Transit Signal Priority Impact Analysis and Evaluation in the City of Edmonton

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Paper prepared for presentation at the Road Safety Strategies and Intelligent Transportation Systems (ITS) Session of the 2013 Conference of the Transportation Association of Canada
Winnipeg, Manitoba

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ABSTRACT

It has been proven that Transit Signal Priority (TSP) strategies can reduce bus travel time as well as increase bus service reliability. Nonetheless, some major issues remain. The performance of TSP strategies may significantly increase traffic control delay if the TSP requests are frequent. Or TSP may further deteriorate the traffic conditions or even cause cycle failures at congested intersections. In this paper, the authors examined and estimated the potential performance of TSP under different scenarios composed of various signal control strategies and traffic demand levels. The authors also conducted a case study using the microscopic traffic simulation software, VISSIM, which contains a fully-functioned signal control emulator with a TSP module. The comparison between TSP and non-TSP strategies in simulation demonstrates that TSP strategies are not necessarily beneficial for all traffic scenarios. The comparison also explores the benefits of TSP with respect to the total traffic volumes, demand distributions and frequency of TSP requests at intersections. Lastly, the authors conducted a simulation study of a bus corridor of the City of Edmonton to identify intersections which can benefit from TSP. The simulation results show that TSP will reduce bus travel times as well as deteriorate the overall traffic performance. Disabling some of the TSP control may result in greater balance for the whole system.

Introduction

Transit Signal Priority (TSP) strategy is widely used to improve transit service reliability, and therefore transit service, in urban areas. It has been shown to have great benefit in reducing transit travel times and increasing transit schedule adherence. In urban areas, it is estimated that TSP will reduce the signal-related bus delay by 10% to 25% of the total bus travel time (1). As such, many agencies advocate TSP applications to improve bus services.

There are mainly two categories of TSP strategies: passive and active. Passive TSP is in essence a kind of fixed signal timing. The offsets and splits are modified in a way that, when a transit bus is scheduled to cross the intersection, the signal light will give it a better green opportunity through pre-determined programming. Passive TSP is not flexible for dynamic traffic or any unexpected transit delay.

In comparison, active TSP is based on detecting newly approaching transit buses and grant more green time accordingly. There are two active priority control tactics that are widely used: green extension and red truncation. Both of these are basic TSP functions that almost every TSP system will support.

One major concern related to the application of TSP is that, although it can greatly benefit bus operations, TSP may also have negative impacts on cross street traffic. TSP may not always improve the overall mobility at intersections or even reduce it under some traffic conditions. For example, if total traffic demands are high both on the mainline and on side streets, TSP may further degrade overall signal performance. As such, installing TSP may not always be an appropriate solution to reducing transit travel time, and it is necessary to estimate TSP's benefits and its impact on mobility at intersections under different traffic scenarios. The findings in this paper will also provide insights for researchers and practitioners when designing TSP systems.

The remaining sections of this paper are structured as follows. Firstly, existing literature about TSP strategies are reviewed. Secondly, the performance of TSP is investigated at a hypothetical intersection in VISSIM. In this part, multiple experiments are conducted to show how different traffic conditions will determine the TSP performance. Thirdly, we apply the findings to a bus corridor in the City of Edmonton using simulation to determine which intersections can benefit from TSP and which cannot. The last section summarizes the findings and conclusions.

Literature Review

In general, there are two approaches to estimating the impact of TSP strategies. One approach uses microscopic simulation to evaluate various TSP strategies. The other type aims to develop analytical models to estimate the impacts of TSP, using measures such as travel time and control delays. Liu et al. designed an analytical TSP model based on deterministic queuing theory (2). Liu's model focuses on uniform delay and residual queue delay, assuming that TSP operations do not significantly affect the random delay. They also developed an analytical model to estimate person delay for both prioritized and non-prioritized approaches. In their study, Liu et al. consider that the traffic condition of each approach was related to the TSP performance and developed a relationship of the saved delay via TSP with respect to traffic condition factors such as traffic demand. Inspired by Liu's study, Abdy and Hellinga conducted a study to estimate TSP's impact on general vehicles delay (3). In their model, sixteen functions are used to represent the total delay of each approach. As an improvement, Abdy and Hellinga's model considers many non-ideal cases. For example, their analysis not only assesses the current cycle but also considers the following cycle after TSP was enabled.

In addition, many researchers have devoted their efforts to understanding the relationship between traffic conditions and TSP performance. For instance, Rakha and Zhang found TSP would work well under some traffic condition, while under others not. They conducted a sensitivity analysis of TSP using the INTEGRATION traffic simulation model (4). In their study, Rakha et al. identified and tested a number of factors contributing to TSP performance. The impact of each factor was simulated and then the control delay was evaluated. The authors concluded that TSP impacts are most sensitive to traffic demand and turning movement distribution at signalized intersections. Under a high demand (defined as 1,200 vehicles/hour in their paper), the demand distribution determines whether TSP will benefit the whole intersection.

