of 12 veh/h, it should be noted from the figure that the average system delay is minimum as the demand on the competing approaches tend to be evenly distributed (case 6 on the x-axis). The higher delays for the non-equal demands result from the non-optimal phase split setting (50:50 phase split). The figure illustrates the impact of transit vehicle priority for vehicle arrivals during phase 1 (eastbound arrivals) and phase 2 (northbound arrivals). Contrary to intuition, the figure clearly illustrates a minor system-wide impact of TSP when priority is allocated to phase 1. This finding can be explained considering that in most cases, the signal timings are not altered by the signal priority logic because arrivals during the green interval of phase 1 and after the conclusion of the green interval of phase 1 do not result in any changes to the signal timings. The only case in which the signal timing can be altered is when the transit vehicle arrives just before the conclusion of the green interval of phase 1. A similar behavior is observed for a higher transit vehicle demand of 60 veh/h, except that the TSP does incur a minor system-wide increase in delay because of the higher transit demand.

Alternatively, a transit vehicle arrival in the northbound direction results in significant system-wide impacts for the 50:50 phase split scheme for two reasons. First, there are more opportunities to alter the signal timings given that any transit vehicle arrival in the northbound direction while phase 1 is being served will result in an early termination of phase 1 in order to serve the priority request for phase 2. Second, the alteration of the signal timings that result from providing priority to the transit vehicle provides a better signal timing plan given that the 50:50 phase split is non-optimal for the approach volumes. Consequently, the extension of phase 2 as a result of the signal priority produces a more optimum signal-timing plan and thus system-wide benefits from TSP. It is clearly demonstrated in the figure that the system-wide benefits of signal priority decrease as the levels of congestion on the eastbound and northbound approaches tend to be equal because the background timing plan that is in place is optimum for the arrival demands. The negative impacts of TSP are further demonstrated when there is a higher demand for signal priority.

In the case of a transit vehicle arrival during the amber of the first phase (arrival after 30 seconds into the cycle) versus a vehicle arrival during the amber of the second phase (60 seconds into the cycle), the TSP logic differs depending on which phase receives a request for transit vehicle priority. Specifically, in the case of a transit vehicle arrival during the first phase of operation, the phase is extended at 5-second increments until the transit vehicle is served. Consequently, the transit vehicle does not have to stop at the signalized intersection. Alternatively, in the case of a transit vehicle arrival during the second phase, given that the logic maintains a constant cycle length, the transit vehicle has to come to a complete stop. However, in the following cycle the green interval of the first phase is reduced to the minimum, and thus the transit vehicle incurs less delay compared to the scenario in which priority is not provided.

The system-wide impacts of TSP vary depending on which phase requests priority in an optimized two-phase signal operation with varying conflicting demand levels and a transit vehicle headway of 5 minutes (transit vehicle demand of 12 veh/h). The figure clearly demonstrates that the system-wide disbenefits of TSP are minor, given that the transit demand is fairly low. Again, TSP requests during latter signal timing phases result in higher system-wide disbenefits because more changes are made to the signal timings. Similarly, an increase in the transit vehicle frequency from a transit vehicle headway of 5 to 1 minute results in minor system-wide disbenefits associated with TSP if the request for priority is during the first phase of operation. However, large system-wide disbenefits are incurred if the request for priority is made during latter phases.

In summary, minor changes to the signal timings result in minor system-wide impacts. In addition, the study has demonstrated that the system-wide impacts of TSP are highly dependent on the optimality of the base case signal timings. In the case that providing TSP improves the signal timings, then system-wide benefits of TSP are achievable.

Impact of Phasing Scheme

The study also considered the impact of the number of phases within a signal-timing plan on the potential impacts of TSP. Specifically, a 2-phase scheme and a four-phase scheme were considered. Both phasing schemes operated at the same cycle length with varying demand levels in order to maintain an identical volume-to-capacity level along the conflicting approaches. Because the 4-phase scheme incurred longer lost times, it required a longer cycle length than the 2-phase scheme; however, for the purposes of this analysis, the cycle length was kept constant. Since there was a higher probability that a transit vehicle would arrive at a signalized approach when the traffic signal indication was green, the 2-phase scheme transit vehicles experienced lower average delays at the intersection approaches. As to the impact of the phasing scheme on TSP, no significant effects were observed in the simulations. Specifically, an analysis of the simulation results demonstrated that in the case of the four-phase scheme, more transit vehicles were required to stop at the intersection. However, the vehicles were able to proceed through the intersection in the subsequent cycle.

