A COMPREHENSIVE STRATEGY

FOR TRANSIT SIGNAL PRIORITY

by

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B.A.Sc (Civil Engineering), The University of British Columbia, 2000

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Department Of Civil Engineering

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

October 2002

ABSTRACT

Transit Signal Priority (TSP) has been deployed in many cities in the North America and the world as a tool to improve transit competitiveness. A number of previous researches have shown that the impacts and effectiveness of a TSP application would depend largely on its surrounding traffic environment. This research attempts to address this issue further by investigating a number of traffic parameters' influence on the impact and effectiveness of TSP applications.

Transit priority schemes are tested with the 98 B-line rapid transit buses along Granville Street in the City of Vancouver as a case study. VISSIM, a micro-simulation software, is used to simulate the TSP operation on the corridor. An imaginary VISSIM simulation model, named the "NoTAC model", is developed to mimic and evaluate the influence of different traffic parameters on the TSP application. This model is developed to isolate the impact of a studied traffic parameter from other factors that would impact the influence of the studied parameter.

Nine sets of experiments are performed to investigate how each studied traffic parameter influences the impacts and effectiveness of TSP. These traffic parameters include: Granville Street (or bus approach traffic) volume, B-Line bus headway, cross street volume/capacity ratio, left-turn and opposing-through volume, right-turn and pedestrian volume, bus stop and bus check-in detector location, TSP strategy (green extension and red truncation), recovery strategy, and signal coordination. Based on the results from these experiments, generic guidelines and decision rules for TSP application on Granville Street are recommended. In general, it is found that a TSP application would be most effective under a traffic condition that has moderate-to-heavy bus approach volume, little or no turning movement hindering the bus movement, slight-to-moderate cross street v/c ratio, farside bus stop, and signal coordination for traffic running in the peak direction. Most importantly, TSP should be avoided under conditions that would generate significant adverse impacts on the cross streets.

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ACKNOWLEDGEMENTS

Completing this thesis is a major achievement in my 6-year University life! I would like to take this opportunity to acknowledge a few groups of people.

First, I would like to express my gratitude to my thesis supervisor, Dr. Tarek Sayed, for all his teaching and supervision. I would like to thank Dr. Akmal Abdelfatah from the American University of Sharjah for his help and expert advice in the modeling and analyses of this research. I would also like to thank Brady Taylor who assisted me with the model running and data analyses. Brady had been working as hard and as "late" as I during this summer as a NSERC undergraduate student.

Many thanks to the National Sciences and Engineering Research Council of Canada (NSERC) for providing me funding for this research. Thanks to the VISSIM technical support staff, Stefan Orehovec and Connie Hotard in particular, who had provided me tremendous help with VISSIM in the past 2 years. Thanks also to Mr. Scott Edwards from the City of Vancouver for his help in my data collection and Mr. Homayoun Vahidi from IBI Group for his information on the TSP implementation of the 98 B-Line buses.

Most important of all, I must thank my family for their support and patience through the years. Thanks to my Daddy for his encouragement and thanks to my mommy for her caring! And thanks to my sister, Venus, for lending me her laptop as my second computer for my research!

Last but not least, I would like to express my special heartfelt thanks to Thomas Kwan for his loving support, sharing, encouragement, and patience during the course of my graduate studies. THANK YOU!!

1.0 INTRODUCTION

Transit Signal Priority (TSP) is an Intelligent Transportation System (ITS) measure that modifies the normal signal operation process to better accommodate transit vehicles. It aims to reduce the delay and travel time of transit vehicles, thereby increasing the quality of transit service; and at the same time, it attempts to provide these benefits with minimum impact on other road users and cross street traffic in particular.

This section introduces the need for this research, the objectives of this research, the scope and evaluation parameters of the experiments, and the structure of this thesis.

1.1 PROBLEM DEFINITION

Transit Signal Priority (TSP) has been widely tested and deployed around the world, especially in the United States and Europe, as a tool to improve transit competitiveness. However, a number of researches and studies had shown that the impacts and effectiveness of TSP application depend largely on its surrounding traffic environment. Consequently, it is important to study how different traffic and transit parameters influence the impact and effectiveness of TSP applications, in order to determine the most ideal traffic condition that would bring about the highest effectiveness, yet the least adverse impact, from TSP application.

Although several studies had investigated the impact of specific traffic and transit parameters on TSP application, most of these efforts were not comprehensive and did not produce a comprehensive strategy for the application of TSP.

1.2 OBJECTIVES OF RESEARCH

This research attempts to perform more comprehensive analyses of the TSP application under different traffic environments and to produce some generic guidelines for TSP applications. Twelve traffic and transit parameters are analyzed to study how each of them affects the TSP effectiveness and the TSP impact. These traffic parameters are analyzed for the impact of TSP, the effectiveness of TSP, and the effectiveness of green extension, whichever is/are applicable. The objectives of this research are:

- To study the influence of different traffic and transit parameters on the impacts and effectiveness of TSP application;
- To develop some generic guidelines for TSP application; and
- To propose some decision rules for the TSP application on Granville Street corridor in the City of Vancouver.

1.3 SCOPE OF RESEARCH

In this research, Transit Signal Priority (TSP) application of the 98 B-line rapid transit buses along Granville Street in the City of Vancouver is used as a case study. The Granville Street corridor, where the 98 B-Line buses run, is one of the busiest traffic and transit corridors in the Greater Vancouver Regional District (GVRD). Along the 6 km Granville Street corridor section from Broadway (or 9th Avenue) to 70th Avenue, the 98 B-Line buses run on the north and south approaches in a mixed traffic environment, which is the evaluation focus for the TSP application in this research. The analyses of TSP application are focused on the northbound (i.e., peak commuter direction) B-Line buses during the morning peak hours on the coordinated Granville Street corridor with 75-second cycle length at all signalized intersections along the corridor.

Twelve traffic and transit parameters are analyzed to study how each of them influence the impacts and effectiveness of the TSP application. The traffic parameters investigated include: Granville Street (or bus approach traffic) volume, left-turn and opposing-through volume, right-turn and pedestrian volume, cross street volume/capacity ratio, bus headway, bus stop location, bus check-in detector location, TSP strategy (green extension, red truncation, etc.), recovery strategy (successive versus non-successive TSP strategy) and signal coordination.

These traffic parameters are analyzed for the impact of TSP, the effectiveness of TSP, and the effectiveness of green extension, whichever is/are applicable. The impact of TSP compares the traffic performance with and without TSP implementation. The effectiveness of TSP measures how a change in the value of a traffic parameter would influence the effectiveness and impacts of the TSP implementation. And the effectiveness of green extension has two measures of effectiveness: (i) green extension success rate, which expresses the rate at which a bus could clear the intersection successfully when a green extension is granted; and (ii) checkout detector effectiveness, which measures the rate at which the check-out detector is useful, i.e., when a bus checks out before the maximum green extension elapsed.

Based on the results from these experiments, generic guidelines for TSP applications are recommended and decision rules for TSP application for the 98 B-Line buses on Granville Street are suggested.

1.4 THESIS STRUCTURE

This thesis consists of six chapters. Following this introductory chapter, Chapter 2 presents a comprehensive literature review on the types, the evaluations and the considerations of Transit Signal Priority (TSP) applications. Chapter 3 details the experimental design of this research, providing a description of the background of the simulation elements and defining the traffic parameters and measures of effectiveness studied in this research. Chapter 4 describes the micro-simulation modeling, the scenarios and the assumptions made for the evaluations. The results and analyses from these evaluations on the impacts and effectiveness of TSP application are discussed in Chapter 5. Finally, the conclusions, recommendations, and suggestions for further researches are included in Chapter 6.

2.0 TRANSIT SIGNAL PRIORITY LITERATURE REVIEW

There has been an increasing demand on public transit system to meet both mobility and as environmental goals. Ironically, traffic congestion and traffic signal cause significant delay and increase operation costs for these bus services [Yagar, 1993]. A number of successful case studies have proven that transit signal priority (TSP) can improve the reliability and efficiency of the transit system, with minimal impact on the general traffic. Yet, there are also cautionary studies of TSP that brought about minimal improvement in transit efficiency and higher delays to the general traffic, the cross street traffic in particular. Due to the inconsistent impact of TSP on bus and general traffic performance, a number of studies have been conducted to examine the criteria and considerations that should be taken for successful implementation of TSP.

This chapter provides a summary of the literatures reviewed on the types of TSP strategies, the evaluations of some selected TSP case studies, and some reported considerations and criteria when planning or implementing TSP.