Another bus priority study on an arterial with highly interrupted traffic signal control was conducted by Janos and Furth (5). The study area is a 6.7 km long corridor in San Juan, Puerto Rico. The authors conclude that it is difficult for an intersection to return to its normal cycle after the signal priority control is interrupted and the queue overflow will be enlarged when the frequency of priority interruptions increases. This conclusion is consistent with a rule of thumb in the United States that signal controllers should not accept new priority requests with about 15 minutes after priority is granted.

More recently, several advanced TSP strategies and technologies have emerged. Christofa and Skabardonis proposed a real-time, traffic-responsive signal control system (6). This system aims to maximize the flexibility and utility of TSP under any traffic condition. It also aims to minimize the total personal delay at intersections rather than just the bus delay. Furth et al. conducted a study about TSP strategy application around transit bus terminals (7). They investigated several traffic flow properties in the vicinity of the terminal, which usually differ from the arterial. Firstly, multiple buses often arrive at the neighboring intersections within one cycle. Secondly, buses enter the intersection from conflicting approaches. Thirdly, the traffic on adjacent routes is often impacted by high bus volumes. The authors concluded that both passive and active control could save the average bus approximately 50 seconds of travel time. For the general traffic, however, there were almost no delay savings at the level of the whole network.

TSP Performance Analysis

In general, the applications of TSP can reduce transit delay. However, TSP may negatively impact cross street traffic. The overall benefit should be used to indicate the TSP performance under a specific traffic condition. As concluded in the previous study, traffic demand is one of the major factors that will significantly influence TSP performance. The following section focuses on a discussion of the overall intersection performance and potential benefits resulting from TSP application.

Transit

Reducing transit bus delay at intersections is the major objective of implementing TSP. Green extension or red truncation will switch some green time from the non-priority approaches to favor the bus so that it can cross the intersection without stopping. As demonstrated in Figure 1, the bus delay can be expressed as the difference between the actual time a bus crosses the intersection approach stop line and the ideal time it should do so, which is expressed as

$$D_B = t_{R,j} - t_A \tag{1}$$

Where:

D_B is the bus delay without signal priority;

$t_{R,j}$ is the Red phase ending time in cycle j, and

t_A is the bus arrival time.

Figure 1

In the case of low traffic demands, traffic turning ratios will not considerably impact TSP performance. However, as traffic volumes increase, the traffic distribution at an intersection will contribute more significantly to overall traffic delay. This can be illustrated using two extreme scenarios where (1) 90% of general traffic demand is in the same direction as the bus, and (2) 10% of general traffic runs with the transit bus (such that 90% of demands are on the cross-streets). In the first scenario, the overall control delay will mainly depend on how the traffic interacts with the transit bus. TSP can grant extra green time to the transit bus and will also give the general traffic additional green time to discharge indirectly shown in Figure 2.

Figure 2

In a scenario of heavy traffic, if the residual queue after a cycle is so long that a bus cannot even reach the check-in point, the bus will have to stay in the queue until it reaches the check-in point to request a TSP priority. In addition, after priority is granted, the bus may still miss the priority time window because of the long queue between the bus and the intersection. In the second scenario, the bus will cross the intersection together with the traffic that accounts for 10% of the total demands. In this case, the transit bus can trigger the TSP request without blocking the residual queue. Thus transit bus delay can be decreased by TSP. Figure 3 can explain this case.

Figure 3

Comparison between the scenario with a high volume and that with a low volume reveals that the transit delay in the high-volume scenario is certainly larger than in the low-volume scenario because of the residual queue. However, in terms of the system delay, it is hard to judge which is larger via the analytic models.

General traffic

The general traffic delay depends on the total traffic volume and the distribution on each approach. If the traffic pattern falls into the first scenario aforementioned, then TSP will be beneficial to the general traffic because it will offer the general traffic additional green time whenever the TSP request is granted. Figure 1 and Figure 2 demonstrate how the TSP affects general traffic. Nonetheless, although the TSP shows positive impact, a large volume on a given approach may still generate congestion and also increase the control delay dramatically, especially if the total demand is high.