Impact of Sub-optimal Signal Timings

The impact of sub-optimal signal timings was analyzed in two aspects in this study. First, the impact of sub-optimal cycle lengths was analyzed followed by an analysis of sub-optimal phase splits. To study the impact of cycle length and phase split, three cycle lengths and five phase split levels were considered in the simulations, as summarized in Table 1. The cycle lengths that were considered in the analysis included a 40, 60, and 80-second cycle length. The five phase split levels included a 30/70, 40/60, 50/50, 60/40, and 70/30 phase split, for the east/west and north/south directions, respectively.

Figure 4 illustrates the variation in TSP impacts as a function of the traffic signal cycle length. The figure illustrates a minimum delay occurring at a cycle length of 40 seconds because this value is closest to the optimum cycle length for the arrival volumes and saturation flow rates (C = 8/(1-1200/1800) = 24 seconds). Consequently, the TSP has minimum impact on transit vehicle delays because minimum changes are required to accommodate the transit vehicles. Specifically, the short queues and short cycle length provide little opportunity for providing TSP. Since the transit demand is fairly low, the impacts of TSP on passenger cars and the entire system are insignificant.

Figure 5 illustrates the impact of the signal-timing phase split on the benefits of TSP. It is clear that transit vehicles benefit from the provision of TSP regardless of the optimality of the phase split. Conversely, system-wide benefits are achieved if the base case signal plan is sub-optimal and the TSP results in an improvement in the signal timings. For example, Figure 5 also illustrates that, for the scenarios in which the green allocation to the eastbound direction was sub-optimal providing signal priority in the eastbound direction, resulted in more green time being allocated to the first phase, and thus overall system-wide benefits. In the cases in which extra green time was allocated in the eastbound direction, the provision of TSP for phase 1 resulted in negative system-wide impacts.

Impact of Near-side Bus Stop Dwell Times

The final sensitivity analysis that was conducted as part of this study involved analyzing the impact of dwell times at nearside bus stops on the benefits of TSP. Five dwell times were simulated in this analysis ranging from 5 to 60 seconds, as summarized in Table 1. Figure 6 clearly demonstrates that the transit vehicles benefit from TSP regardless of the duration of the dwell time. However, it is also demonstrated in Figure 6 that the system-wide disbenefits of TSP increase as the dwell times increase. The increase in system-wide delays is attributed to two factors. First, because the roadway is a single lane, the general traffic approaching the signalized intersection has to queue behind the transit vehicle when the vehicle is stopped. Second, because the bus stop is located within the detection zone, the signal timings are adjusted to allow the transit vehicle to proceed through the intersection; however, given that the transit vehicle is loading and unloading passengers, a portion of the green time is lost with no utilization.

FINDINGS AND CONCLUSIONS OF THE STUDY

The objective of this study was to conduct a systematic evaluation of TSP on a signalized intersection within a coordinated arterial. The conclusions of the study can be summarized as follows:

a. Generally, TSP provides benefits to transit vehicles that receive priority. These benefits are highly dependent on the time of arrival of the transit vehicle within the cycle length and the phase of the traffic signal that is requesting priority.

b. TSP has a marginal system-wide impact for low traffic demands; however, as the demand increases, the system-wide disbenefits of TSP increases.

c. The system-wide impact of TSP is dependent on the frequency of transit vehicles. As the transit vehicle frequency increases, larger system-wide disbenefits are observed.

d. TSP impacts are sensitive to the demand distribution at a signalized intersection. Transit vehicle arrivals on heavily congested approaches may result in system-wide benefits if the conflicting approaches are not congested. Alternatively, transit vehicle arrivals on lightly congested approaches may produce significant system-wide disbenefits if the conflicting approaches are heavily congested.

e. The system-wide benefits of TSP are dependent on the phase at which the transit vehicles arrive, especially if the cycle length is maintained within the priority logic. Transit vehicle arrivals during the early phases produce minimum disruptions to the general traffic while transit vehicle arrivals for the latter phases produce significant system-wide disbenefits.

f. The system-wide benefits of TSP are highly dependent on the optimality of the base signal timings. Specifically, if the priority logic enhances the signal timings, system-wide benefits can be achieved by virtue of improving the signal timings.

g. Transit vehicle dwell times at near-side bus stops can have significant system-wide impacts on the potential benefits of TSP. Specifically, the system-wide disbenefits increase with an increase in bus dwell times if the bus stop is located within the detection range of the traffic signal.

