

Impact of Cycle Recovery Algorithms on the Performance of Red Truncation Transit Signal Priority

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ABSTRACT

Transit Signal Priority (TSP) is an operational strategy that is capable of enhancing traditional transit services by facilitating transit vehicle movements in the prioritized direction. A wide variety of different TSP strategies have been proposed; however, the majority of TSP applications use a Red Truncation (RT) and/or a Green Extension (GE) strategy. A considerable amount of research has been directed to evaluate TSP operational capabilities for various traffic and control conditions.

The results of this research suggest that there is widespread agreement among practitioners and researchers that GE is superior to RT as a TSP strategy when evaluated on the basis of delay impacts. The inferiority of the RT strategy appears to be a result of inefficiencies in the recovery algorithm. This paper examines the performance of the RT TSP strategy for different cycle recovery algorithms. The results suggest that the typical practice of implementing RT with out giving compensation to the non prioritized approach considerably undermines the potential benefits of RT. Consequently, an alternative cycle recovery algorithm is proposed and evaluated.

The findings suggest that the magnitude of cross street vehicular delay is greatly influenced by the cycle recovery algorithm. Even a relatively naïve compensating cycle recovery algorithm was able to achieve on average a 93% reduction in cross street vehicle delays as compared to a no compensation RT cycle recovery algorithm. Moreover, the strategic use of RT with compensation substantially reduces the existing deficit in the performance of RT TSP as compared to GE.

INTRODUCTION

Transit Signal Priority (TSP) is an operational strategy that is capable of enhancing traditional transit services by facilitating transit vehicle movement in the prioritized direction and reducing the mean and variance of transit vehicle delay. TSP can be implemented by either a passive or active mode. Passive TSP consists of implementing a signal timing plan that favours the prioritized approach (i.e. by increasing the green interval duration for the prioritized approach or by designing coordination on the basis of bus travel times). Active TSP consists of altering signal timings in real time when individual buses are detected to arrive on the prioritized approach. A range of active TSP strategies have been developed and implemented, including bus activated exclusive phases, phase skipping and phase rotation, but the most commonly used strategies for buses operating in mixed flow are: Red Truncation (RT) (also called “Early Green” and “Extended green upon call”) and/or Green Extension (GE) (1). We refer in this paper to these two strategies individually as Red Truncation and Green Extension, and collectively as the 2E’s strategies.

As illustrated in Figure 1, RT consists of giving advance green to the prioritized approach by terminating the competing (non prioritized approach) green earlier than normal. GE consists of extending the green time on the prioritized approach beyond its normal termination time to permit a bus on the prioritized approach to clear the intersection. The 2E’s strategies result in the temporary re-allocation of green time from the non-prioritized approach to the prioritized approach in order to facilitate the movement of the transit vehicle through the intersection. Typically the non-prioritized approach is not compensated in subsequent cycles for this lost green time (2, 3).

Though 2E’s are the most commonly used active TSP strategies, evaluation studies published in the literature appear to suggest that GE is superior to RT in terms of the resulting impact on transit vehicle delay (2). In this paper we (i) Demonstrate that the poor performance of RT relative to GE primarily is caused by the cycle recovery algorithms used; (ii) Propose an alternative RT cycle recovery algorithm; and (iii) Evaluate its performance using simulation.

The remaining sections of this paper address the following topics: (i) Relevant findings from previous research; (ii) The proposed cycle recovery algorithm; (iii) Evaluation methodology; (iv) Findings and conclusions.

LITERATURE REVIEW

The impact of granting signal priority does not always end when the vehicle for which priority is granted, passes through the intersection but may persist for several cycles. Traffic signal pre-emption, which is often implemented for emergency vehicles only, typically causes more severe disruptions to the signal timings than does transit signal priority. After a pre-emption call, a recovery operation is required to transition back to normal signal operation. The pre-emption recovery algorithm may compensate phases that were truncated or skipped during the event or adjust offsets in order to restore coordination along the corridor (4). Given the severity of the impact that pre-emption has on signal timings and corridor performance, and the complexity of developing and implementing appropriate recovery algorithms, pre-emption is rarely used as a means of providing priority for transit vehicles. Furthermore, compensating recovery algorithms appear to be rarely used for transit signal priority applications.

There have been a large number of studies conducted to evaluate the impact of TSP on bus delays and general purpose vehicles on the prioritized and non-prioritized approaches (2,5,6). These studies have all indicated that GE is more effective than RT as a TSP strategy. The effectiveness of GE is in not requiring additional clearance intervals and yet allowing transit vehicles to be served with significant reduction in delay compared with RT strategy (6).

The TSP evaluation studies reported in the literature have modelled a Red Truncation strategy that terminates the competing approach green time after satisfying minimum green time, amber, and all red intervals of all the intermediate phases in the phase sequence (Figure 1). The green time on the prioritized approach is extended till it coincides with its normal end point (2) implying that the cycle recovery algorithm does not compensate the cross street for the reduced green interval. The only consideration given to compensating the cross street has been in limiting the number of TSP calls for either n number of cycles or for a specified duration after the TSP call has been granted (2,5).

Using this approach RT tends to result in a negative impact on the general traffic. For example Dion et al (2) found that RT with a no compensation cycle recovery algorithm resulted in increased person travel time and delays.

One cause for this negative net impact on travel time and delay is the disproportionately larger delay caused to cross street traffic. When priority is requested, the cross street green interval is terminated prematurely so as to provide green to the prioritized direction. This results in a reduction of the green

time provided to the cross street, increasing the volume to capacity ratio for that cycle, and also interrupts signal coordination on the both main and cross streets.

This issue is further aggravated at cross street locations operating at high volume to capacity ratios. These cross streets have relatively little spare green time under normal conditions. Any reduction to the green time due to a TSP priority call can cause over saturation. Skabardonis (7) identified this situation as a condition under which TSP is likely to result in net disbenefits (i.e. an increase in person delay). Consequently, Skabardonis proposed that TSP should be granted only if there is sufficient spare green time in a signal cycle. This step ensures that signal priority does not result in over saturated movements at the signalized intersection or loss of signal coordination. The spare green time was computed as:

$$g_{sp} = \sum_{i=1}^{N_{ph}} g_i (1 - X_i) \quad (1)$$

Where:

- C = cycle length (seconds),
- g_{sp} = spare green time (seconds),
- g_i = green time for phase i (seconds),
- N_{ph} = total number of phases in a cycle.
- X_i = degree of saturation of the critical link in phase i . $X_i = \frac{\lambda_i}{\mu_i \frac{g_i}{C}}$,
- λ_i = average arrival rate for phase i (vehicles/second),
- μ_i = average service rate (saturation flow rate) for phase i (vehicles/second),

However there is no indication on the magnitude or percentage of g_{sp} required before TSP is warranted (i.e. before TSP is expected to provide net reductions in delay). Furthermore, in their evaluations, Skabardonis et al., found that granting TSP based on spare green time produced excessive queues on several side streets, and it appeared to discharge buses and other vehicles from the front of one queue at the upstream intersection only to deliver them to the back of a queue at the next downstream intersection. From these results it appears that this method is only helpful for identifying locations at which the installation of TSP, operating with a non compensation recovery algorithm, would not be beneficial. The method is not directly applicable to TSP strategies that include a compensation cycle recovery algorithm and it does not identify locations at which TSP is expected to be beneficial nor can it estimate the magnitude of the benefits.

Sunkari et al. (8) presented a modelling approach, in which a simple evaluation model was developed using the delay equation from the 1985 Highway Capacity Manual. However, according to Liu et al. (3), this method was oversimplified and did not lead to practical applications. In a recent publication Kevin et al. (9) developed and evaluated “intelligent bus priority” in which phase extension, phase insertion, and early return strategies could be implemented without causing the controller to drop from coordination. The results of simulation studies suggest that the proposed intelligent bus priority could be used at moderate traffic levels (up to volume-to-capacity levels of 0.9 or less) without significantly affecting cross street delays.

Several evaluation approaches are available by which to examine the impact of cycle recovery algorithm on TSP performance, including;

- Field measurements
- Analytical expressions for quantifying delay
- Micro-simulation

There are several challenges with conducting an empirical study using field data, including measuring intersection delays and observing a sufficiently broad range of conditions (i.e. v/c, bus arrival times, and signal timings) while controlling for external factors such as weather and geometry.

The use of analytical expressions is attractive as it provides an objective and verifiable means of evaluating the impact of the recovery algorithms for a wide range of conditions. However, the development of a closed form analytical expression usually requires simplifying assumptions about the system (including distribution of vehicle arrivals) and these assumptions may limit the applicability of the results to field conditions.