Figure 4

Figure 4 shows cumulative vehicle count curves versus timing for both the approach with TSP and non-TSP approach at an isolated intersection. According to the HCM 2010 (8), the control delay at a signalized intersection is composed of uniform delay, incremental delay and initial queue delay. Under low traffic demands, the initial queue delay can be ignored since there are no cycle failures. The vehicle arrival is assumed to be uniform. The free-flow speed and saturation flow rate are assumed constant. The cross-hatched areas represent the delay reduction on the priority approach and delay increment on the non-priority approach due to the extended green on the priority approach. The delay reduction area for the priority approach represents a reduction of total traffic delay, including the bus delay after the TSP is activated. The reduction due to the extended green time for the buses can be expressed as:

$$D_{red} = \frac{(t_3 - R)t_{ex}}{2t_3}(R + t_3 - t_{ex}) \tag{2}$$

Where:

- $\mathrm{D}_{\mathrm{red}}$ is the delay reduction on the priority approach;
- t_3 is queue clearance time after the red phase at priority approach;
- t_{ex} is extended time for priority approach;
- R is red phase duration time; and
- s is saturation flow rate.

The additional delay area for the non-priority approaches represents the total delay increase caused by the extended red on the non-TSP approaches (i.e., corresponding to the extended green on the priority approaches). The additional delay can be expressed by:

$$D_{add} = \frac{st_{ex}}{2}(t_1 + t_2 - t_{ex}) \tag{3}$$

Where,

D_{add} is the delay addition on the non-priority approach;
t_1 is queue clearance time without TSP at non-priority approach;
t_2 is queue clearance time with TSP at non-priority approach;
t_{ex} is extended time for priority approach; and
s is saturation flow rate.

System delay

The system delay change caused by TSP depends on three elements: delay reduction on priority approach, delay addition on non-priority approach and bus delay reduction due to the TSP. To make these three parts comparable, a weight factor is introduced. Let's assume that the bus weight is constant. If the bus delay only accounts for a small part of total delay, the TSP may or may not affect the total system delay. One previous study shows that, if the approaches have re`latively balanced volumes, the TSP will have the least negative impact on the total delay (4). The system delay change can thus be express as:

$$\Delta D_{sys} = (D_{add} - D_{red}) - w_b D_B \tag{4}$$

Where,

ΔD_{sys} is system delay change;
w_b is weighting factor

The increase of delay D_{add} on the non-priority approaches shall be less than the reduced delay D_{red} on the priority approach. In other words, ΔD_{sys} must be equal to or greater than zero.

Simulation-based Case Study

In the case study, VISSIM is used to evaluate the relative effectiveness of several TSP strategies. The ASC/3 control module was selected as the signal control emulator (9). The ASC/3 module in VISSIM is a full-scale control firmware of NEMA TS-2 controllers. Green Extension (GE) and Red Truncation (RT) are the two basic TSP strategies residing in the emulator.

The study includes two parts. We first simulated a standard isolated signalized intersection and ascertained the factors that can impact TSP performance. We also determined those situations in which the TSP does not work well or even has a negative effect. In the second part, we modeled a bus corridor in the City of Edmonton in VISSIM. According to the findings at the isolated intersection and traffic patterns at each intersection, some intersections along the bus corridor may deteriorate the whole system performance after implementing the TSP. The bus travel times were then compared to justify the estimation of TSP performance.

At an isolated Intersection

Setting

The isolated intersection is configured as four approaches with two 3.6-meter-wide lanes on each approach. Each approach is 250 meters long in the model. Left-turn, right-turn and through movements are assumed to share through lanes. A four-phase signal timing is set as the background timing plan. The ASC/3 controller uses coordinated phase split when no priority is served but adjusts the split according to the settings of green extension and red truncation when priority is served.

The aim of this isolated intersection simulation study is to investigate TSP performance response to the intersection traffic demand. In order to find how demand affects TSP performance, several values were selected as different scenarios. Demand distribution is another variable since it would determine the traffic flow for each approach. The values of each variable tested can be found in Table 1.

Table 1

In the simulation, the minimum green time was set to 20 seconds. Yellow time was 3 seconds, all red time was 2 seconds and TSP extend time was 5 seconds. The simulation period is 1 hour with a 400-second warm-up period. Only one bus route, which operates northbound through the intersection with 5 minutes headway, was simulated. There are no bus stops represented in this simulation.

In VISSIM, the controller uses check-in/check-out detectors to detect the transit vehicle. The check-in detector is 80 meters upstream of the northbound intersection stop line. The check-out detector is located close to the exit of the intersection. Each scenario (consisting of a total traffic demand level and demand distribution) was run 100 times, so that the general trends will be appeared.

Results and Analysis

To investigate the relationship between demand and TSP performance, other variables must be held constant, such as bus headway. The results of the simulation study are shown in Table 2.