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Table 1: Scenario Experimental Design

Variable	Variable Description	Level Description
A	Bus departure time	0.0, 7.5, 15.0, 22.5, 30.0, 37.5, 45.0, and 52.5
B	Phase scheme	2-phase and 4-phase
C	Total traffic demand	800, 1000, 1200, 1400, and 1600 veh/h
D	Demand distribution	100/1100, 200/1000, 300/900, 400/800, 500/700, 600/600, 700/500, 800/400, 900/300, 1000/200, and 1100/100
E	Cycle length	40, 60, and 80 seconds
F	Phase split	30/70, 40/60, 50/50, 60/40, and 70/30
G	Bus approach	Eastbound and northbound
H	Bus stop duration	5, 10, 15, 30, and 60 seconds
I	Bus frequency	12, 30, and 60 buses/h

Table 2: Volume-to-Capacity Ratios at Signalized Approaches for 2-Phase 50:50 Phase Split

Demand Distribution Scenario	**Eastbound**		**Northbound**	
	Demand	**v/c Ratio**	**Demand**	**v/c Ratio**
1	100	0.13	1100	1.41
2	200	0.26	1000	1.28
3	300	0.38	900	1.15
4	400	0.51	800	1.03
5	500	0.64	700	0.90
6	600	0.77	600	0.77

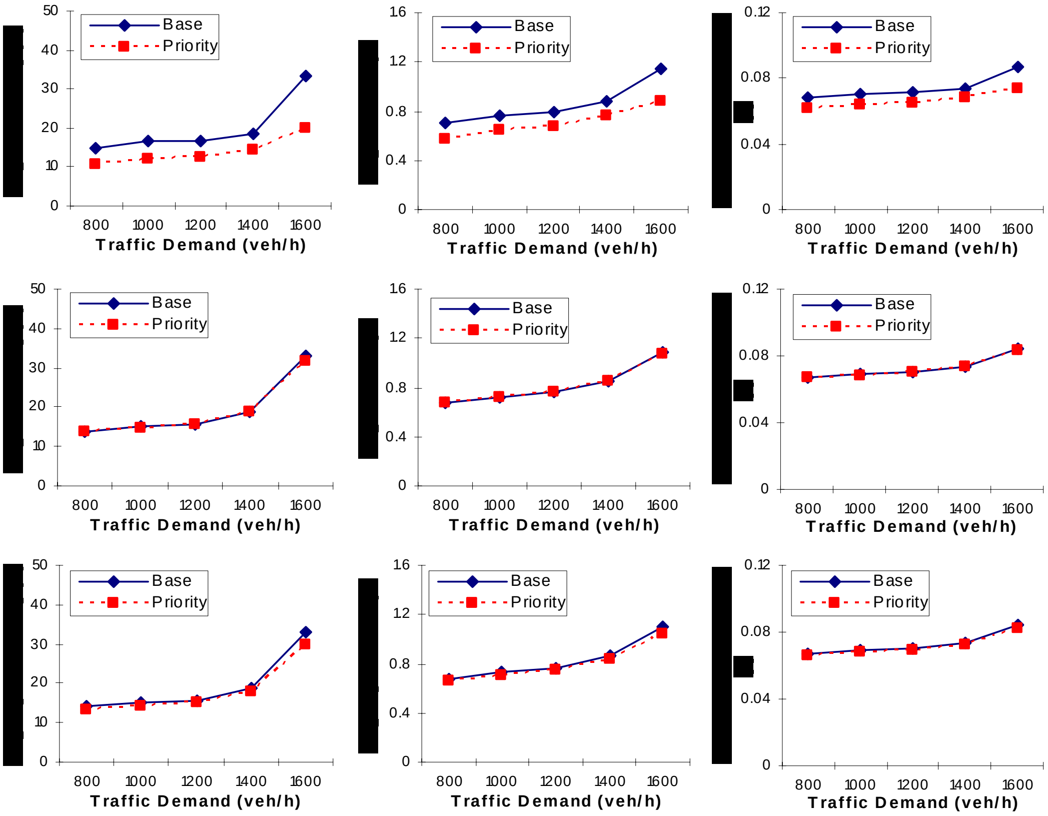


Figure 1: Average Impacts of TSP (2-phase Signal Operation – Transit Demand of 12 veh/h)