Micro-simulation models are able to represent a wide range of conditions that are encountered in the field (e.g. signal timings, vehicle arrival patterns, intersection geometries, transit vehicle arrival times, and TSP strategies). However, running the simulation model for a wide range of conditions is typically resource intensive.

In this study, we have elected to use micro simulation to carry out the evaluation of the influence of cycle recover algorithms on the performance of red truncation TSP.

CYCLE RECOVERY ALGORITHMS

No Compensation Cycle Recovery Algorithm

The standard RT cycle recovery algorithm terminates the cross street green interval and does not compensate the cross street green interval in subsequent cycles. Figure 2 shows the impact on cross street delay of implementing RT with a no compensation recovery algorithm and assuming deterministic arrivals and service times. Furthermore it is assumed that the approach is under saturated when operating without TSP. The operation of the signal with no TSP is also shown. Once the bus is detected on the prioritized street the controller terminates the cross street green interval (ensuring minimum green time and other constraints are satisfied). Consequently, the green interval for the prioritized approach begins earlier than it would have without TSP and extends the end point of the green until it coincides with its normal point in the cycle. At high volume to capacity ratios, the reduction in the cross street green interval duration may result in temporary over saturation (as illustrated in Figure 2) that may take several signal cycles to dissipate. For the conditions assumed in Figure 2, the cross street vehicle delay (i.e. area between the arrival and departure curves) is larger with TSP than without TSP. The magnitude of the increase in delay for the cross street traffic is a function of the amount by which the cross street green is shortened which is a function of the bus arrival time (and signal constraints such as minimum cross street green time). The closer the bus is detected towards the end of the cross street green interval the smaller is the impact of RT operational strategy on the delay.

Proposed Compensation Cycle Recovery Algorithm

To overcome the potentially large penalty experienced by the cross street due to the no compensation cycle recovery algorithm, we propose a recovery algorithm (named Compensation Cycle recovery algorithm). The algorithm compensates the cross street approach for green interval time lost during the cycle in which transit priority is granted, by providing additional time to the cross street green interval in subsequent cycles. The operation of this algorithm is illustrated in Figure 3.

In this approach once a bus is detected on the main street the green time on the cross street is terminated after satisfying the minimum green time and pedestrian walk times. The normal green interval on the main street is served and upon completion the cross street green is started. This cross street green interval is extended by an amount equal to that by which it had been reduced in the earlier cycle. In this way the end of the cross street green interval coincides with its normal point in the cycle. This recovery algorithm is expected to be more efficient for high volume to capacity ratios

on the cross street when there is no or little spare green time available. Nevertheless, it can be observed from Figure 3 that (for the conditions assumed), once again, cross street vehicle delay resulting by TSP is greater than with no TSP. However, comparing Figure 2 and Figure 3 it can be observed that the No compensation cycle recovery algorithm requires substantially more signal cycles to dissipate the queue than does the compensating cycle recovery algorithm. Furthermore, cross street vehicle delay resulting from the RT compensation TSP is smaller than from the No Compensation cycle recovery algorithm.

Naturally, compensation of green to time back to the cross street results in higher delays for the prioritized approach and therefore the evaluation of the performance of the cycle recovery algorithms must consider impacts on both approaches.

SIMULATION EXPERIMENTS

The VISSIM microscopic traffic simulation model (10) was selected within this study to evaluate the performance of two different red truncation cycle recovery algorithms. VISSIM performs traffic simulations by tracking the movement of individual vehicles every $1/10^{\text{th}}$ of a second. The model is composed of various sub-models, each of which defines the logic associated with a specific behavioural attribute, such as car-following, lane selection, routing, vehicle generation, etc.

Model Calibration

Field saturation flow rate (SFR) data were collected over five days at two exclusive through lanes at two signalized intersection approaches in the City of Waterloo, Ontario. The HCM methodology was used to collect the field data and to estimate the corresponding SFR values. The average field SFR ($\bar{X}^f$) was estimated to be 1773 pcphpl, and the Coefficient of Variation of SFR (C_v^f), computed as the standard deviation divided by the mean, was found to be 0.02.

There are several approaches that have been suggested in the literature by researchers and practitioners to calibrate micro simulation models for various specific and general applications (11). Most of the approaches have considered calibration of only a subset of parameters that can be adjusted by the user. For example, the VISSIM model (10) has up to 36 parameters that control the various driver behavioural sub models. The literature (12, 13) indicates that there are two parameters namely; *bx_add* (Additive part of safety distance) and *bx_mult* (Multiplicative part of safety distance) of the Weidemann car following model (14) that have a particularly important

influence on the VISSIM model's outputs. Consequently, these two parameters were calibrated as part of this study.

The calibration method proposed by Dowling et al. (15) was used for this research. A hypothetical 4-legged intersection was created with each approach consisting of an exclusive through lane. All lane widths, grade, curb radii, etc. were considered to be ideal and adequate storage and discharge space was provided. Three fixed time 2 phase signal timing plans were developed. The cycle length consisted of 60 sec, 80 sec and 100 sec. The green time to cycle length ratio (g/C) of each phase was set equal to 0.5. No amber time or all red time was modelled. Consequently, the green interval of each phase represented the effective green interval. The traffic stream consisted of only passenger cars. Cyclists, pedestrians, heavy vehicles, transit vehicles (buses), transit stops and on-street parking were not modelled.

A total of 27 combinations (Table 1) of bx_add , bx_mult and cycle length (C_L) were simulated to predict the average and COV of SFR from VISSIM. Ten replications, each with a different random number seed, were simulated for each combination. Two calibration objective functions were formulated, one that minimizes the mean square error (MSE) between the model estimates and field measurement of the mean SFR (Equation 2) and the other that minimizes the MSE of the COV of SFR (Equation 3).

$$\min MSE_X = \frac{1}{n} \sum_{D_{a,m}} \sum_{C_L} (X_{d,c}^p - \bar{X}^f)^2 \quad (2)$$

$$\min MSE_C = \frac{1}{n} \sum_{D_{a,m}} \sum_{C_L} (C_{v(d,c)}^p - C_v^f)^2 \quad (3)$$

Where:

- MSE_X = mean squared error of the SFR
- MSE_C = mean squared error of the COV of SFR
- $X_{d,c}^p$ = SFR obtained from VISSIM model for d^{th} combination of $D_{a,m}$ and for c^{th} combination of C_L
- $\bar{X}^f$ = Average Field measurement of SFR
- $C_{v(d,c)}^p$ = Coefficient of variation of SFR obtained from VISSIM for d^{th} combination of $D_{a,m}$ and for c^{th} combination of C_L
- C_v^f = Coefficient of variation of SFR from field measurements.

The parameter values that simultaneously satisfied Equations 2 and 3 were found to be $bx_add = 4$ and $bx_mult = 3$ with a regressed equation:

$$X^p = \alpha \pm \beta C_L \quad (4)$$

Where:

$$X^p = \text{Predicted SFR (vphpl)}$$

The regression parameters were found to be $\alpha = 2083$ vph and $\beta = -3.62$ vph / sec ($R^2 = 0.98$, t-value 40.3).

Geometric and Traffic considerations

A hypothetical signalized 4-leg intersection was simulated. Each approach consisted of an exclusive left turn lane, exclusive through lane and a shared through and right turn lane. All lane widths, grade, curb radii, etc. were considered to be ideal with no on-street parking and adequate storage and discharge space. The intersection geometry was developed using links and connectors and modelled in VISSIM. The intersection approach was controlled by a two-phase signal timing plan with a cycle length of 80s; 36s effective green for the main street approach; 36s effective green for the cross street phase; and 4 seconds of inter green between each phase. Right-turn on red was not permitted. Turning movement proportions were determined for each traffic demand scenario to control for the the v/c ratio of each movement (as defined in Table 2). Variations arising from day-to-day variability of the peak hour volume ([16](#)) were not considered. The intersection is assumed to not be coordinated with any upstream or downstream signals.

Transit Operations

A bus route on the main street approach was created. However, in order to avoid the influence of stopped buses on the general traffic, no bus stops were modelled. Rather, the simulation was structured to isolate the influence of TSP operation on delays to buses, Main Street vehicles and cross street vehicles.

The time within the cycle at which the transit vehicle arrives at the intersection has a large influence on the performance of TSP. Many factors influence transit vehicle arrival time, including level of congestion, degree of signal coordination, distance to upstream signalized intersection, number of bus stops between the upstream and current signalized intersection and passenger activity at these stops.