2.1 DESCRIPTIONS OF TSP STRATEGIES

Strategies of transit signal priority have been developed and tested in the field or with computer simulation over the past 20 to 30 years [Garrow & Machemehl, 1998]. A number of studies have provided quite a comprehensive review of the types of TSP strategies. According to Furth & Muller (2000), TSP strategies can be categorized as giving full, partial, and relative priority.

Full Priority: Full priority tends to give transit vehicle zero-delay service. This type of priority is most common in Europe.

Partial Priority: Partial priority only allows the least disruptive priority tactics, such as green extension and early green. It usually employs rather stringent limits on the extension lengths. This type of priority is more common in the U.S.

Relative Priority: Under relative priority, transit vehicles compete with other traffic for green time and permission to get priority. Transit vehicles are usually given a higher weight to account for their higher passenger loads, but may be denied priority depending on competing traffic volumes and queues.

TSP strategies are most commonly categorized by the following three categories: Passive Priority, Active Priority, and Traffic Adaptive or Real-time Priority.

2.1.1 PASSIVE PRIORITY STRATEGY

Passive Priority strategy uses a predetermined analysis of transit routes and demands as input for the design of traffic signal operation at an intersection [IBI Group, 2000]. This strategy does not require any monitoring or detection system of transit vehicles [IBI Group, 2000]. It attempts to favor bus operation by reducing cycle length or providing phase sequences that give more frequent green time for buses [Mirchandani et al, 2001]. Some commonly employed passive priority strategies are summarized below:

Cycle length adjustment: Shortened cycle length could reduce the stopped time delay for both transit vehicles and private vehicles. This strategy is effective even with the absence of transit vehicles and does not penalize vehicles along the cross streets like other forms of active transit signal priority (described in the next sub-section) [Garrow & Machemehl, 1998]. However, the merits of a shortened cycle length must be weighted against the capacity reduction along the arterial [Garrow & Machemehl, 1998].

Phase splitting: This strategy splits a transit's signal phase into multiple phases such that the total time equals its original duration. This shortens the cycle length for transit vehicles' approach, without altering the overall intersection cycle length [Garrow & Machemehl, 1998].

Area-wide Timing Plans: Area-wide timing plans provide priority treatment to buses through preferential progression, which can be accomplished simply by designing the signal offsets in a coordinated signal system using bus travel times [Sunkari et al, 1995].

Metering-Vehicles: This method allows buses to bypass metered signals with special reserved bus lanes and special signal phases, or allows them to be re-routed to non-metered signals [Sunkari et al, 1995].

Skabardonis (2000) used TRANSYT-7F, a traffic signal optimization program, to develop signal timing plans that favored transit along signalized arterials. The algorithm optimized the system cycle length and offsets at each intersection to minimize the Performance Index (PI), which was expressed by:

$$PI = \sum_{i=1}^{N} W_{Di} * D_i + K * W_{Si} * S_i$$

Where N = number of links in the system, W_{Di} = weighting factor of link delay, D_i = total link delay (veh-hr), K = the stop penalty (the weights of stop relative to delay), W_{Si} = weighting factor of link stops, and S_i = number of stops on a link.

In the optimization, higher weighting factors were given to buses in each link delay. The weighting factors for buses were determined based on the bus frequency, the traffic pattern and the network characteristic [Skabardonis, 2000]. Skabardonis (2000) reported that higher weighting factors of buses would lead to higher bus delay reduction but higher increase in auto traffic delay.

Changes in regular signal timing plans for the Passive Priority can be of limited value because transit vehicles can still arrive during the red interval due to variation in travel time; in addition, the bus-priority-based green phases for the bus approach can delay the cross street traffic regardless of the presence of a transit vehicle [IBI Group, 2000].

2.1.2 ACTIVE PRIORITY STRATEGY

Active Priority strategy is currently the most widely used and tested TSP strategy in North America. This strategy requires the ability to detect or identify buses at or approaching a signalized intersection and causes alteration of the regular signal operation in response to the presence, or imminent presence, of a transit vehicle determined by a detector [IBI Group, 2000]. There are four types of active priority treatments:

- Green Extension;
- Red truncation / Early Green;
- Special Bus Phase; and
- Selective Strategies.

2.1.2.1 Green Extension

Green extension involves the extension of the green phase of the transit route upon detection of a transit vehicle before the normal green period ends. In most cases, the green time for the transit approach is held or extended until the bus clears the intersection or when the pre-specified maximum green extension (or max-timer) is reached. A max-timer is usually used to set the maximum extension limit of the green phase, which is needed to control the disruption of other general traffic and to terminate the excessively long bus priority calls should a reader fail [Khasnabis & Rudraraju, 1997]. Check-in and check-out detectors are installed by roadside or embedded in pavement to call for and to cancel a green extension request. Figure 2-1 shows an example of green extension, with "Phase A" representing the bus phase and "Phase B" representing the non-bus phase.

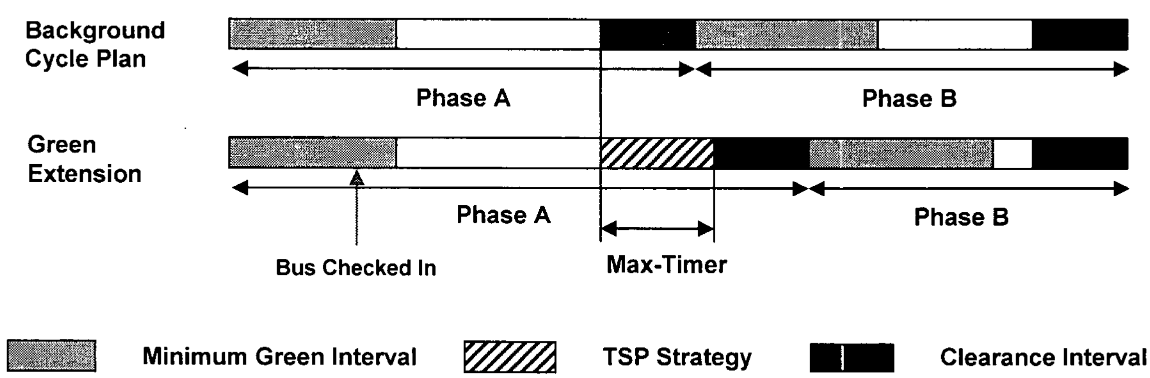

Figure 2-1 Timing Plan with Green Extension

The amount of maximum green extension used for different TSP implementations or simulations varies. Most maximum green extensions fall in the range from 10 seconds to 20 seconds. Cima et al (2000) even reported a green extension of as high as 30 seconds for the Toronto Transit Commission (TTC)'s light rail preemption in Toronto, Ontario, Canada. Table 2-1 lists the green extensions reported in the studies reviewed and from current practice of transit agencies.

Table 2-1 Green Extension Usage

Author	Year	Location	EVALUATION		GE Range (sec)	Max GE (sec)
			Actual	Simulation		
Literature Research						
Zaworski	1994	Powell Boulevard, Portland, U.S.A.	✓			10
Kloos et al	1995	Powell Boulevard, Portland, U.S.A.	✓		10-20	20
Zaworski & Danaher	1995	NE Multnomah Street, Washington, U.S.A.	✓			15, 20 or 25 *
Garrow & Machemehl	1998	Austin, Texas, U.S.A.		✓		10 or 20
Cima et al	2000	Toronto, Ontario, Canada	✓		3-30	30
Cima et al	2000	Snohomish County, Washington, U.S.A.	✓			15
IBI Group	2000	Route 123, Greater Vancouver, B.C., Canada		✓	10-16	16
Chatila & Swenson	2001	Route 522, King County, Washington, U.S.A.		✓		20% of cycle length
Transit Agency's Current Practice						
City of Calgary	2001	Calgary, Alberta, Canada	✓			20
City of Vancouver	2001	Vancouver, B.C., Canada	✓			14

* Actual green extension employed varies by location, based on each location's characteristic.

2.1.2.2 Red truncation / Early Green

This strategy provides early green phase to the transit route upon detection of a transit vehicle during the red phase. The strategy involves the truncation (skipping or shortening) of either all or some selected non-bus phases. However, when designing the maximum length of an early green, special attention should be paid to the minimum green restriction, the clearance safety of the other phases (including vehicle and pedestrian phases), and the excessive delay of the truncated approaches. Figure 2-2 shows an example of early green, again, with "Phase A" representing the bus phase and "Phase B" representing the non-bus phases.