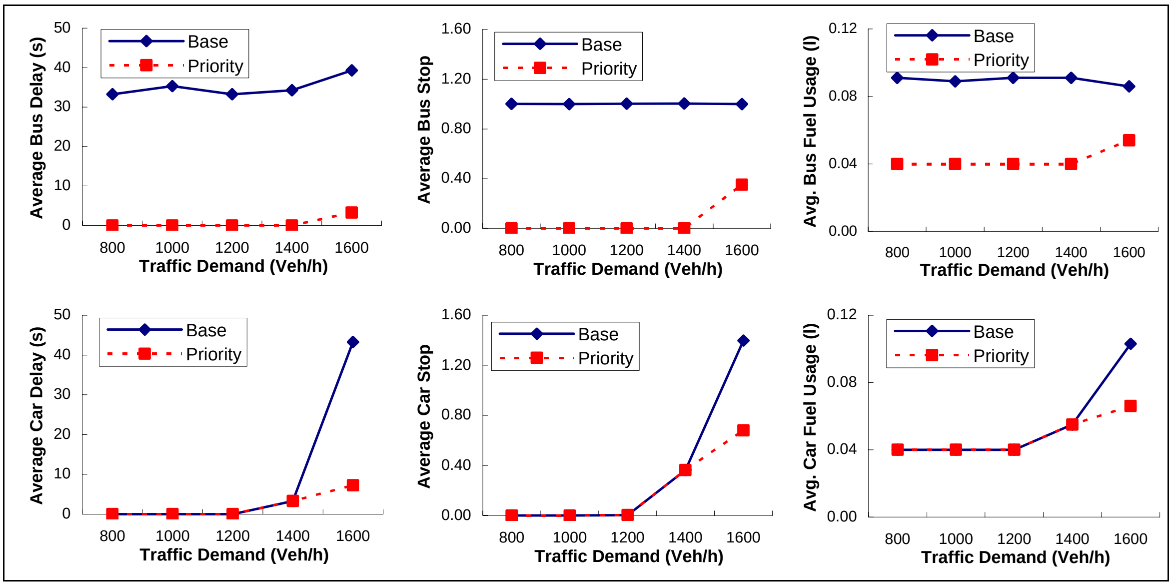
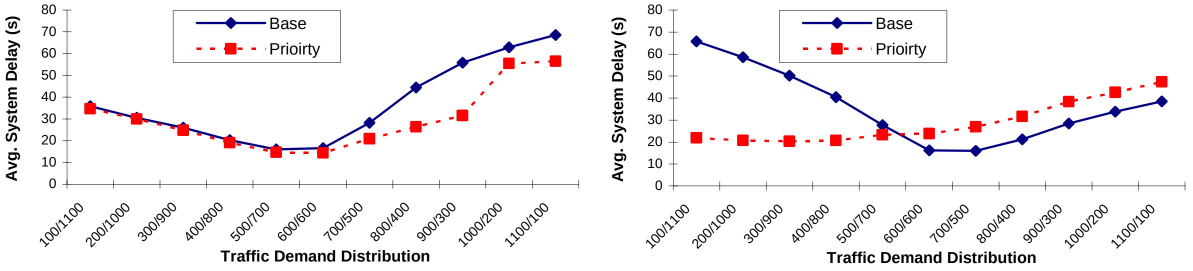
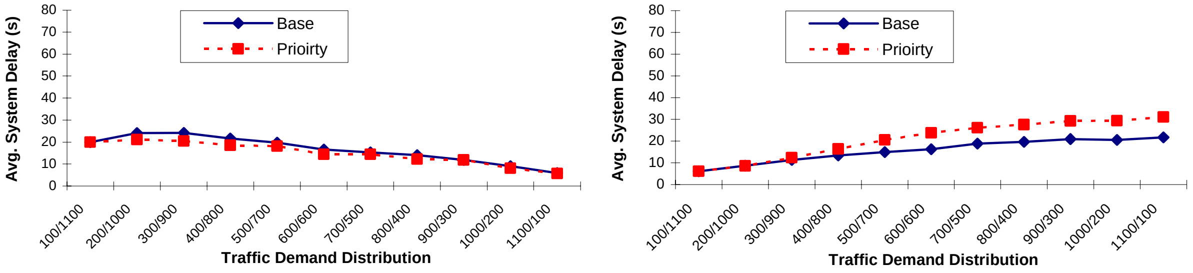