Each simulation modelled 60 minutes of operation in which 12 buses, with an average headway of 5 minutes were modelled. In order to avoid biasing the analysis, we have assumed that bus arrival times during the cycle are random, and therefore buses are equally likely to arrive at any time in the cycle. To achieve this, bus headways were defined as 5 minutes plus an offset of Δ seconds where Δ was selected to ensure bus arrivals at the bus check in detector were spread uniformly throughout the cycle. In these simulations, a 60 second cycle was used, and therefore Δ was equal to 5 seconds (60/12). The resulting bus arrival times with respect to the signal cycle is illustrated in Figure 4.

Modelling TSP within VISSIM

The optional add-on-module Vehicle Actuated Programming (VAP) of VISSIM version 4.3 was used to simulate the phase based transit actuated signal controls. The control logic is created in a text file using a VAP language. During the VISSIM simulation runs, the VAP interprets the control logic commands and creates signal control commands for the VISSIM network. At same time, the transit detector variables reflecting the current traffic situation are retrieved from the simulation and processed in the logic ([10](#)).

The logic codes were created considering Red Truncation and Green Extension recalls for four different cycle recovery algorithms. The main features of the logic are:

- Buses are detected 140 m upstream of the signal stop line
- When a Red Truncation call is received, the green signal is returned to the prioritized approach as quickly as possible.
- Red truncation calls are granted if the bus is detected while traffic on the cross street approach is being served.

Several different TSP response cases can be identified and differentiated on the basis of when the call for the priority is received. These cases are illustrated in Figure 5 and defined mathematically below.

Case	Criteria (Bus Detection Time)	Termination Time
1	$0 < t \leq (g_{\min} + A_A + AR_A)$	$t_r = \max \begin{cases} g_{\min} + A_A + AR_A \\ t + t_T \end{cases}$
2	$t > (g_{\min} + A_A + AR_A)$ and $t \leq \min \begin{cases} A_A + AR_A + g_I - t_T \\ g_I + A_I + AR_I \end{cases}$	$t_r = \max \begin{cases} t \\ t + t_T \end{cases}$
3	$t > \min \begin{cases} A_A + AR_A + g_I + A_I + AR_I - t_d + t_q \\ g_I + A_I + AR_I \end{cases}$ and $t \leq (A_A + AR_A + g_I + A_I + AR_I)$	$t_r = (g_I + A_A + AR_A)$

Where:

- A_A = Amber interval duration for Main Street (seconds)
- AR_A = All red interval duration for Main Street (seconds)
- A_I = Amber interval duration for Cross Street (seconds)
- AR_I = All red interval duration for Cross Street (seconds)
- g_A = Normal green interval duration for Main Street (seconds)
- g_I = Normal green interval duration for Cross Street (seconds)
- $g_{\min}$ = Minimum green time for approach (seconds)
- t = Time call for priority is received by controller (seconds) measured from the start of A_A
- t_d = Time for bus to travel from detector to stop line in the absence of any queues (seconds)
- t_q = Time required to serve existing queue on Main Street at beginning of green (seconds)
- t_r = Time at which cross street green is terminated as a result of TSP (seconds)
- t_T = Bus travel time minus intergreen time and time required to serve queue
 $t_T = t_d - A_I - AR_I - t_q$

The logic was further subject to the following constraints:

- All minimum green times are served for each phase.
- Cycle length is preserved in order to maintain coordination with adjacent intersections.
- No Phase skipping is allowed while a transition is made to and from a TSP phase.

Four signal control strategies were modelled, namely:

1. No TSP (i.e. fixed time with no cycle recovery algorithm)

2. RT TSP with a no compensation cycle recovery algorithm
3. RT TSP with the proposed compensation cycle recovery algorithm
4. GE TSP with a no compensation cycle recovery algorithm

For the simulations conducted within this study the following parameters values were used: Cycle length (C) = 80 seconds, $g_A = g_I = 36$ seconds, $A_A = AR_A = A_I = AR_I = 2$ seconds, $t_d = 14$ seconds and $t_q = 10$ seconds.

For each signal control strategy 12 traffic demand scenarios were developed (Table 3). For each traffic demand scenario and each signal control strategy, 10 simulation runs were conducted to account for the stochastic nature of the traffic simulation model. It should be noted that though this approach is consistent with most other published modelling studies it does not explicitly reflect day-to-day variability of peak hour volumes (1717). For each run the delay and queue statistics were obtained for the Main Street and Cross Street.

Each simulation run consisted of an initial 5 minute warm up period during which data were not recorded, followed by 60 minutes of recording time. An additional 30 minutes were simulated to ensure that all generated vehicles were able to complete their trips and have their travel times included within the recorded statistics.

IMPACT OF RECOVERY ALGORITHM ON PERFORMANCE

The main goal of this study was to quantify the sensitivity of RT TSP performance to the recovery algorithm and to propose and evaluate a recovery algorithm that compensates the cross street for lost green time. The impact of TSP was measured as:

$$P = \frac{(M_{TSP} - M_{NOTSP})}{M_{NOTSP}} \quad (5)$$

Where:

- P = Percent change in performance measure due to selected cycle recovery algorithm
- M_{TSP} = Performance measure with selected cycle recovery algorithm
- M_{NOTSP} = Performance measure without transit signal priority

We examined 3 relevant performance measures: Cross Street mean vehicle delay; Main street mean bus delay; and intersection mean person delay.

Results from the simulation runs in terms of the change in cross street average vehicle delay (computed using Equation 5) are illustrated in Figure 6 for the three TSP strategies. It is evident from Figure 6 that there is considerable variability in the performance of the TSP strategies across the different simulation runs, even within a specific traffic demand scenario. This variability confounds the ability to observe trends within the data. Consequently Figure 7, Figure 9, and Figure 10 illustrate the mean change in performance measure, computed using Equation 6, for the cross street delay, bus delay, and intersection person delay respectively.

$$\bar{P} = \frac{1}{10} \sum_{i=1}^{10} P_i \quad (6)$$

Where:

- $\bar{P}$ = Average percent change in performance measure due to selected cycle recovery algorithm
 P = Percent change in performance measure as computed using Equation 5.

Results from the use of Equations 5 and 6 that are positive imply that the associated TSP strategy has increased delays relative to the no TSP case (i.e. net dis-benefit). Values that are negative imply that the associated TSP strategy has decreased delays (i.e. provided net benefits).

On the basis of these results, we wish to answer the following questions for each performance measure:

1. Is the proposed compensation cycle recovery algorithm statistically superior to the no compensation cycle recovery algorithm for all performance measures?
2. How does the performance of RT TSP strategy (with a no compensation cycle recovery algorithm and with the proposed compensation cycle recovery algorithm) compare with the GE TSP strategy?
3. How TSP performance is influenced by the Main Street and Cross Street v/c ratios?

The answers to above questions are investigated in following sections.

Impact on Cross Street Mean Vehicle Delay

Figure 7 shows the impact of TSP strategy on the cross street mean vehicle delay. As expected, in general, the provision of TSP to buses on the main street increases delays to vehicles on the cross street. The magnitude however, was greatly influenced by the strategy used to provide priority. The RT with No Compensation algorithm caused cross street average vehicle delay to increase from 16%

to 105% and a strong correlation is observed (Figure 8) between cross street v/c ratio and the magnitude of the increase in delay. In contrast, RT with the proposed Compensation cycle recovery algorithm caused cross street average vehicle delay to increase by only 0.4% to 6.3% and was much less sensitive to the cross street v/c ratio. The results represent a reduction in cross street delays of between 87% and 100%.

The results from red truncation were also compared with a standard GE strategy. In this approach the extension is made to the prioritized approach with out giving compensation to the non prioritized approach. The results obtained in this study are in agreement with the common consensus expressed in the literature that red truncation with out compensation results in poorer performance than does the Green extension strategy (2,5). However, the results also show that the performance of red truncation on cross street delay is greatly dependent on the recovery algorithm that has been implemented to compensate the non prioritized approach. The results in Figure 8 show that in terms of cross street vehicle delays, the proposed RT Compensation cycle recovery algorithm performs better even than the green extension TSP strategy.

The above results are not entirely unexpected. Providing compensation to the cross street for green time lost when granting TSP would be expected to reduce cross street vehicle delays, especially when the cross street v/c ratio is large. However, providing compensation is also expected to create additional delays for the main street. Consequently, impacts on the main street must also be considered in the evaluation.