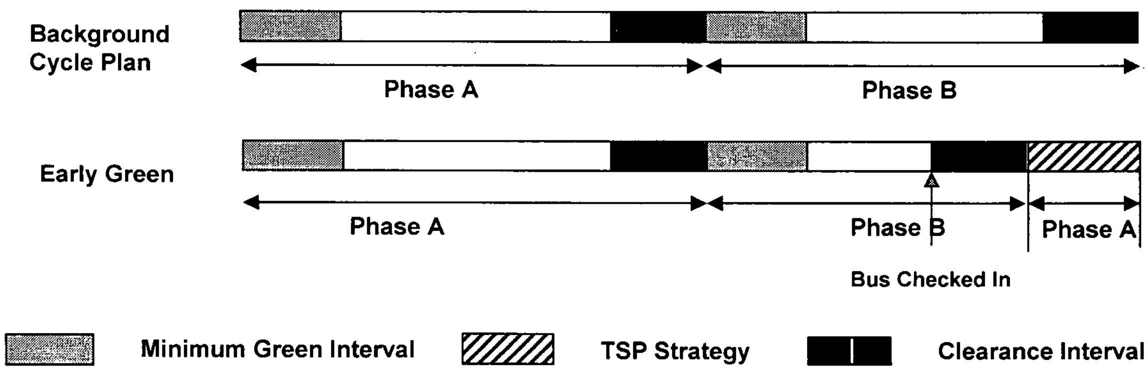

Figure 2-2 Timing Plan with Early Green

The amount of maximum early green also varies from case to case. It is observed from the reviewed case studies that the red truncation time tends to be shorter than the green extension time. And the red truncation time is very dependent on the minimum walk and clearance times of the pedestrian phase opposing the bus approach. Chatila & Swenson (2001) set the maximum red truncation time to 20% of the normal split length of the conflicting phases preceding the bus phase.

McLeod (1998) reported that early green or red truncation tended to bring about less benefit to buses than green extension did. He believed that early green or red truncation would cause more disruption to other traffic than green extension would because it would incur more interference to the traffic signal settings. Al-Sahili & Taylor (1996) also reported that phase skipping would cause highest vehicular delay because it brought the highest disturbance to the system.

2.1.2.3 Special Bus Phase

A special bus phase involves the insertion of a short bus phase into the normal phase sequence [Sunkari et al, 1995]. This strategy is applicable to signal timing plan with more than two phases. Figure 2-3 shows an example of a special bus phase inserted between Phase B and Phase C, with "Phase A" representing the bus phase and "Phase B", "Phase C" and "Phase D" representing the non-bus phases.

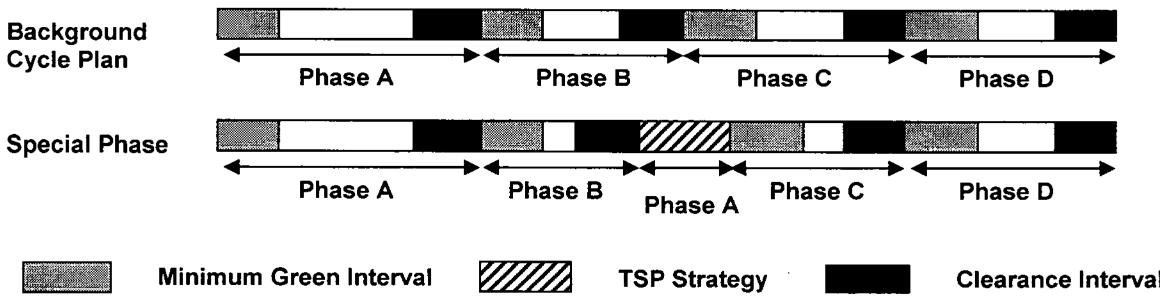

Figure 2-3 Timing Plan with Special Bus Phase.

2.1.2.4 Selective Strategies

The notion of selective transit priority strategies was developed to provide priority to transit vehicles subjected to the projected arrival time of a bus in a cycle [Balke et al, 2000]. These strategies can include green extension, early green, and special phase. Figure 2-4 illustrates a background cycle plan, with "Phase A" representing the bus phase and "Phase B", "Phase C" and "Phase D" representing the non-bus phases. And the table below shows the conditions, proposed by Balk et al (2000), for the implementation of each TSP strategy at an intersection with fixed cycle length.

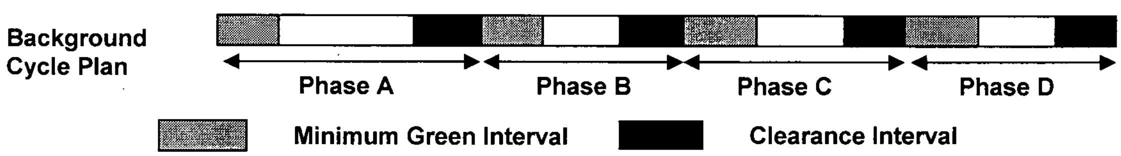

Figure 2-4 Background Cycle Plan

SELECTIVE TSP STRATEGIES CONDITIONS (Balk et al, 2000)

If bus arrive during	& If bus projected to arrive at intersection		Then
	From	To	
Phase A	0	$A-A_{Clear}+B-B_{Min}-B_{Clear}$	Green Extension
Phase B	$A+B_{Min}+B_{Clear}$	$A+B+C-C_{Min}-C_{Clear}$	Special Phase between B & C
Phase C	$A+B+C_{Min}+C_{Clear}$	$Cycle-D_{Min}-D_{Clear}$	Special Phase between C & D
Phase D	$Cycle-D+D_{Min}+D_{Clear}$	Cycle	Early Green

Note: X = Period for phase X, for X = A, B, C, or D.
X_{Min} = Minimum green time for phase X, for X = A, B, C, or D.
X_{Clear} = Clearance time required by phase X, for X = A, B, C, or D.
Cycle = Cycle length of the signal plan.

2.1.2.5 Unconditional Versus Conditional Active Priority

Depending on the locations and capabilities of the bus detectors, active priority can be either conditional or unconditional [Mirchandani et al, 2001].

Unconditional Transit Priority:

Under unconditional priority, signal priority is provided to every transit request or transit call regardless of whether the priority is really "needed". This type of strategy provides priority to transit vehicles "blindly", without due consideration for private cars. This can be haphazard because this can result in excessive delays and queues, making it more difficult to accommodate transit vehicles that arrive later [Yagar & Han, 1994]. To address for this shortcoming and to control the disruption to the general traffic, conditional priority or selective priority is implemented in most of the recent studies and practices.

Conditional Transit Priority:

Conditional priority grants signal priority to transit request based on some predefined criteria. Most TSP projects based their conditional transit priority decisions on one or more of the following criteria:

- Schedule Adherence: Transit Priority would only be provided to buses that are behind schedule or late. The definition of "lateness" can vary for different control systems. Some consider any negative deviation from the bus schedule as "late"; while some systems consider a bus as "late" if it arrives outside a pre-defined "variable window". For example, Kloos & Turner (1999) set the variable window for a Bus Dispatch System from 2 minutes early to 7 minutes late; in this case, priority is granted only if a bus is more than 7 minutes late.

- Passenger Occupancy: Higher transit priority would be provided to buses with higher passenger occupancy and priority would not be provided to empty buses. Skabardonis (2000) pointed out that it would not be beneficial to provide priority to buses that were empty.

- Spare Green Time: Under this criterion, transit priority may be granted only if there is sufficient spare green time in a signal cycle. This guarantees that normal phasing sequence at an intersection is kept and coordination along an arterial is maintained. Skabardonis (2000) stated that signal preemption should not result in over-saturated movements at a signalized intersection or loss of signal coordination. According to Skabardonis (2000), the spare green time (G_{Spare}) can be expressed by:

$$G_{Spare} = \sum_{i=1}^{N} G_i * (1 - X_i)$$

For G_i = green time for phase i, X_i = degree of saturation of the critical link in phase i, N = total number of phases in a cycle.

McLeod (1998) also pointed out that transit priority would have higher benefit to an intersection with plenty of spare capacity; whereas, little or no benefit would be gained to provide priority at highly saturated junctions (i.e., with little or no spare capacity).

- Bus Route Progression: The traffic conditions at downstream intersection(s) are considered for transit priority provision. Skabardonis (2000) pointed out that no bus delay benefit would be achieved if advancing the green time at an upstream signal for the buses would bring them to a queue downstream, thereby increasing their delay downstream.