Figure 2: Transit Vehicle Impacts of TSP



50:50 Split Signal with EB Transit Demand of 60 veh/h

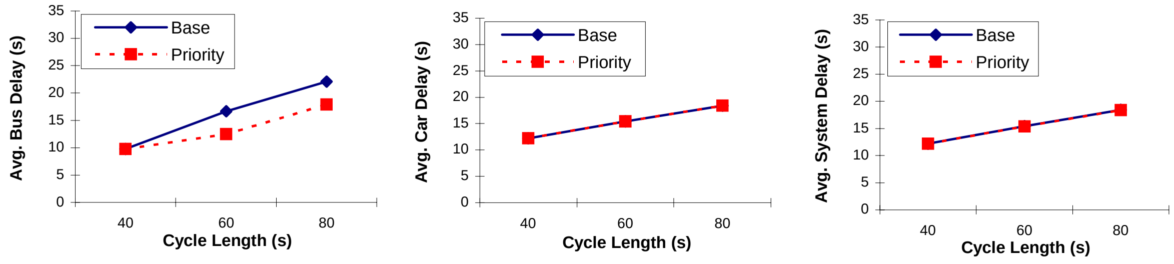
50:50 Split Signal with NB Transit Demand of 60 veh/h



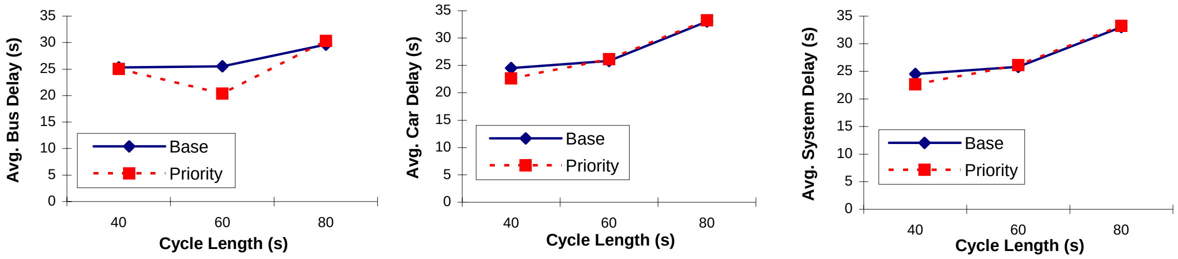
Optimised Signal Split with EB Transit Demand of 60 veh/h

Optimised Signal Split with NB Transit Demand of 60 veh/h

Figure 3: TSP System-wide Benefits as a Function of Demand Distribution (2-Phase Signal Operation)



2-phase Signal Operation



4-phase Signal Operation

Figure 4: TSP Impacts as a Function of Cycle Length (2-phase Signal Operation, Transit Demand of 12 veh/h)