Impact on Bus Delay

The impact of cycle recovery algorithm on the bus delay is depicted in Figure 9. As expected, the simulation results indicate that the provision of transit signal priority is generally beneficial to buses for all recovery algorithms but that the magnitude of the benefit varies substantially between different algorithms and with the traffic demand. Highest reduction in bus delays were observed with a RT with no compensation cycle recovery algorithm. The bus delay reductions were up to 46.5%. As expected bus delays with a RT with compensation cycle recovery algorithm resulted in lower bus reduction than that for RT with No Compensation cycle recovery algorithm. The reduction in bus delays using a RT with compensating cycle recovery algorithm were comparable to GE no compensation cycle recovery algorithm, especially at main street v/c ratio 0.9 and 0.95.

Impact on Intersection Person Delay

Intersection delay (Figure 10) considers impacts of TSP on both cross street and main street simultaneously. General purpose vehicles are assumed to have an average occupancy of 1.1 persons/vehicle. Buses are assumed to have an average occupancy of 20 persons/bus.

The results suggest that RT with Compensation performs better than RT with No Compensation when cross street v/c ratio is relatively large. Furthermore, RT with Compensation appears to be much less sensitive than RT with No Compensation strategy to the level of traffic demands on the main and cross streets.

It is clear from these results that any study that has been carried out using a non compensation RT recovery algorithm and has compared the results with a standard Green extension recovery algorithm can be misleading.

Impact of cycle recovery algorithms on RT TSP performance

The relative performance of the two cycle recovery algorithms was assessed statistically by conducting “two factor with replication” ANOVA tests on the simulation results. The purpose of the ANOVA was to determine whether or not the performance of RT is significantly impacted by traffic demands (i.e. v/c ratio) and/or cycle recovery algorithm. The two factors in each test were: (1) the v/c ratio (12 levels as defined in Table 3), and (2) TSP strategy. Each ANOVA test was conducted at the 95% level of confidence and the significance of the main effects and interaction effects were tested. Two sets of ANOVA tests were conducted for each of the three performance measures. The first set of tests compared the performance of the proposed RT Compensation cycle recovery algorithm with the RT No Compensation recovery algorithm. The second set of tests compared the proposed RT Compensation cycle recovery algorithm with the GE No Compensation algorithm.

Table 4 summarizes the results of the tests. The test results indicate that:

- Consistent with observations made on the basis of Figure 8, traffic demand level (i.e. volume to capacity ratio) has a significant influence on the impact of TSP for all three performance measures.
- The performance of the proposed Compensation cycle recovery algorithm was statistically different from the performance of the No Compensation cycle recovery algorithm when measured in terms of cross street delay and bus delay. There was no evidence to conclude

these two algorithms perform differently when evaluated on the basis of intersection person delay.

- The performance of the proposed Compensation cycle recovery algorithm was statistically different from the performance of the GE algorithm for all three performance measures.

It is possible to determine which TSP strategy maximizes the reduction in intersection person delay by considering the results from all traffic demand levels. However, given the influence that main street and cross street v/c ratio have on TSP performance (as determined from the ANOVA tests), it is appropriate to identify the best TSP strategy for each traffic demand level separately. A paired two sample t-test was used to compare the mean change in intersection person delay for each of the 12 demand levels (tests were conducted at the 95% confidence level implying means are statistically different when the p-value is $\leq 5\%$). Table 5 shows the results for three sets of comparisons (RT No Compensation vs. RT with Compensation; RT No Compensation vs. GE; and RT Compensation vs. GE) for each v/c ratio. From the t-test results it is possible to determine the TSP strategy that is statistically superior (i.e. has greatest reduction in intersection person delay compared with the no TSP case). The GE strategy is statistically superior to the RT No Compensation strategy for six of the 12 v/c ratios. Coincidentally, the GE strategy is statistically superior also to the RT Compensation strategy for six of the 12 v/c ratios. These results seem to support the general consensus expressed in the literature that the GE strategy is superior to the RT strategy. However, further inspection reveals that the superiority of the GE strategy to the two RT strategies is not consistent across the 12 v/c ratios. For example, the GE strategy is superior to the RT Compensation strategy for the first six v/c ratios. However, there is insufficient evidence to conclude that the GE strategy is superior to the RT No Compensation strategy for demands scenarios 1, 4, and 5.

The last column in Table 5 identifies the statistically superior strategy when considering all three strategies simultaneously. Cell entries of “same” indicate that there is not sufficient evidence to conclude that one strategy is statistically superior to the others. The GE strategy is identified as the superior TSP strategy for only three of the 12 v/c ratios examined. These results suggest (a) that the performance superiority of the GE strategy is in large part a result of the lack of a suitable compensation cycle recovery algorithm; and (b) that the implementation of RT with even a relatively naïve compensating cycle recovery algorithm can substantially narrow the performance deficit between RT and GE TSP strategies.

CONCLUSIONS AND RECOMMENDATIONS

In general, the provision of RT TSP for buses on the main street increases delays to vehicles on the cross street. However, the magnitude of this impact on cross street vehicle delay is greatly influenced by the cycle recovery algorithm. A cycle recovery algorithm that provides compensation to the cross street for green time lost as a result of granting TSP can reduce the increase in cross street vehicle delays. Even the relatively naïve compensating cycle recovery algorithm tested in this study achieved an average reduction in the increase of cross street vehicle delays of 93% as compared to a no compensation RT cycle recovery algorithm.

The performance advantages of GE (as measured in terms of intersection person delay) over RT are significantly reduced if RT is implemented with a compensating cycle recovery algorithm under suitable traffic conditions.

It is recommended that a compensation cycle recover algorithm be used with RT TSP implementation when the v/c ratio on the cross street approach is equal to or greater than the v/c ratio on the prioritized approach.

Additional research should focus on quantifying the impacts of vehicle arrival distributions (i.e. effect of coordination and platooning) on GE and RT TSP performance and on developing an analytical tool that can be used to quantify the expected benefits of TSP implementations as a function of TSP strategy, traffic conditions, signal controls, and geometry.

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Table 1: Calibration of VISSIM parameters to achieve desired saturation flow rates

$D_{a,m}$		X^p regression parameters				$\bar{X}^{[2]}$	SFR (X^p)		
							Cycle Length (C_L)		
a	M	α	β	R^2	$t(28)^{[1]}$		60	80	100
3	3	2203.7	-3.44	0.960	-26.1	1928	1997	1929	1860
4	3	2083.2	-3.62	0.983	-40.3	1794	1866	1794	1722
5	3	2020.3	-4.16	0.963	-26.8	1685	1771	1688	1604
3	4	2121.9	-3.33	0.970	-30.0	1856	1922	1856	1789
4	4	2016.7	-3.59	0.982	-39.0	1729	1801	1730	1658
5	4	1914.8	-3.57	0.979	-36.3	1629	1701	1629	1558
3	5	2087.9	-3.65	0.978	-35.7	1796	1869	1796	1723
4	5	2008.5	-4.04	0.971	-30.5	1686	1766	1686	1605
5	5	1881.7	-3.71	0.984	-41.4	1585	1659	1585	1511

Notes: [1] Significance of β tested at 95% confidence level, $t_{0.05,28} = 2.16037$ for two tailed t-test.

[2] $\bar{X}$ is average SFR based on 30 runs resulting from three C_L levels and ten replications n .