Table 2

Table 2, the second column displays histograms of the average bus delay. As the demand increases, TSP starts to show the effectiveness. Under very low demand (i.e., 1000vph), there are almost no improvement for average bus delay after TSP is active. On contrary, in a relatively high demand (i.e., 3000vph and 4000vph), TSP will show significant effect for the bus delay. From the two figures, they show TSP not only save the bus delay, but also keep the delay more constant. The total delay and average auto delay shows the same trend respected to increasing demand. TSP will not significantly hurt entire intersection performance, although the variance get larger when TSP active under very high demand.

From the above, it can be conclude that TSP will little influence the entire system when major and minor equally share the demand. As for bus delay, as the demand increasing, transit will obtain more benefit from TSP.

Table 3

In order to find the relationship between the demand distribution and TSP performance for one intersection, total demand need be fixed first. As the aforementioned analysis, the TSP starts to show a decrease of the bus delay when the demand is high. Thus, in this section, the total demand is constant as 3,000 vph. The demand split variable and the results is shown in the Table 3. When the main street (bus route) has more traffic, the TSP has almost no improvement and there is no impact to both bus and general traffic (this is illustrated by the fact that the total, bus, and auto mean delays appear to be similar). When the major street and cross street equally share the total demand, the TSP begins to benefit the transit bus – this is illustrated by the fact that bus delay histogram is shifted left. As the figure shows, under this situation, the TSP will minimize the bus travel time. As the cross street has more and more traffic, the TSP will reduce more bus delay. However, at the same time, the system performance starts deteriorating. As the figures of last two rows show, the system total delay and the general average delay are significantly increased due to the TSP. The delay increment is about 50% more than the non-TSP strategy. Under this condition, although the TSP can still reduce the bus delay, it will create more delay to the general traffic.

From the above analysis, two conditions will ensure TSP performs well. One is the total traffic demand need be a relatively higher level. The demand depends on the geometry and physical conditions of intersections. According to the findings at the isolated intersection, a demand around 3,000vph will be appropriate to achieve benefits out of TSP. The other is that major street and cross-street need evenly share the total demand. Only evenly sharing can guarantee the TSP saving the bus delay without increasing the other delay.

Corridor Study

The main objective of this task is to evaluate TSP performance along a corridor. Several scenarios were tested through simulation. Firstly, the performances of non-TSP and TSP scenarios were compared, and the overall performance improvements after the TSP were evaluated. Secondly, the performances of TSP implemented in fixed-coordinated and actuated corridors were compared. Lastly, the system performance was tested using different TSP implementation schemes. As explained above, the TSP operation, in some situations, may have a negative effect on intersections. For the whole network system, if all the intersections are implemented TSP, it cost more budgets and also the system may not be optimized. Testing different TSP implementation schemes can determine the optimal solution for minimizing both system and transit delay and save some expense at the same time.

Setting

In the corridor study, a bus corridor in Edmonton was modeled in VISSIM. The corridor is from the Millgate Transit Centre north to the Low Level Bridge. The total distance is 7.4 kilometers.

The network is shown in Figure 5. Eight signalized intersections are included (as identified in the figure) as well as several unsignalized intersection.

We considered two peak periods in simulation. The morning peak is from 7:00AM to 9:00AM and the evening peak is from 4:00PM to 6:00PM. The No.8 bus line is along the whole corridor and a normal operation line. The bus frequency was determined accordance to the schedule available online.

Figure 5

Results and Analysis

The study considers two scenarios and examines how the TSP works in each scenario. In the fixed-coordinated scenario, all intersections are coordinated and use the optimal plan controlled by RBC whereas the actuated control is realized by the ASC/3 controller. All the optimal signal timing plans are obtained using Synchro 7 software (10).

Figure 4

Figure 4 lists the results of the corridor study, including the average bus delay and travel times for both directions during two study periods. The simulation ran 10 times and records results for each run.

It can be observed that the actuated control may create less bus delay and travel time than fixed control while the standard deviation is also probably larger, meaning that actuated control is more flexible than the fixed control. Furthermore, the results show that TSP can reduce bus delay and travel time. Specifically, the TSP may save about 3%-10% of transit travel time and up to 30% delay under the fixed coordination strategy. Under the actuated control strategy, the bus travel time and delay can be reduced by approximately 2.1% and 4.4%, respectively. The TSP under the actuated control thus does not work well relatively. One reason for this difference is that the actuated control strategy benefits all transit on the corridor. As buses operate on the main street where there has a higher volume, the actuated control strategy will give more green time to them along with the other traffic.

There are still some cases in which TSP did not show any advantage to the transit. For instance, in actuated control during the AM peak, the travel time on the northbound lanes did not reduce after TSP was active. This problem may result from other factors that we do not consider.