- Bus Headway Deviation: McLeod (1998) proposed an algorithm, called the "Headway Algorithm" to grant selective priority to buses based on the ratio of the actual headway to the scheduled headways. Higher level of bus priority would be given to buses with higher deviation from their scheduled headways. According to McLeod (1998), the "Headway Algorithm" consisted of two steps:

1. Calculation of bus headway ratio, R:

$$R = \frac{ActualHeadway}{ExpectedHeadway}$$

For ExpectedHeadway = the expected scheduled bus headway.

2. Assignment of priority level to buses by comparing the calculated "R" with some pre-defined threshold ratios. For example, given R_3, R_2 and R_1 are the headway ratios thresholds in descending order (from large to small), the assignment of priority level can be as follows:

Condition	Priority Level
$R >= R_3$	High
$R >= R_2$	Medium
$R >= R_1$	Low
$R < R_1$	No

Note: R3 > R2 > R1

McLeod (1998) used four threshold ratios: 1.0, 1.25, 1.5 and 1.75. And the final decision of transit priority was determined by both these priority level conditions and criteria defined on the degree of saturation at the intersection.

The conditional criteria on bus lateness and passenger occupancy have been widely implemented and tested among researches and practices. However, only very few studies have reported condition transit priority practices based on spare green time, bus route progression, and bus headway.

Due to the increasing attention to the influence of TSP on the overall traffic performance, a new type of priority strategy evolved in recent years. The priority strategy is commonly known as Traffic Adaptive Strategy or Real-Time Priority Strategy.

2.1.3 TRAFFIC ADAPTIVE PRIORITY STRATEGY

Traffic Adaptive Priority advances to provide priority to transit vehicles, and at the same time, to maintain the overall performance at an intersection or in a traffic network. It is sometimes referred to as Real-Time Priority Strategy because it uses actual observed vehicle arrivals to evaluate alternative traffic signal timing plans to select the most favorable option [Mirchandani et al, 2001]. Instead of using pre-specified transit priority strategies such as green extension or red truncation, the priority decision is based on a performance index or some user-defined decision algorithms.

Various attempts have been reported in the development of methods to select the "best" signal timing plan or the most favorable phase duration and phase sequence, which grants priority to buses while incurring the least adverse effect to the entire traffic system. The literatures reviewed show three general approaches of the Traffic Adaptive or Real-Time Priority Strategy:

1. Optimization Model;
2. Genetic Algorithm and Neural Network; and
3. Fuzzy Algorithm.

2.1.3.1 Optimization Model

This approach attempts to provide transit priority based on the optimization of performance criteria such as passenger delay, vehicle delay or some combinations of these measures [Mirchandani et al, 2001]. Most traffic-adaptive optimization models consist of four modules:

Traffic State Estimation Module: Prediction of subsequent propagation of vehicular and bus flows estimated from real-time flow profiles in the network [Mirchandani et al, 2001]. The predictions can be on vehicle arrivals, bus arrival, turning probability, or queue length at an intersection or on an approach.

Signal State Estimation Module: Monitoring of the signal state, computation of the elapsed green time, and estimation of the minimum green duration in real-time [Chang et al, 1995].

Signal Plans Selection Module: Pre-selection of the timing plans or phase durations and sequences according to the predicted traffic and signal states and subjected to pre-defined constraints. The constraints can include restriction of any subsequent request in the green approaches with higher priority, minimum walk and clearance time of pedestrian phases, and minimum green and clearance time of the vehicular phases.

Evaluation and Optimization Module: Evaluation of the signal plan decision based on some pre-defined performance criteria.

Yagar & Han (1994) proposed a traffic signal optimization algorithm to obtain a signal timing plan that minimized the total delay at an isolated intersection for a projection period (T_p). The four modules described above were employed in the algorithm. In the algorithm, the queue length or any event that might lead to a request for a phase or signal switching would be examined.

Yagar & Han (1994) considered that it was not practical to search for the global optima that could consume considerable computing time. To speed up the real-time traffic responsive signal optimization routine for the selection of an optimal signal plan on-line, a list of simple generic rules was offered instead for pre-evaluation. A sample priority list given in their paper is:

1. Streetcars on main street – peak direction.
2. Queue on main street – peak direction.
3. Streetcars on cross street.
4. Queue on cross street.
5. Streetcars on main street – off peak direction.
6. Queue request on main street – peak direction.
7. Queue in main street – off peak direction.
8. Queue request from cross street.
9. Queue request from main street – off peak direction.

Yagar & Han (1994) pointed out that the strategies should not "waste" valuable capacity by catering to the off-peak direction because they believed that it would be taken care of as a by-product of the priority provision to the peak direction in the long run.

The candidate signal plans were then evaluated based on its corresponding performance index (PI), expressed in total delay. The plan with the smallest PI (or delay) would be selected. The total delay (*D*) was estimated based on the event-based modeling method, expressed by:

$$D = \sum_{j=1}^{n} \sum_{k=1}^{l} (T_{jk} * \sum_{i=1}^{Q_{jk}} W_{ijk})$$

For D = total delay for the projection period (T_p); n = number of approaches; l = number of intervals within T_p; T_{jk} = sub-interval time period; Q_{jk} = queue length (or number of vehicles) of approach j between $t_{(k-1)}$ and t_k; and W_{ijk} = weighting factor for vehicle i in the queue on approach j during time interval T_{jk} (a streetcar usually has a higher weight than a private car).

Chang et al (1995) also used performance index (PI) to assess the integrated system for adaptive bus-preemption control that they developed. In their proposed system, automated vehicle location system was absent and conditional priority was given to buses over passenger cars. The system developed consisted of only three modules: Traffic State Estimation Module, Signal State Estimation Module, and Evaluation Module.

Chang et al employed a performance index (PI) to measure the benefits of a transit signal priority decision and to select the optimal signal control solution. The PI was computed as the sum of the tradeoff in passenger delay, vehicle delay, and bus schedule delay due to any proposed signal control decision, as follow:

$$PI = TradeOff_{PassengerDelay} + TradeOff_{VehicleDelay} + TradeOff_{BusScheduleDelay}$$

The tradeoff would be positive if the decision was beneficial but negative if the decision was disadvantageous. The TSP strategy would be accepted if it led to a positive PI. The control decision with a more positive PI value would be more favorable and be selected.

The incorporation of bus priority into RHODES (Real-time, Hierarchical, Optimized, Distributed, and Effective System) was proposed by Mirchandani et al (2001). The propagation of flow is predicted based on second-by-second real-time traffic data from loop detection. The traffic prediction was then inputted into RHODES to optimize a performance objective (e.g., average delay and number of stops). A weight was given to each vehicle based on the vehicle's delay or queue. To incorporate bus priority into the optimization algorithm, two approaches were investigated to assign weighting factors to buses:

- Phase-constrained Approach: In this approach, all buses were given a higher weight than other vehicles.

- Weighted-bus Approach: For this approach, a bus with more passengers and higher "lateness" would be given higher weight. The weight (w_i) for a bus is defined by the function:

$$w_i = n_i * (1 + f_i)$$

For n_i = number of passengers on bus i; $f_i = 0$ (if lateness (d_i) <0) or $f_i = K*d_i$ (if lateness (d_i)>0, where K is positive some constant).

2.1.3.2 Genetic Algorithm and Neural Network

Duerr (2000) proposed DARVIN (Dynamic Allocation of Right-of-Way for Transit Vehicles In Urban Network) to improve transit progression in a mixed traffic condition while optimizing the overall performance of the coordinated network. The main objectives of DARVIN were to reduce transit vehicles travel time, to maximize bus schedule adherence, and to minimize the disruption to the general traffic. The DARVIN algorithm involved two processes: Static Optimization and Dynamic Adaptation.

Static Optimization consisted of Genetic Algorithm (GA), which selected the optimal solutions that possessed better "fitness" than the other solutions by a series of iterations and alternations. According to Duerr (2000), the GA approach was used for the following reasons:

- The algorithms were very efficient and could search rapidly for very large solution spaces;
- Parameter optimization could be performed using any tool as an evaluator;
- All parameters could be optimized simultaneously;
- Computation process could be performed in parallel; and
- Undirected (random number selection and recombination/mutation process) and directed (probability of selection) searches could be combined.

However, Duerr (2000) pointed out GA would produce inconsistent results from run to run.