Table 2: Turning movement proportion for each traffic demand scenario

v/c	Right	Through	Left
0.1	27%	62%	12%
0.2	27%	63%	10%
0.3	28%	65%	7%
0.4	28%	66%	6%
0.5	29%	67%	4%
0.6	29%	68%	3%
0.7	29%	69%	2%
0.8	29%	69%	2%
0.9	30%	69%	1%
1.0	30%	69%	1%

Table 3: Design of Experiment

Traffic Demand Scenario	Main v/c	Cross v/c	Number of replications	Number of Recovery Algorithm	Total Runs
1	0.7	0.5	10	4	40
2	0.7	0.6	10	4	40
3	0.7	0.7	10	4	40
4	0.8	0.6	10	4	40
5	0.8	0.7	10	4	40
6	0.8	0.8	10	4	40
7	0.9	0.7	10	4	40
8	0.9	0.8	10	4	40
9	0.9	0.9	10	4	40
10	0.95	0.8	10	4	40
11	0.95	0.9	10	4	40
12	0.95	0.95	10	4	40
Grand total					480

Table 4: ANOVA Test Results

Performance Measure	Factor	RT No Compensation vs RT Compensation		RT Compensation vs GE	
		F Value	Outcome	F Value	Outcome
Cross Street Vehicle Delay	v/c ratios	9.9	D	2.1	D
	Recovery Algorithm	214.6	D	22.0	D
	Interaction	9.6	D	1.2	S
Bus Delay	v/c ratios	7.9	D	5.7	D
	Recovery Algorithm	43.1	D	36.6	D
	Interaction	4.5	D	4.6	D
Intersection Person Delay	v/c ratios	4.6	D	1.3	S
	Recovery Algorithm	3.1	S	9.4	D
	Interaction	4.5	D	0.7	S

Note: S = There is no difference in Recovery Algorithm performance

D = There is a significant difference in Recovery Algorithm performance

Table 5: t-test Results

Traffic Demand (v/c)			Average Change in Inter. Person Delay ($\bar{P}$)			t-test Results (p-value)			Best Strategy
#	Main	Cross	RT No Comp.	RT Comp.	GE No Comp.	RT No Comp vs. RT Comp	RT No Comp vs. GE	RT Comp vs. GE	
1	0.7	0.5	0.0%	5.8%	-1.7%	0.02%	22.42%	0.01%	same
2	0.7	0.6	4.2%	5.5%	0.0%	27.72%	1.78%	0.11%	GE
3	0.7	0.7	7.1%	4.7%	1.1%	18.80%	0.56%	0.24%	GE
4	0.8	0.6	-2.7%	3.0%	-3.3%	0.28%	76.71%	0.25%	same
5	0.8	0.7	1.4%	3.6%	-1.3%	25.57%	14.82%	0.17%	same
6	0.8	0.8	17.4%	3.3%	-0.6%	3.77%	1.08%	2.58%	GE
7	0.9	0.7	-7.3%	10.6%	3.6%	1.19%	1.87%	9.10%	RT No Comp.
8	0.9	0.8	5.7%	4.7%	2.0%	89.48%	62.06%	47.01%	same
9	0.9	0.9	27.5%	4.2%	10.2%	4.02%	13.68%	44.20%	same
10	0.95	0.8	-12.0%	3.2%	-6.2%	2.15%	17.28%	8.63%	same
11	0.95	0.9	30.9%	9.2%	3.2%	6.14%	1.13%	21.10%	same
12	0.95	0.95	33.3%	3.9%	3.4%	0.02%	0.74%	94.76%	same

Shaded cells indicate v/c ratios for which GE strategy is better than the comparison strategy.

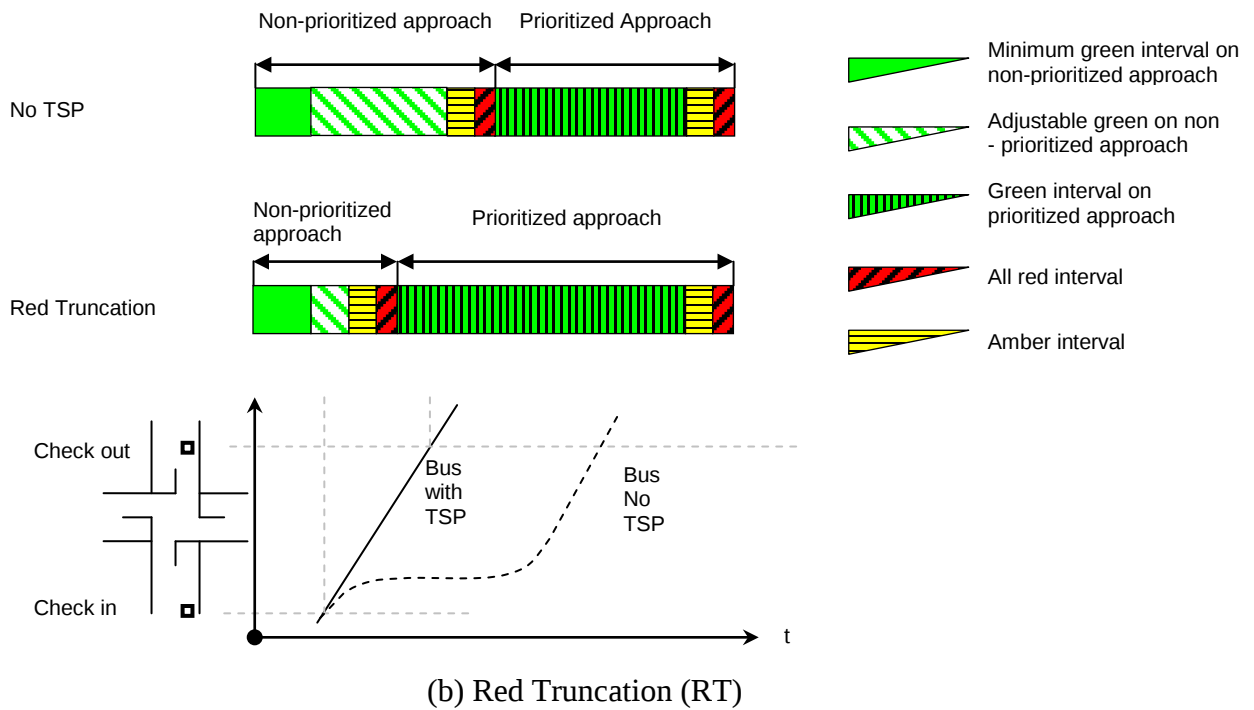
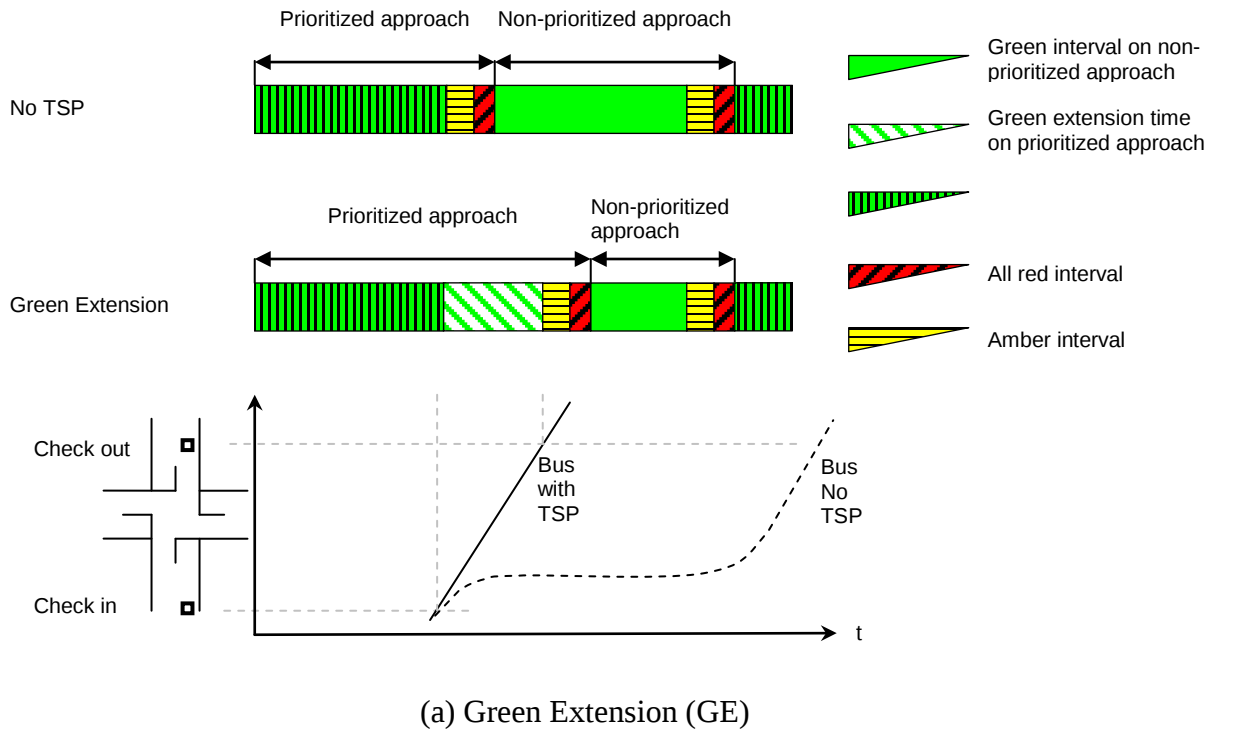


Figure 1: Standard GE and RT TSP No Compensation Cycle Recovery Algorithm.