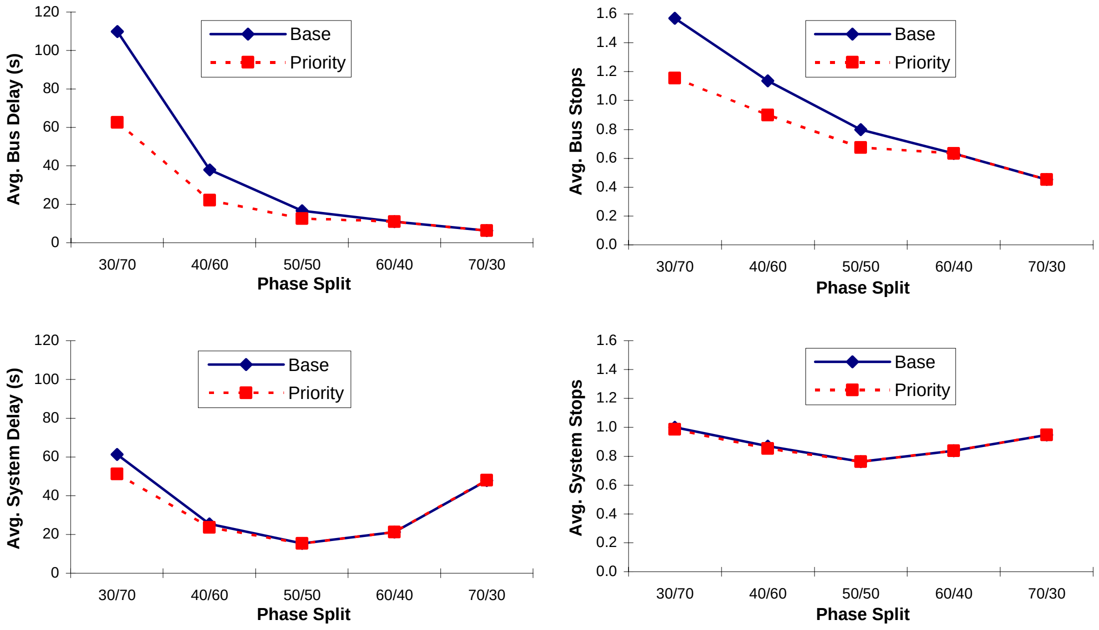


Figure 5: TSP Impacts as a Function of Phase Split (2-phase Signal Operation, Transit Demand of 12 veh/h)

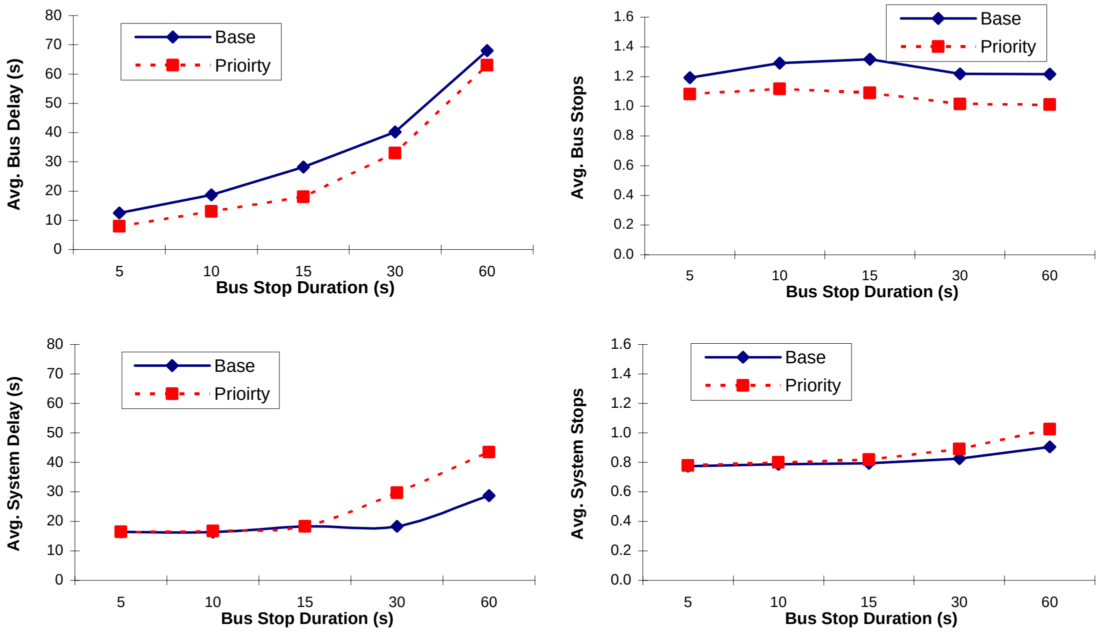


Figure 6: TSP Impacts as a Function of Dwell Time (2-phase Signal Operation, Transit Demand of 12 veh/h)