According to Duerr (2000), Genetic Algorithm aimed to select the "most favorable" timing plan that:

- Minimized the weighted delays and stops of "all" vehicles in the coordinated network,
- Minimized the interference between public transit and other vehicles,
- Allocated green times dynamically according to the needs of entering public transit vehicles, and
- Returned to signal coordination as fast as possible.

The "fitness" in the algorithm was based on the overall delay by adjusting the signal timing plans of the network [Duerr, 2000]. The overall delay of a signal timing plan decision (D_I) was formulated as:

$$D_I = \sum_j \sum_i ((d_{ij} + \lambda * s_{ij} + H_i) * \gamma_i + P) \big| C_I$$

For j = index for intersection or node, i = index for vehicle, d_{ij} = delays of vehicle i at node j, λ = weighting factor for stop, s_{ij} = number of stops of vehicle i at node j, H_i = horizon penalty for vehicle i remaining in the network, γ_i = weighting factor of vehicle (depending on load factor and vehicle type), P = overflow penalty on every vehicle that causes the queue length to exceed a link's storage capacity, and C_I = signal timing plan.

According to Duerr (2000), the Dynamic Adaptation component of the DARVIN algorithm involved the dynamic adaptation of the static GA-solution for online implementation by a neural network. The neural network applied a conjugate gradient technique that determined the influence of the input parameters on the value of the output parameters. By modifying the connecting weights between the input and output vectors using a set of interim network layers, a functional relationship could be established. The training process would terminate as soon as a mapping function, which produced close to optimal signal timing adjustment, is derived.

The optimal solutions for discrete traffic situations selected by GA were used to train the neural network to establish a relationship between the input vectors (e.g., traffic inflow and public transit trajectory) and output vectors (e.g., signal timing plan, phase duration, and phase sequence) [Duerr, 2000].

Figure 2-5 illustrates a generic relationship of the two processes (Static Optimization and Dynamic Adaptation) described above.

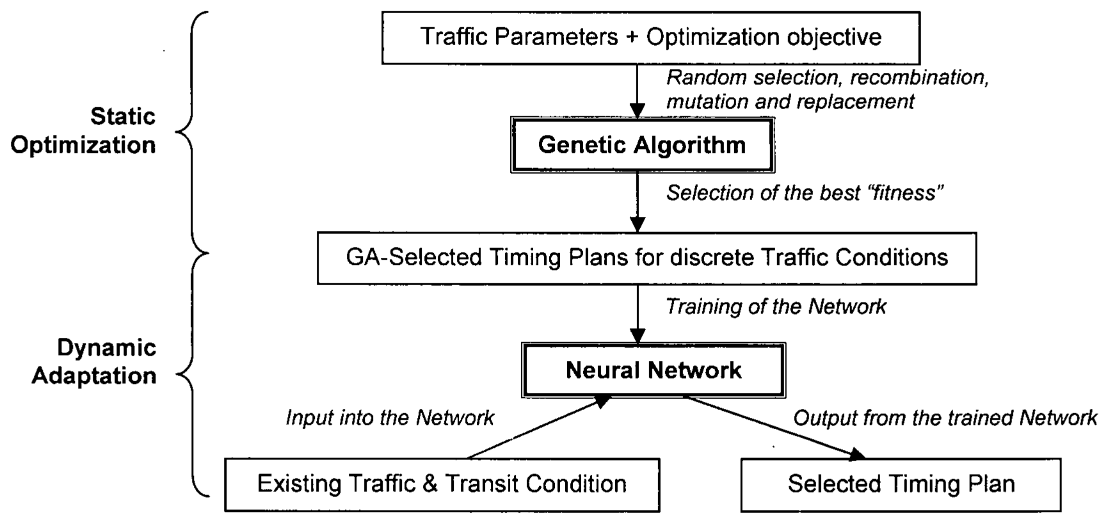

Figure 2-5 Traffic Adaptive Transit Priority with Genetic Algorithm & Neural Network

It should be noted that genetic algorithm and neural network are beyond the scope of this research, thus, no detailed description of the two methods are discussed.

2.1.3.3 Fuzzy Logic

Niittymaki (1998) presented a "Fuzzy Rule Base" control algorithm for the decision of transit priority provision at an isolated intersection. The base idea of the fuzzy signal control algorithm was to model the signal control based on human expert knowledge, which comprised of control policies and goals. Fuzzy logic had the ability to comprehend linguistic instruction and to generate control strategies based on priori verbal communication [Niittymaki, 1998]. It could also capture the key factors of a complex process without requiring detailed mathematical formulas; thus, it had many advantages in real-time applications [Niittymaki, 1998].

As stated by Nittymaki (1998), "the main reason why fuzzy set theory is a suitable approach to traffic signal control is the nature of uncertainties in signal control, decisions are made based on imprecise information, the consequences of decisions are not well-known, and the objectives have no clear priorities. It has been known through various experiments and applications that fuzzy control is well suited when the control involves these kinds of uncertainties and human perception, like signal control." Additionally, Niittymaki (1998) also gave some reasons for using "fuzzy" public transport priorities:

- Transit priorities added complexity to control policy, which had at least one additional objective;
- The consequences of public transport priority were not known;
- There could be large uncertainties in the traffic situation (e.g., large variations in travel time during the peak hours, which fluctuated with the green extension).
- The rule base could easily be modified by all kinds of isolated intersections, and the structure of fuzzy logic could be extended to evaluate coordinated signals.

The rules used in Niittymaki (1998)'s model were "if-then-rules", which consisted of the if-clause referring to an antecedent (premise) and the then-clause representing a consequence. The output (Y) can be calculated from the input (X) through a system transfer relation (R). Defuzzification of the output would be required.

The main goals of the fuzzy rule base of public transport priority proposed by Niittymaki (1998) were to give a priority function and to make a priority decision based on the current traffic situation at an intersection [Niittymaki, 1998]. In Niittymaki (1998)'s fuzzy model, green extension and red truncation were recommended for a two-phase signal control; and green extension, red truncation, and special phase were recommended for a multi-phase signal control (i.e., signal cycle with more than 2 phases).

Under the two-phase signal control, the priority decision rules evaluated the current traffic situation based on two fuzzy parameters:

- Time since the public transport vehicle checked-in, *PT(time)*: zero, short, medium, long; and
- Weight of the non-bus phase, *W(red)* (if bus detected in green) or *W(green)* (if bus detected in red): short, medium, long.

The rules are typical if-then rules. When a bus was detected in green, the if-then rules can be:

> If PT(time) is zero and W(red) is low then use basic rules (i.e., no priority given), or
> If PT(time) is short and W(red) is medium then extend phase.

Niittymaki (1998) summarized the green extension rules, as shown below:

GREEN EXTENSION RULES (Niittymaki, 1998)

		PT(time) Zero	Short	Medium	Long
W(red)	**Low**	Basic	Extend	Extend	Basic
	Medium	Basic	Extend	Extend	Basic
	High	Basic	Basic	Basic	Basic

Note: W(red) is the fuzzy importance factor of the following non-bus phase. The importance can be determined by the number of queue vehicles and the estimated green time needed for the following non-bus phase.

Similarly, when a bus was detected in red, the if-then rules could be:

> If PT(time) is zero and W(green) is low then use basic rules (i.e., no priority given), or
> If PT(time) is long and W(green) is low then red truncate (RT).

Niittymaki (1998) summarized the red truncation rules, as shown below:

RED TRUNCATION RULES (Niittymaki, 1998)

		PT(time) Zero	Short	Medium	Long
W(green)	**Low**	Basic	RT	RT	RT
	Medium	Basic	RT	RT	Basic
	High	Basic	Basic	RT	Basic

Note: W(green) is the fuzzy importance factor of the current non-bus phase. The importance can be determined by the number of vehicles arriving and the estimated green time needed for the current non-bus phase.

Under the multi-phase signal control, transit priority decision rules could be more complicated because the rules could affect the phase and sequence order too. The decision rules for priority would be based on:

- The phase in which the public transport vehicle (PTV) is detected (crisp input); and
- The importance factor of the phase following the phase when the PTV is detected (fuzzy parameters), *W(next)*: low, medium, long.

Niittymaki (1998) summarized the multi-phase control rules, as shown below:

MULTI-PHASE CONTROL RULES (Niittymaki, 1998)

		Phase when PTV Request		
		A	**B**	**C**
	Low	Extend	Special Phase	RT
W(next)	**Medium**	Extend	Rapid Cycle	RT
	High	Special Phase	Rapid Cycle	Basic

Note: Assuming phase sequence as A-B-C, with "phase-A" denoting the bus phase.