According to the previous findings, there are two intersections are not suitable for TSP: the 86th Street at the 51th Avenue and the 83rd Street at 82nd Avenue. According to the analysis of the isolated intersection above, it is considered that the TSP may or may not negatively impact the system while also offering little benefit for the buses. We further evaluated what the results would be if the TSP was turned off at these two intersections.

Actuated signal control was selected in this test. Other intersections always let TSP on since there is no doubt that TSP will provide benefits when it is implemented at those intersections. The study tested what the performance was when TSP at each of these two intersections is on or off. The study period focused on the AM peak. The different TSP implementation schemes are defined in Table 5.

Table 5

The total system delay and transit travel time are recorded from the simulation. As shown in Table 5, when the two intersections enable TSP, the total system delay will be larger than when TSP is turned off at one of these intersections. However, the bus travel time will be the minimum when all intersections enable TSP. Thus there is a trade-off between a minimized total system delay and bus travel time. One appropriate solution may be just to turn off the TSP for one of the selected intersections.

CONCLUSION

In this paper, we analyzed the TSP performance and its potential impacts on the general traffic at isolated intersections and corridors. From the results and analysis, some conclusions can be drawn:

1. Traffic demand is a major influential factor for TSP performance. In the low demand scenario, TSP does not perform well in reducing the bus delay. However, in a high demand scenario, the TSP is likely to reduce more bus delay. As the demand keeps increasing, TSP starts to hurt the system performance.
2. Demand distribution is another factor that can affect TSP performance. Generally, even demand distribution promises a good situation for TSP to reduce bus delay without impacting other traffic.
3. The TSP benefits to buses depend on whether there is a queue on the same approach or not. Once the queue is built up, TSP may lose its effectiveness because the residual queue may hinder the activation of TSP.
4. TSP will be less effectiveness when actuated signal control has been used because actuated signal control has better performance than pre-timed signal control.
5. TSP can save the bus travel time along corridors. Whether the signal is coordinated will not affect the TSP performance. The delay saving depends on the specific corridor condition. In this case study, up to 30% bus delay will be saved by TSP on the bus corridor in Edmonton.

ACKNOWLEDGEMENT

This research work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada. The data used in this paper was from assumption, rather than the practical data from the field. The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the City of Edmonton. This paper does not constitute a standard, specification, or regulation.