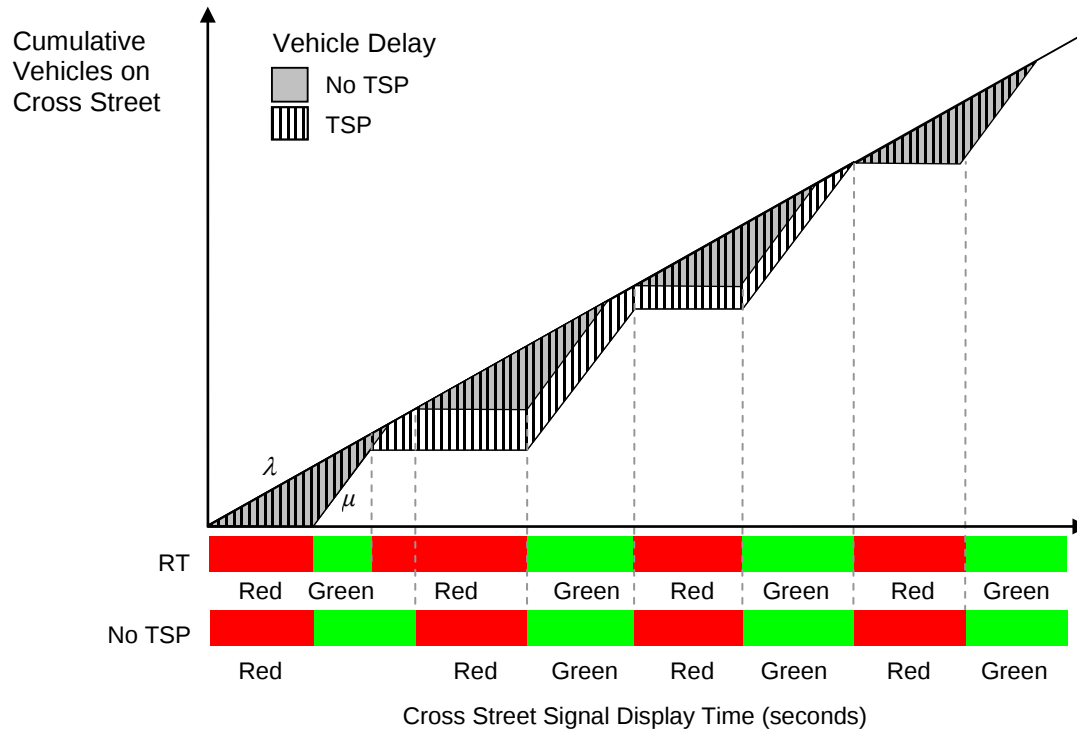


Figure 2: D/D/1 Queuing diagram for the No Compensation RT Cycle Recovery Algorithm.

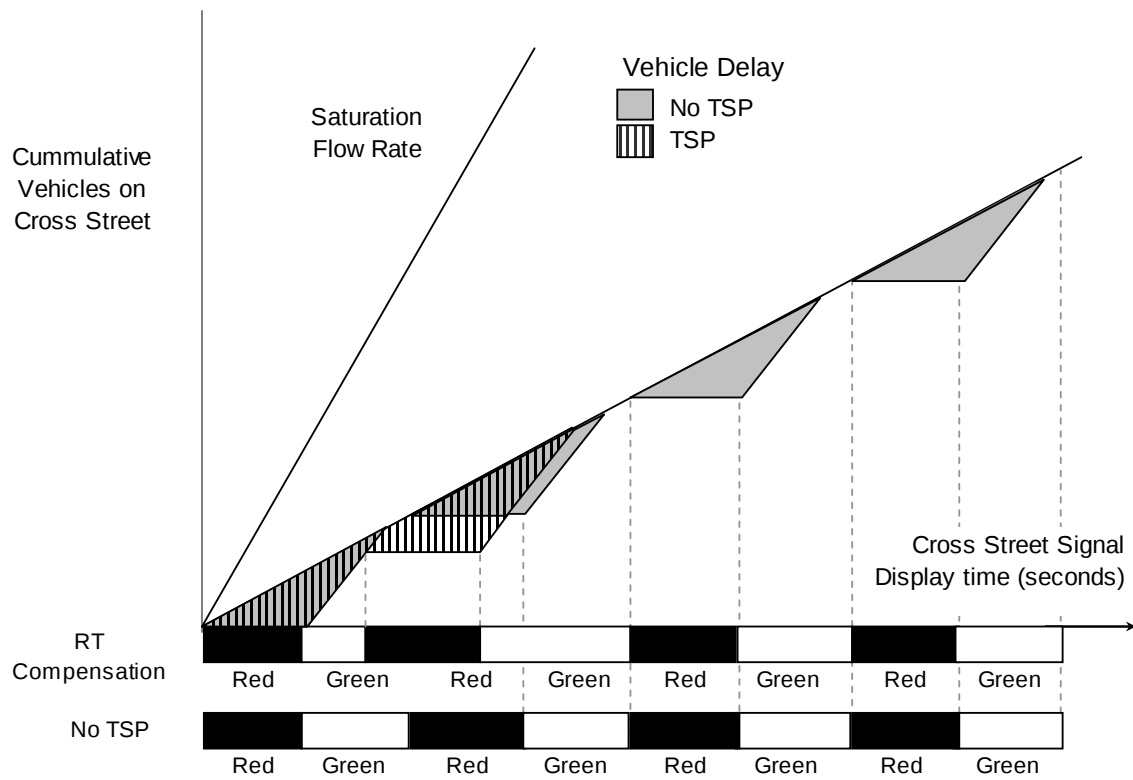


Figure 3: D/D/1 Queuing diagram for the Compensation RT Cycle Recovery Algorithm.

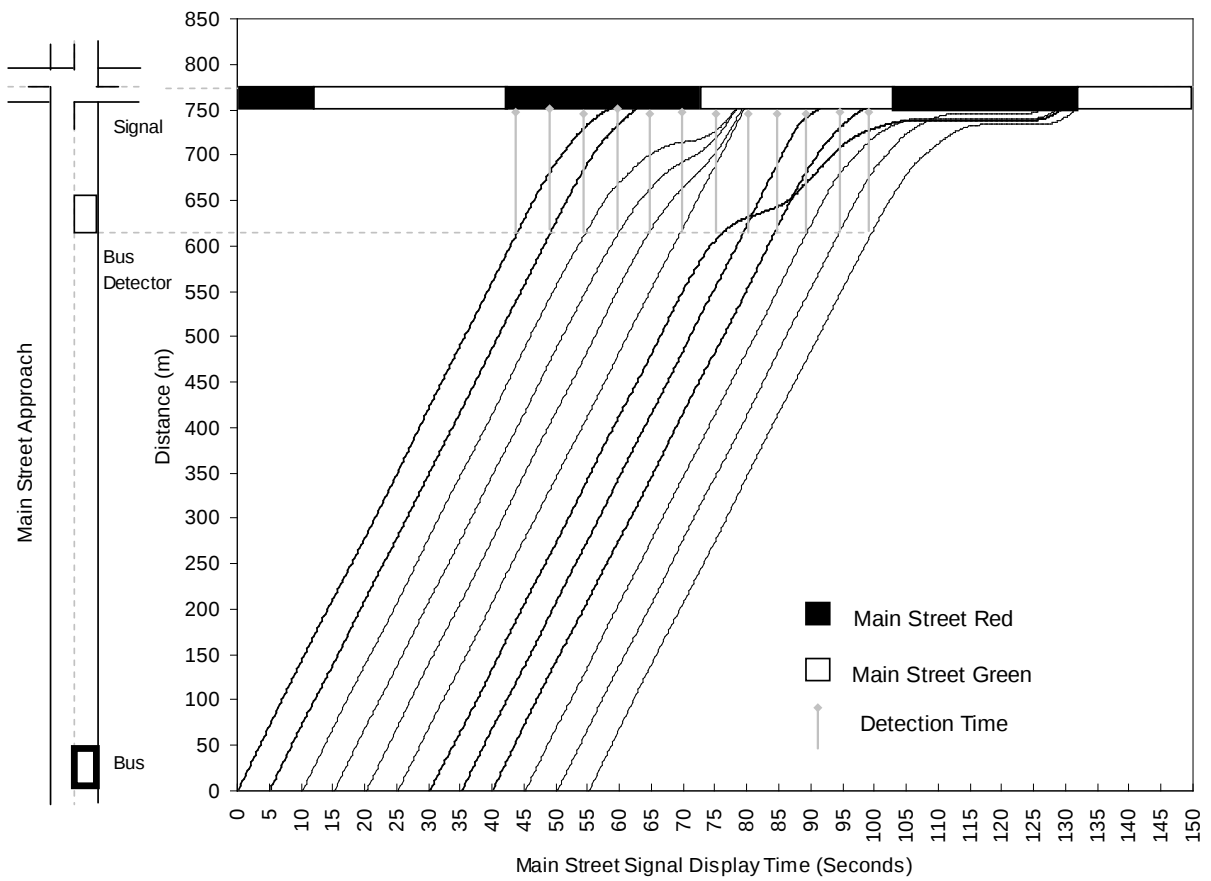


Figure 4: Time Space of Transit Arrival Time Distribution (VISSIM).