Based on the rule base for fuzzy public transport priorities, each case had its own membership function [Niittymaki, 1998]. Niittymaki (1998) proposed the use of neural networks, genetic algorithms or other methods to define the final membership functions. In addition, some defuzzification methods (e.g., min-max, mean of maximum and the center of gravity) are required to generate the final decision on the "most favorable" signal plan.

It should be noted that fuzzy logic and defuzzification method are beyond the scope of this research, thus no detailed descriptions of these methods are included.

2.2 EVALUATION OF TSP STRATEGIES

The implementations and evaluations (actual and simulated) of transit signal priority (TSP) strategies have been well documented in previous literatures. From the researches reviewed, evaluation of TSP strategies could be categorized into two main streams:

- Traffic performance evaluation; and
- Economic evaluation.

2.2.1 TRAFFIC PERFORMANCE EVALUATION

The effectiveness of a transit signal priority could be measured by one or more of the following traffic performance criteria:

- Bus performance, including bus travel time, delay and speed;
- Bus reliability (or schedule adherence);
- General vehicle performance, such as vehicle delay and cross street delay; and
- Overall intersection / network performance, such as overall delay and total passenger delay.

These performance criteria were determined either by actual TSP implementation or traffic simulation. For priority measures evaluated by simulation, the measures of effectiveness could be obtained using pre-defined equations in the corresponding simulation software; whereas, for the evaluation of actual priority measures, actual traffic data surveys would be needed.

The following sections summarize results (actual or simulated) of various transit priority strategies under each traffic performance criterion listed above.

2.2.1.1 Bus Performance Evaluation

One of the main purposes of implementing transit signal priority is to improve the travel time performance and efficiency of a bus, thereby to increase the competitiveness of riding a bus over driving. In a transit operator's perspective, a successful TSP would bring upon the following improvements in bus performance: reduction in bus travel time, reduction in bus delay, and increase in bus traveling speed.

Table 2-2 summarizes selected bus performance evaluation results from publications reviewed. The results are categorized by the type of transit priority strategy used: Passive Priority, Active Priority, or Traffic Adaptive / Real-Time Priority. The table illustrates that all published studies reported a positive impact of transit priority on a bus's performance, i.e., a reduction in bus travel time and delay and an increase in bus traveling speed. This would be reasonable because the strategies implemented or simulated were intended to favor bus performances in travel time, delay and speed.

Table 2-2 Bus Performance Evaluations with TSP

Author	Year	Location	Evaluation	Change in Bus Performance with TSP		
				Travel Time	**Delay**	**Speed**
Passive Priority (Cycle length adjustment or pre-defined signal plan)						
Jepson et al	1997	Gold Coast Hwy, Australia	Simulation	-36 sec	--	--
Skabardonis	2000	San Francisco Bay Area, U.S.	Simulation	-13%	--	--
Active Priority (Green extension and/or Red truncation)						
Hounsell	1990	London District, U.K.	Simulation	-9 sec/bus/ junction	--	--
Zaworski	1994	Powell Boulevard, Portland, U.S.	Actual	AM: -5% (32 sec) *; PM: -8% (45 sec) *	--	--
Ghali et al	1995	City of York, U.K.	Simulation	No MaxGE: -14%; MaxGE: -11.7%	--	No MaxGE: +15.6%; MaxGE: +12.7%
Zaworski & Danaher	1996	NE Multnomah Street, U.S.	Actual	-4.7% to -7%	--	--
Al-Sahili & Taylor	1996	Ann Arbor, Michigan, US	Simulation	-6%	--	--
Funkhouser	1996	Lousiana Avenue, Minnesota, U.S.	Actual	-13%	--	--
Funkhouser	1998	City of Tacoma, U.S.	Actual	-6% to -8.6%	--	--
Huffman et al	1998	Chicago, U.S.	Actual	-7% to -20%	--	--
Jepson et al	1997	Gold Coast Hwy, Australia	Simulation	Absolute: -147 sec; Conditional: -75 sec	--	--
McLeod	1998	Edgware Road, London, U.K.	Simulation	0 to -7.6%	--	--
Johnson	1999	Illinois, U.S.	Simulation	- >5 min	--	--
Balke et al	2000	Hypothetical network	Simulation	-25% to -27%	--	--
Furth & Muller	2000	Eindhoven, Netherlands	Actual	--	AM: -75%*; PM: -52%*	--
IBI Group	2000	Vancouver, B.C., Canada	Simulation	-9.9 min / 2-way cycle	--	--
Skabardonis	2000	San Francisco Bay Area	Simulation	--	-14%	+3.4%
Hu et al	2001	Los Angeles, U.S.	Actual	-8% to -10%	--	--
Chatila & Swenson	2001	King County, U.S.	Simulation	AM: -3% *; Midday: -7% *	--	--
Traffic Adaptive / Real-Time Priority (Optimization, or Genetic Algorithm & Neural Network)						
Yagar & Han	1994	Toronto, Ontario, Canada	Simulation	--	-12.2%	--
Duerr	2000	City of Wurzburg, Germany	Simulation	-25%	--	--
Mirchandani et al	2001	N/A	Simulation	-13.4%	-17.8%	--

* Result obtained for the specified peak hour period.

Note:

- Negative change denotes a reduction, and positive change denotes an increase with TSP implementation.
- The percentage represents overall percentage with respect to the "no TSP" criterion.
- "NoMaxGE" = Scenario with no maximum green extension; "MaxGE" = Scenario with maximum green extension.

2.2.1.2 Bus Reliability

A number of published studies used bus reliability (or schedule adherence) as the main evaluation parameter for TSP applications. Schedule adherence is an important performance measure for service reliability, which is measured by punctuality (arrive as scheduled) and regularity (keeping proper headway between consecutive buses) [Furth & Miller, 2000]. Conditional bus priority that grants priority only to buses behind schedule is one of the measures used to achieve this goal. Some studies even proposed to incur higher signal delay to buses ahead of schedule to "kill" off time [Furth & Miller, 2000].

Table 2-3 below summarizes the bus performance reliability results from some selected TSP studies.

Table 2-3 Bus Reliability Evaluations with TSP

Author	Year	Location	Evaluation	Bus Reliability
Huffman et al	1998	Chicago, U.S.A.	Actual	Improved
Furth & Miller	2000	Eindhoven, Netherlands	Actual	Rarely >60 sec early or >120 sec late

However, IBI Group (2000) noted that schedule adherence might not be a good criteria to reveal the effectiveness of a TSP implementation because most schedules took into account signal and congestion delay. Jacobson (1993) also pointed out that the intended benefit of TSP would be lost if a transit agency failed to make adjustments to bus schedules after TSP was implemented.

2.2.1.3 General Vehicle and Cross Street Performance

In addition to the investigation of TSP impacts on bus performance, general (i.e., non-bus) traffic performance has also been extensively studied. In most cases, performance of general traffic, cross street traffic in particular, would be traded off for the improvement in bus performance. However, blind priority to transit vehicles without due consideration for private cars could be haphazard and could result in excessive delays and queues, making it more difficult to accommodate transit vehicles that arrive later [Yagar & Han, 1994].

Table 2-4 summarizes the results of general traffic performance from various actual or simulated TSP applications. The TSP impacts on general traffic performance and bus performance (if available) are included in the table to compare TSP impacts on these road users. Two performance criteria are compared in the table:

- Travel time: bus versus general traffic; and
- Delay: bus versus general traffic versus cross street.