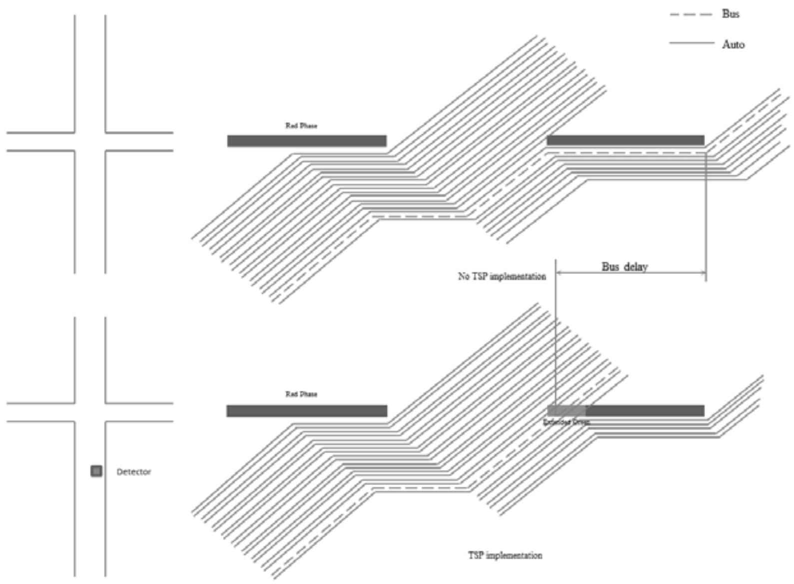


Figure 1 Time space diagram for green extension TSP intersection

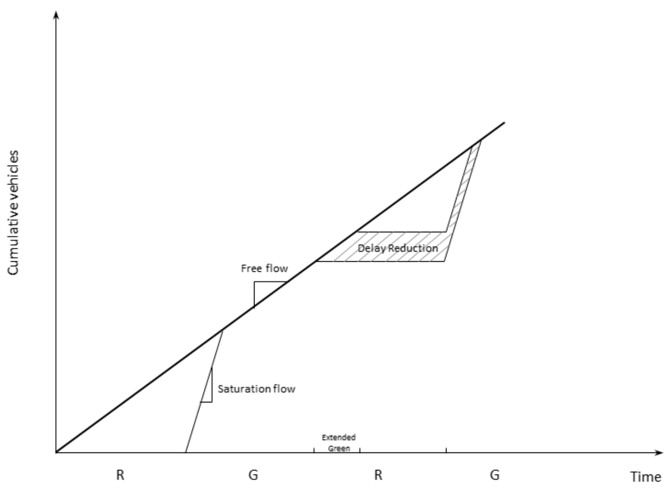


Figure 2 Cumulative vehicles versus time in green extension TSP intersection

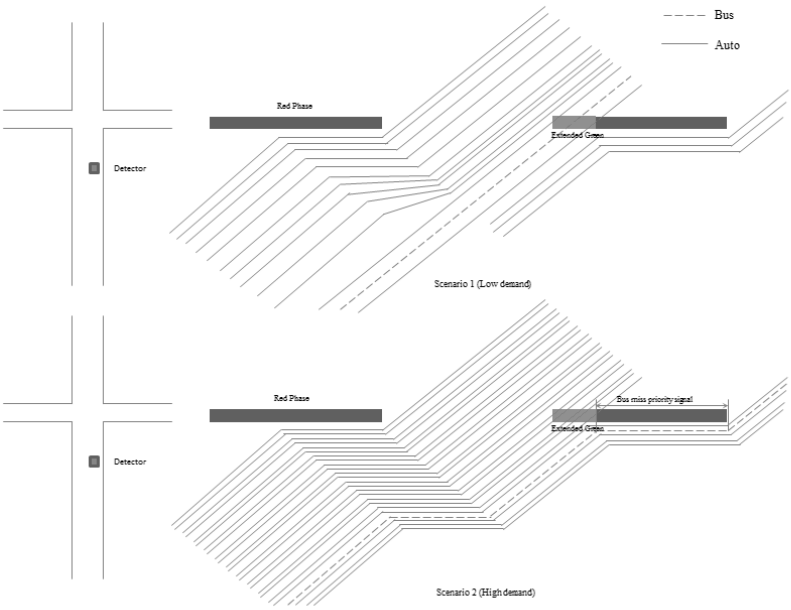


Figure 3 Queue impact in extension TSP intersection

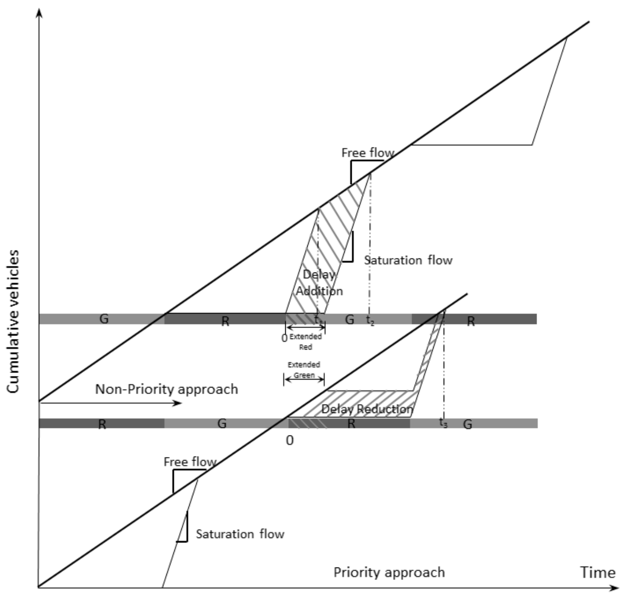


Figure 4 Cumulative vehicles versus time in conflict approaches

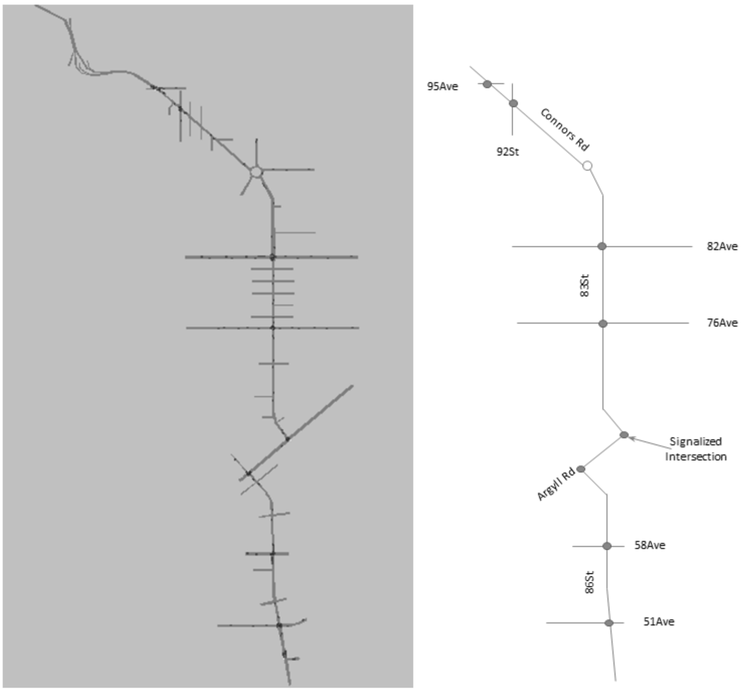


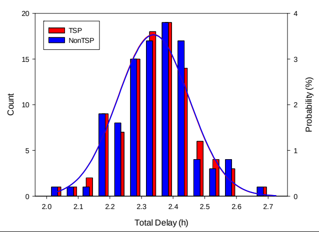
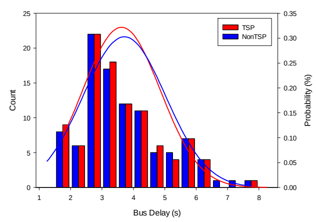