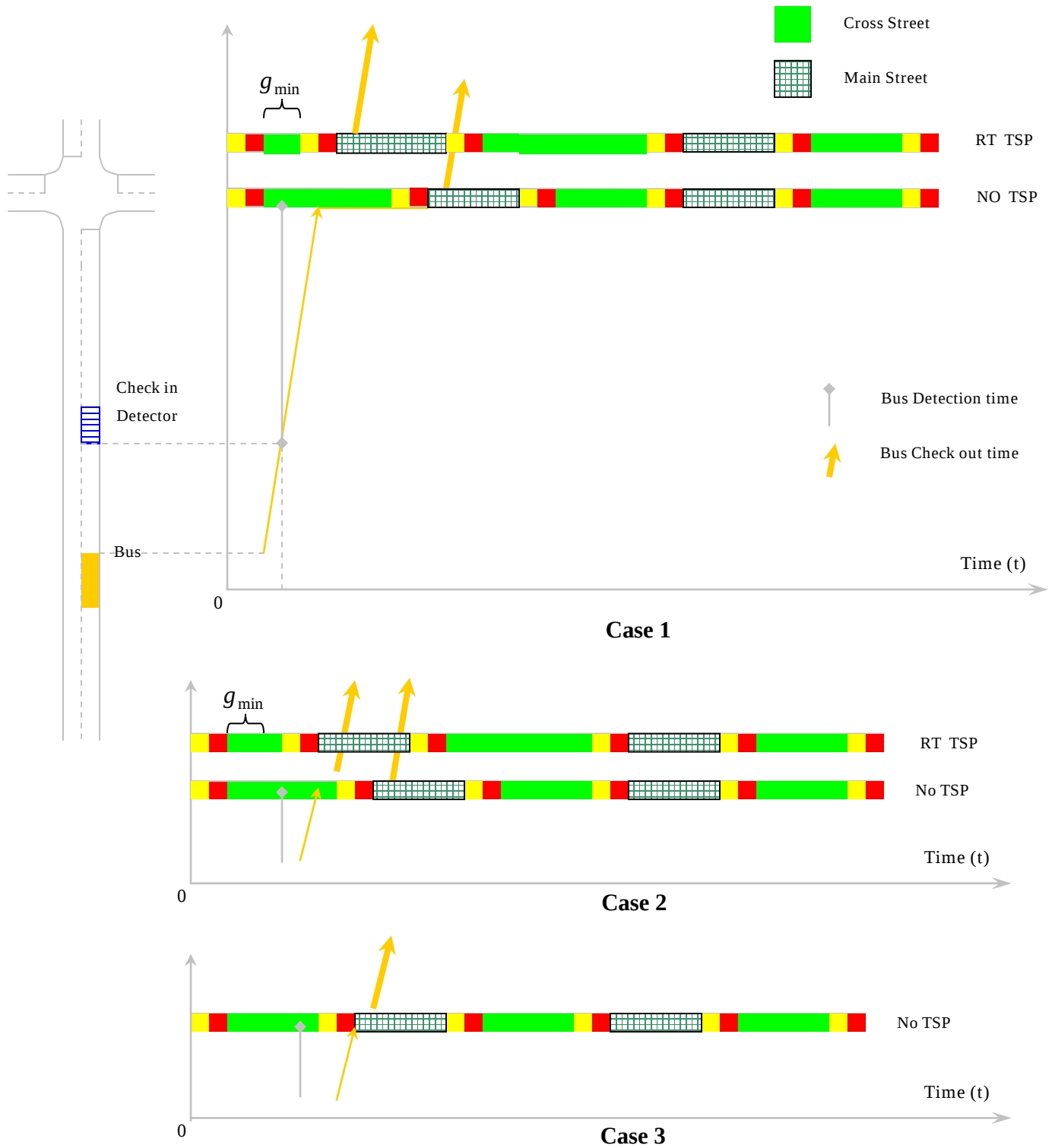


Figure 5: Transit Signal Priority Red Truncation response.

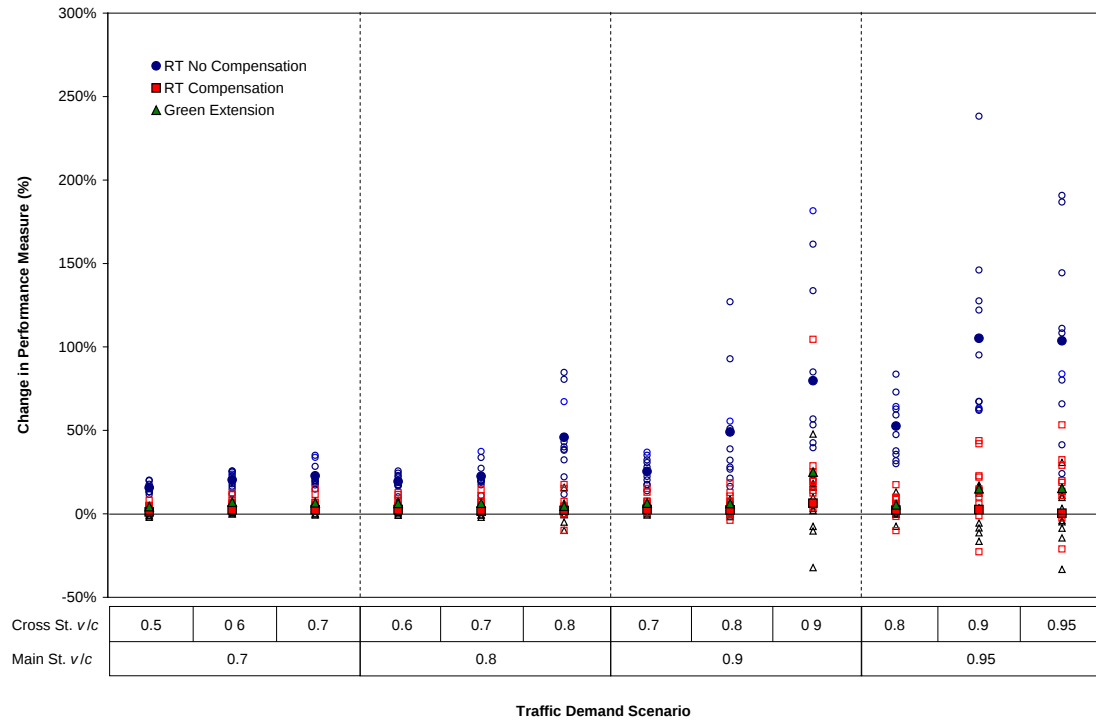


Figure 6: Simulation results (Individual runs and mean values for Cross Street Vehicle Delay).