Table 2-4 General Traffic Performance Evaluations with TSP

Author	Location	Change in Travel Time		Change in Delay		
		Bus	General Traffic	Bus	General Traffic	Cross Street
Passive Priority (Cycle length adjustment or pre-defined signal plan)						
Jepson et al (1997)	Gold Coast Hwy, Australia	-36 sec	--	--	--	+120 sec
Skabardonis (2000)	San Francisco Bay Area, U.S.	-13%	--	--	+5%	--
Active Priority (Green extension and/or Red truncation)						
Hounsell (1990)	London District, U.K.	-9 sec/bus/ junction	--	--	+2.7 sec/veh	--
Zaworski (1994)	Powell Boulevard, Portland, U.S.	AM: -5% (32 sec) *; PM: -8% (45 sec) *	--	--	Slightly increased	--
Kloos et al (1995)	Powell Boulevard, Portland, U.S.	AM: -5%; PM: -7.8%	--	-12.3%	--	--
Funkhouser (1996)	Lousiana Avenue, Minnesota, U.S.	-13%	Minimal	--	+4.4 sec	Minor delay
Funkhouser (1998)	City of Tacoma, U.S.	-6% to -8.6%	--	--	--	Minor delay
Jepson et al (1997)	Gold Coast Hwy, Australia	Absolute: -147 sec; Conditional: -75 sec	--	--	--	+22 sec
Balke et al (2000)	Hypothetical network	-25% to -27%	-2% to -5%	--	--	+2% to +26%
Furth & Muller (2000)	Eindhoven, Netherlands	--	--	AM: -75%*; PM: -52%*	Minimal	--
Skabardonis (2000)	San Francisco Bay Area	--	--	-14%	+1%	Excessive queue
Chatila & Swenson (2001)	King County, U.S.	AM: -3% *; Midday: -7% *	+1%	--	--	--
Traffic Adaptive / Real-Time Priority (Optimization, or Genetic Algorithm & Neural Network)						
Yagar & Han (1994)	Toronto, Ontario, Canada	--	--	-12.2%	-4.3%	--
Duerr (2000)	City of Wurzburg, Germany	-25%	-5%	--	--	--
Mirchandani et al (2001)	N/A	-13.4%	Major: -8.5% Minor: -21.2%	-17.8%	-19.1%	-35.8%

* Result obtained for the specified peak hour period.
Note:
- Negative change denotes a reduction, and positive change denotes an increase with TSP implementation.
- The percentage represents average percentage with respect to the base case (i.e., no TSP).

The comparisons in Table 2-4 above show that Passive Priority and Active Priority generally improved bus performance (i.e., bus travel time and delay), but worsened general traffic and cross street traffic performance. Whereas, Traffic Adaptive Priority could improve bus, general traffic and cross street traffic performance concurrently.

2.2.1.4 Overall Traffic Performance

The overall traffic performance can be defined for an intersection or an entire traffic network, with all types of vehicles and all approaches taken into account. It is commonly represented by two measures: overall delay and passenger delay.

Overall delay measures the average delay per vehicle (including private vehicles and buses) from all approaches at an intersection or in a traffic network. All types of vehicles are given the same weighting.

Passenger delay measures the delay per passenger (including private vehicle passengers and bus passengers). A weighting is assigned based on the actual or average occupancy of each type of vehicles. A bus usually has higher weighting because it carries more passengers than a private vehicle does. Table 2-5 lists some previously published assumptions on bus and private vehicle occupancies:

Table 2-5 Assumed Bus & Private Vehicle Occupancies

Author	Year	Assumed Occupancy	
		Bus	Private Vehicle
Yagar & Han	1994	30	1.5
Al-Sahili & Taylor	1996	25	1.3
Daniel	1997	40	1.4
Khasnabie & Rudraraju	1997	40	1.4
Al-Akhras et al	1999	20	1.3
Garrow & Machemehl	1998	10	1.2

It should be noted that the selections of the occupancy values should be considered carefully because the value of passenger delay is highly sensitive to the assumed occupancy values. An overestimation of the occupancy values would overvalue the passenger delay, and vice versa. Therefore, some studies use the actual bus and private vehicle occupancies to obtain a more accurate value of person delay.

Mirchandani et al (2001) used the "Weighted-bus" approach to assign a weight to a bus based on its occupancy as well as its "lateness". The weight (w_i) for a bus is defined by:

$$w_i = n_i * (1 + f_i)$$

For n_i = number of passenger on bus i; $f_i = 0$ (if lateness (d_i) <0) or $f_i = K*d_i$ (if lateness (d_i)>0, where K is some positive constant).

Table 2-6 summarizes the overall traffic performance results from various actual and simulated TSP applications along with the corresponding bus and vehicle delays for comparisons.

Table 2-6 Overall Traffic Performance Evaluations with TSP

Author	Location	Change in Delay			Overall Delay	Person Delay
		Bus	General Traffic	Cross street		
Active Priority (Green extension and/or Red truncation)						
Zaworski (1994)	Powell Boulevard, Portland, U.S.	--	Slightly increased	--	--	Overall decrease
Kloos et al (1995)	Powell Boulevard, Portland, U.S.	-12.3%	--	--	--	Minimal
Zaworski & Danaher (1995)	NE Multnomah Street, Portland, U.S.	--	--	--	--	Increase
Al-Sahili & Taylor (1996)	Ann Arbor, Michigan, U.S.	--	--	--	--	+8%
Garrow & Machemehl (1998)	Austin, Texas, U.S.	--	--	--	--	0% to +3%
Khasnabie & Rudraraju (1997)	Ann Arbor, Michigan, U.S.	--	--	--	--	-5 to +3.2 person-minute
Dale et al (1999)	Downtown Portland, U.S.	--	--	--	+0 to +5 seconds	--
Balke et al (2000)	Hypothetical network	--	--	+2% to +26%	+2% to +11%	--
Furth & Muller (2000)	Eindhoven, Netherlands	AM: -75%*; PM: -52%*	Minimal	--	No impact	--
Traffic Adaptive / Real-Time Priority (Optimization, or Genetic Algorithm & Neural Network)						
Yagar & Han (1994)	Toronto, Ontario, Canada	-12.2%	-4.3%	--	--	-6.1%
Duerr (2000)	City of Wurzburg, Germany	--	--	--	--	-33%

* Result obtained for the specified peak hour period.
Note:
- Negative change denotes a reduction, and positive change denotes an increase with TSP implementation.
- The percentage represents average percentage with respect to the base case (i.e., no TSP).

Table 2-6 shows that there is no consistent pattern of the change in overall delay or passenger delay when TSP is implemented.

2.2.2 ECONOMIC EVALUATION

The previous section describes the results from previous studies that used traffic performance such as delay and travel time as measures of effectiveness (MOEs) of various transit priority projects. However, among the literatures reviewed, only a few assessed the transit signal priority project economically. One of the main reasons for this, as suggested by Khasnabis et al (1999), is the "inherent difficulty in converting the operational consequence data (e.g., delay, queue length, etc) to a dollar value". Yet, a number of studies have attempted to report an estimated monetary value of time and delay time, as listed in the Table 2-7.

Table 2-7 Dollar Value of Time and Delay Time

Author	Year	Time Value	Delay Value
Jacobson	1993	--	\$7.00/hr
McLeod	1998	\$8.90/hr	\$9.50/hr
Khasnabie et al	1999	--	\$11/hr to \$15/hr
IBI Group	2000	--	\$8.00/hr

Various attempts have been made to evaluate a transit priority strategy economically. Two common approaches are:

- "Economic Consequence of a TSP System": Use the known costs and traffic MOEs to predict the consequential economic impact of a transit priority project.
- "Criterion for an Economically Feasible TSP System": Obtain the cost or traffic MOEs for an economically acceptable and feasible transit priority project (e.g., benefit-cost ratio > 1).

2.2.2.1 Economic Consequence of a TSP System

This economic evaluation approach uses the known costs and traffic MOEs to estimate the economic impact or consequence of a transit priority project. The traffic MOEs are converted to dollar values to compare with the costs of the project.

Jacobson (1993) performed a comprehensive cost effectiveness analysis to evaluate transit signal priority projects. Benefit-cost ratio was used as an economic MOE and was computed as:

$$B/C = \frac{HOV\_travel\_time\_benefit}{Cost\_of\_implementation}$$

According Jacobson (1993), the ratio of high occupancy vehicle (HOV) travel time benefit (obtained from computer simulation analysis) to the cost of transit priority implementation (estimated for each intersection) was compared at different levels of service (LOS) under different bus volumes and passenger loadings. The following assumptions were made in the analysis:

- Time value: $7 per hour.
- Cost estimate: $15,000 per intersection.
- Travel time savings (% of bus delay saved): 30%.
- Project life: 10 years.
- Real discount rate: 3.5%

The results obtained are summarized below:

COST EFFECTIVENESS ANALYSIS OF TRANSIT SIGNAL PRIORITY TREATMENT (Jacobson, 1993)

LOS	Passenger Load	Bus Volume (Veh/hr)				
		2	4	6	8	10
B	20	0.1	0.3	0.4	0.5	0.7
	30	0.2	0.4	0.5	0.7	1.0
	40	0.3	0.5	0.6	**1.0**	**1.3**
C	20	0.3	0.6	0.9	**1.1**	**1.5**
	30	0.5	0.9	**1.4**	**1.7**	**2.3**
	40	0.6	**1.2**	**1.8**	**2.3**	**3.0**
D	20	0.4	0.8	**1.3**	**1.6**	**2.1**
	30	0.6	**1.3**	**1.9**	**2.4**	**3.2**
	40	0.8	**1.7**	**2.5**	**3.2**	**4.2**
E	20	**1.0**	**2.0**	**3.0**	**3.7**	**5.0**
	30	**1.5**	**3.0**	**4.5**	**5.6**	**7.5**
	40	**2.0**	**4.0**	**6.0**	**7.5**	**10.0**

Note: B/C ratio >1 (Bolded value) is considered as economically feasible.