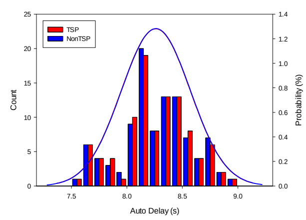
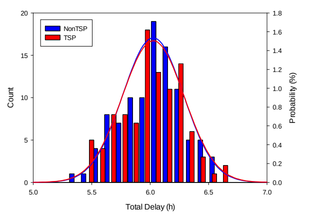
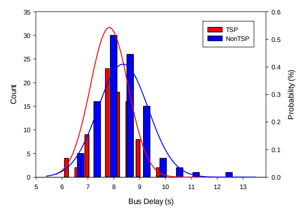
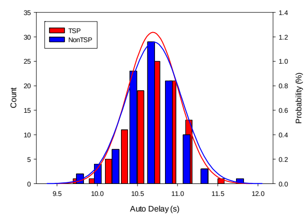
Figure 5 Simulation corridor in southeast Edmonton

Table 1 Simulation case variables

Total Traffic Demand (vph)	Demand Distribution (NS*/WE)
1000, 2000, 3000, 4000	0.9/0.1, 0.7/0.3, 0.5/0.5, 0.3/0.7, 0.1/0.9

* Bus operating approach

Table 2 Results of the Relationship between total demand and TSP performance for isolated intersection simulation, with demand split set at 0.5/0.5