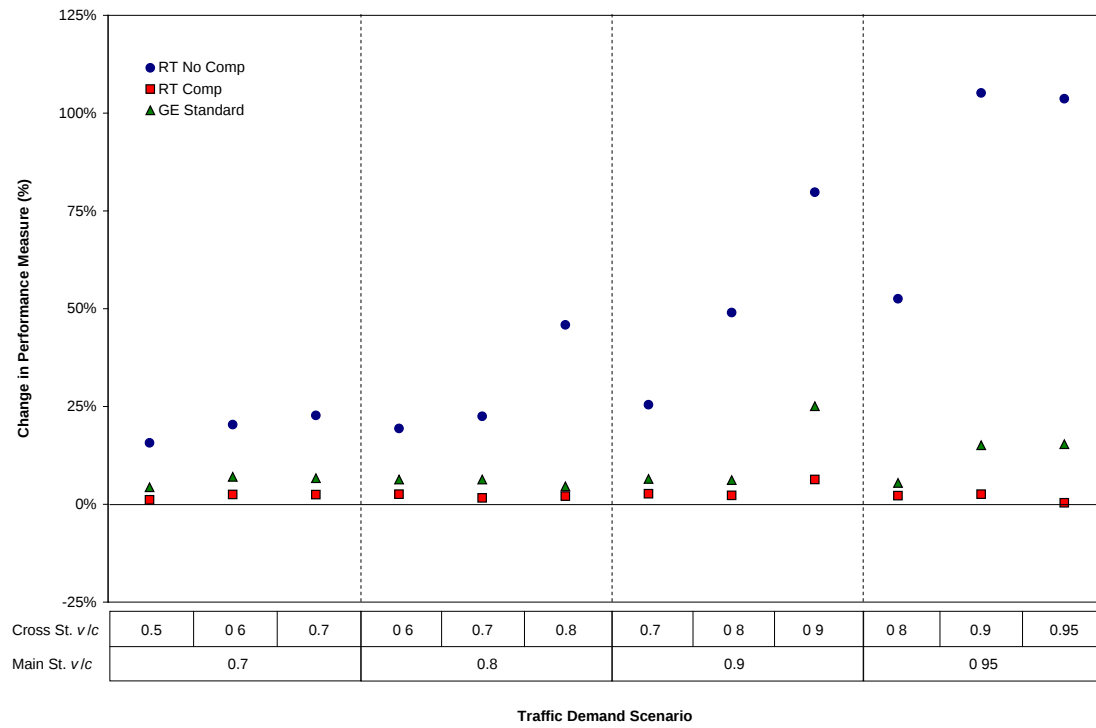


Figure 7: Mean Impact of TSP on Cross Street Mean Vehicular Delay.

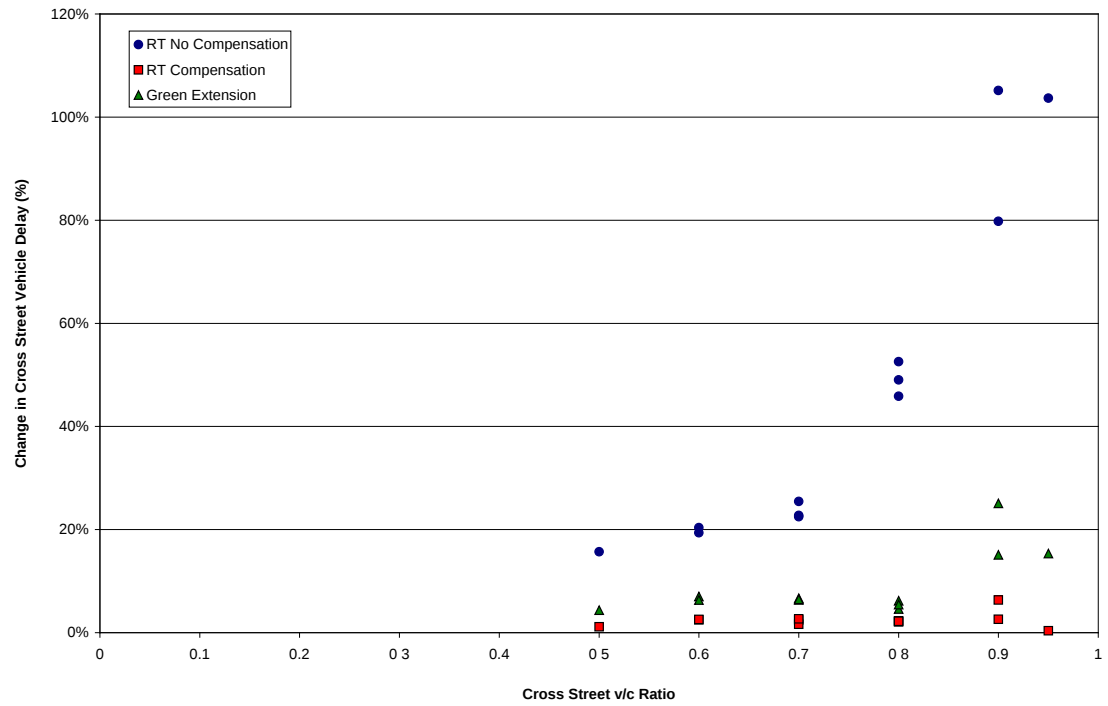


Figure 8: Impact of TSP strategy as a function of Cross Street v/c.

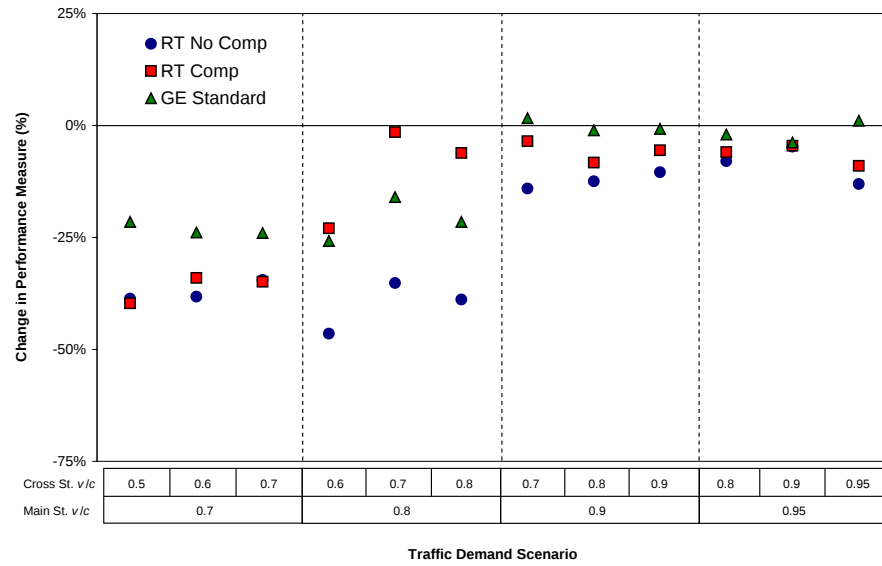


Figure 9: Mean Impact of TSP on Bus Delay.

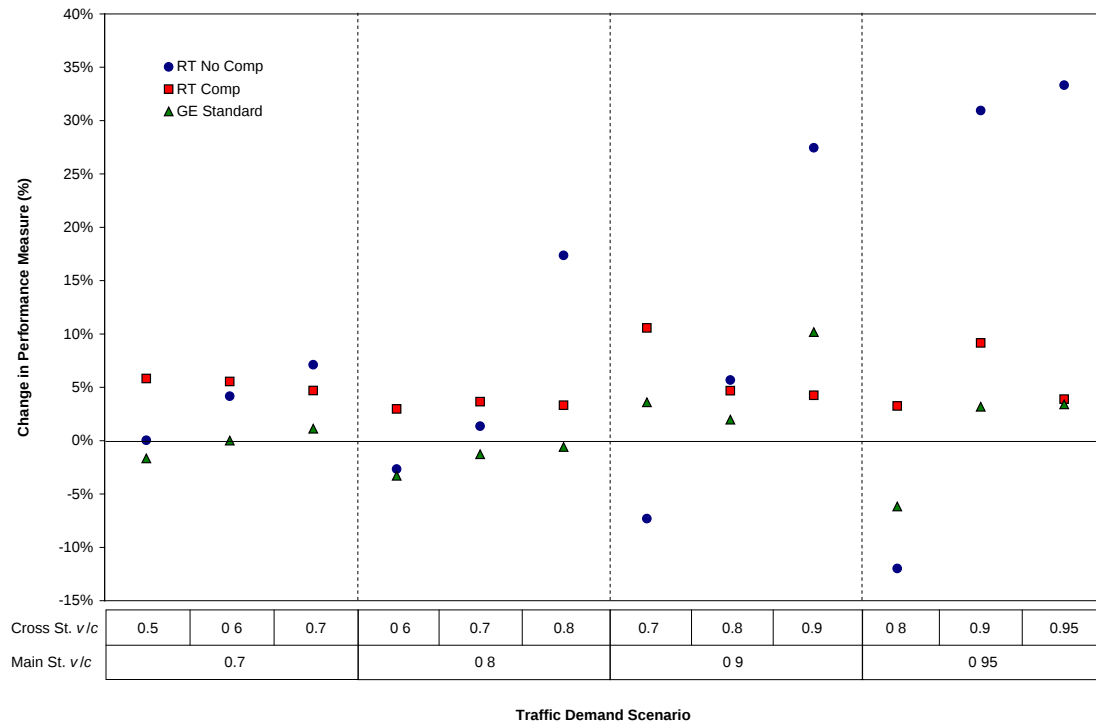


Figure 10: Mean Impact of TSP on Intersection Person Delay.