Total Demand (vph)	Total Delay (h)	Bus Delay (s)	Auto Delay (s)
1000			
2000			

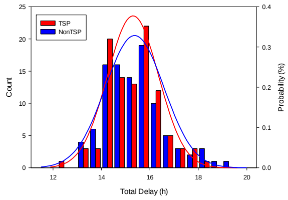
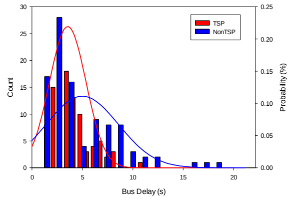
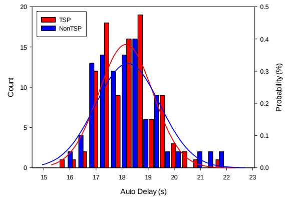
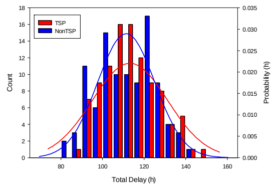
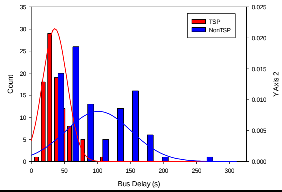
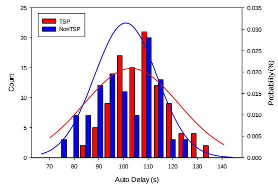
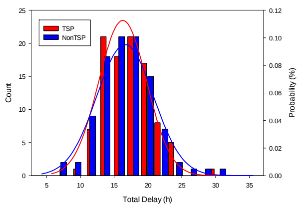
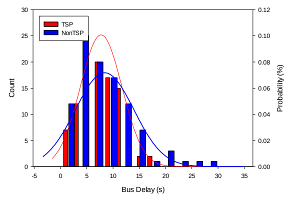
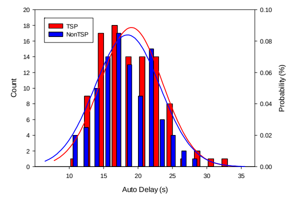
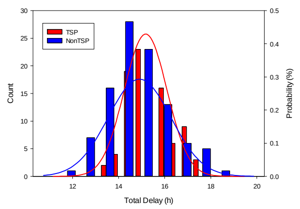
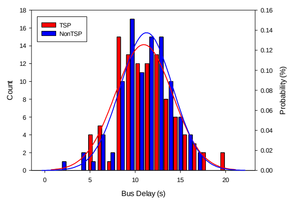
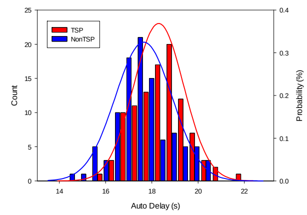
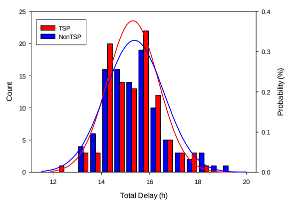
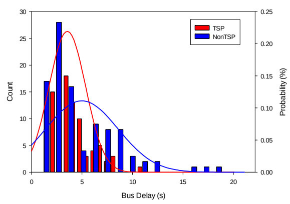
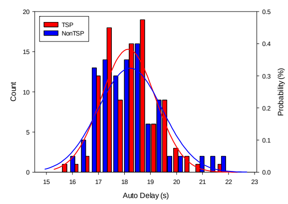
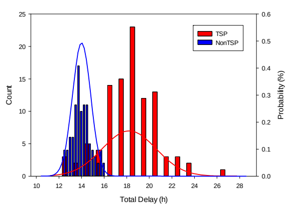
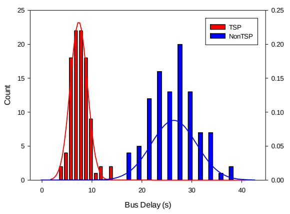
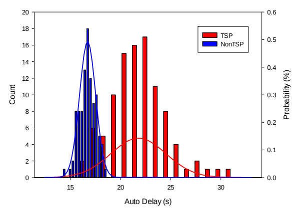
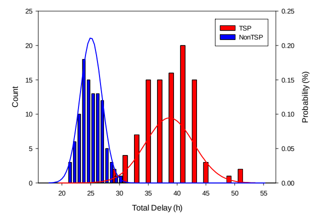
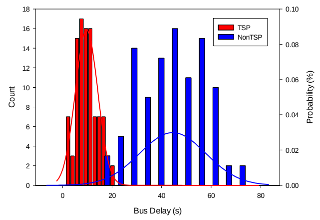
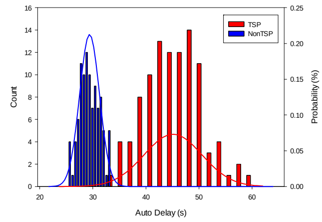
3000			
4000			

Table 3 Relationship between demand distribution and TSP performance for isolated intersection, under total demand 3000vph

Demand Split NS*/WE	Total Delay (h)	Bus Delay (s)	Auto Delay (s)
0.9/0.1			
0.7/0.3			
0.5/0.5			
0.3/0.7			

0.1/0.9			

* Bus operating approach

Table 4 Bus Corridor Simulation results

Control Type	**TSP Usage**	**Period**	**Average Bus Delay (s)**		**Average Bus Travel Time (s)**	
			Northbound	Southbound	Northbound	Southbound
Fixed	No TSP	AM	435.4(24.6)	287.1(17.3)	1834.2(41.5)	1778.3(26.4)
		PM	240.9(9.4)	491.8(54.6)	1637.9(33.8)	1903.8(58.7)
	TSP	AM	383.1(41.3)	238.7(15.2)	1802.0(33.3)	1604.3(28.8)
		PM	199.6(11.2)	438.8(34.1)	1596.2(32.2)	1843.9(39.6)
Actuated	No TSP	AM	323.3(30.8)	294.7(15.5)	1187.5(31.9)	1177.3(17.2)
		PM	392.5(89.2)	444.7(42.1)	1294.3(85.1)	1333.2(45.4)
	TSP	AM	330.3(38.2)	290.0(11.4)	1194.0(43.8)	1170.9(30.7)
		PM	369.5(60.0)	389.8(49.3)	1252.3(64.3)	1273.2(46.1)

Table 5 Simulation results of different TSP implement schemes

TSP implement scheme		**Total System Delay(h)**	**Bus Travel Time(s)**	
86st@51ave	83st@82ave		Northbound	Southbound
Enable	Enable	630.9(35.61)	1194.0(32.2)	1170.9(30.7)
Disable	Enable	602.2(32.58)	1224.8(36.4)	1209.1(59.3)
Enable	Disable	624.5(57.09)	1202.4(35.0)	1173.7(66.5)
Disable	Disable	631.9(43.25)	1229.6(34.7)	1178.6(62.9)

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