The result of the analysis showed that higher benefit-cost ratios (in terms of HOV travel time) could be obtained at higher LOS, higher passenger loads, and higher bus volumes. According Jacobson (1993), the result was reasonable for the following reasons:

- As the traffic condition approached congestion (higher LOS), a bus would benefit more with transit priority since higher number of priority calls would be requested.
- As passenger load increased, the benefit gained by a bus priority would be higher in terms of "person-delay" savings.
- As the bus volume increased, more buses would benefit from the transit priority, thereby increasing the benefits to the buses.

Al-Akhras et al (1999) proposed a method to predict the net savings (i.e., benefit minus cost) of a transit priority project at any location (New Case) based on the net savings at a "base" location (Base Case). The net savings of the base location was determined by the actual cost of implementation and the delay savings (or benefits) at all approaches obtained from CORSIM simulation. It could be expressed by:

$$OvearllSavings_{Base} = Benefits(\$) - Costs(\$)$$

According to Ak-Akhras (1999), the net savings at any location (New Case) could be estimated based on following five criteria:

- Number of signals: It was believed that the benefits would increase with the number of signals;

- Number of bus stops: It was believed that the benefits would increase with the number of bus stops;
- Length of route: It was believed that the benefits would increase with the length of the bus route;
- Number of buses per route per day: It was believed that the benefits would increase with the number of buses per route per day; and
- Average daily traffic along the route: It was believed that the benefits would decrease with the average daily traffic along the route.

A multiplier is obtained for each criterion described immediately above. The multipliers are expressed as shown:

	No. Signals (M_1)	No. Bus stops (M_2)	Route Length (M_3)	Bus per route (M_4)	Daily Traffic (M_5)
Multiplier of Each New Case	$\frac{NewCase}{BaseCase}$	$\frac{NewCase}{BaseCase}$	$\frac{NewCase}{BaseCase}$	$\frac{NewCase}{BaseCase}$	$\frac{BaseCase}{NewCase}$

According to Ak-Akhras (1999), a final multiplier of any new case was expressed as the product of the five multipliers (i.e., $FinalMultiplier = M1 * M2 * M3 * M4 * M5$). Cost savings of the new case is then calculated as the product of the base case cost savings and the final multiplier:

$$OverallSavings_{New} = OverallSavings_{Base} * FinalMultiplier$$

2.2.2.2 Criterion for an Economically Feasible TSP System

This evaluation approach determines the criteria to make a transit priority project economically justified and feasible. These criteria are mostly used for transit priority strategy selection.

Jepson et al (1997) examined various bus priority measures by comparing the bus travel time benefits to the costs of the projects. A break-even assessment was applied to identify the minimum number of bus passengers required to justify for each bus priority measure. The minimum bus passenger was expressed as:

$$MinimumPassenger = \frac{(Delay_{Car1} * Vol_{Car1} * OCC_{Car}) - (Delay_{Car2} * Vol_{Car2} * OCC_{Car})}{Delay_{Bus2} - Delay_{Bus1}}$$

For Vol = Volume; OCC_{Car} = Occupancy of general vehicles; Car 1 = for general vehicle with no transit priority; Car2 = for general vehicle with transit priority; Bus 1 = for bus with no transit priority; and Bus2 = for bus with transit priority.

Khasnabis et al (1999) performed a more comprehensive economic analysis to calculate the maximum initial implementation cost to justify for the expected benefits of a transit priority project (i.e., benefit-cost ratio >= 1):

$$B/C = \frac{EUAB}{EUAC} = 1 \quad or \quad EUAC = C_{Max}(CRF) + C_{O\&M} - S(SFF) = EUAB$$

For EUAB = equivalent uniform annual benefit; EUAC = equivalent uniform annual cost; CRF = capital recovery factor; SFF = sinking fund factor; C_{Max} = maximum initial implementation cost; and $C_{O\&M}$ = operation and maintenance cost (assumed to be 15% of the initial implementation cost).

The annual net benefit (EUAB) of the project was obtained from CORSIM simulation, estimated to be the annual benefits in delay and fuel savings and the annual disbenefit in emission increase. In computing the EUAB, the following assumptions were made by Khasnabis et al (1999):

- The simulation output was annualized from a 2-hour peak period for 225 operation days a year.
- The savings in delay valued from \$11/hr to \$15/hr.
- The gasoline price was \$1.25/gal.
- Emission was valued at \$0.10/kg.

Other assumptions in the analysis included a discount rate of 10%, a project service life of 15 years, and the operation and maintenance (O&M) cost being 15% of the initial implementation cost (C). The maximum initial implementation costs (C_{Max}) for various delay saving values were reported, as shown in the table below:

C_{MAX} VALUES FOR VARYING COSTS OF DELAY (Khasnabis et al, 1999)

Net Benefit					Cost	
Delay		Fuel	Emission	EUAB	O&M	C_{Max}
-1360 seconds		-356.8 gal	+2170 kg			
\$/hr	\$ Savings	\$ Savings	\$ Savings			
11	\$14,960	\$446	-\$217.90	\$15,188	0.15C	\$53,954
12	\$16,320	\$446	-\$217.90	\$16,548	0.15C	\$58,785
13	\$17,680	\$446	-\$217.90	\$17,908	0.15C	\$63,616
14	\$19,040	\$446	-\$217.90	\$19,268	0.15C	\$68,448
15	\$20,400	\$446	-\$217.90	\$20,628	0.15C	\$73,278

Note: EUAC = EUAB because B/C =1.

The result of the analysis showed that savings in delay was the major component of the EUAB; while, the fuel savings and emission increase only had minor effects on the computation of C_{Max}.

2.3 CONSIDERATIONS FOR TSP IMPLEMENTATION

Transit priority techniques are designed to provide preferential treatments for buses at signalized intersections. A priority strategy, if designed properly, could provide continuous green phase for buses at successive intersections, thereby reducing the travel time and delays along the bus route [Khasnabis & Rudraraju, 1997]. However, transit priority may also incur negative impact on the general traffic in the traffic network, particular with the cross street traffic. As a result, considerations of the surrounding traffic environment and assessment of all possible transit priority impacts should be taken into account when designing a transit priority system that provide priority to buses while maintaining a satisfactory performance of other road users.

The case studies described in Section 2.2 showed that the effectiveness of a TSP strategy would have some association with the actual traffic conditions and bus characteristics on a transit corridor. In other words, one transit priority measure could be successful (e.g., provide overall delay reduction) in one corridor while failing (e.g., lead to overall delay increase) in another, or it could be successful on a corridor during a specific time period but not during another period. Of note, the success of a TSP project can be determined by an improvement in the traffic performance or the cost effectiveness of the project. Therefore, Noyce et al (1997) recommended that the transit signal priority technique must be flexible and meet the viable needs of transit and traffic operations throughout the day. ITS America (2002) also pointed out that traffic environment such as roadway geometry, traffic volumes, traffic signal operations, pedestrians and transit stop locations could influence the design and operations of a TSP system. As a result, multiple types of priority treatment for different environments might be more appropriate than trying to apply one solution everywhere [ITS America, 2002].

Jacobson (1993) pointed out several factors of the non-sustained existence of several transit priority systems in the US. First, it is due to the failure of these TSP projects to strike a balance between adequately providing the needs of general traffic while concurrently providing sufficient benefits to transit to make such a system cost effective. Second, advanced control strategies and auto vehicle identification (AVI) have only become available recently. Third, there is a lack of sufficient commitment to the HOV philosophy on the operational level; an example Jacobson gave was the failure to make adjustment to bus schedule with TSP implementation and the benefit was, therefore, lost.

Considerations for TSP implementation have been reported in a number of studies. These considerations can be categorized into five main areas:

- Signal Coordination,
- Vehicular Volumes,
- Bus Volumes & Headways,
- Bus Stop Location, and
- Pedestrian Considerations.

Considerations of each of the five areas are summarized in the following sections.

2.3.1 SIGNAL COORDINATION

Signal coordination can be used to platoon vehicles through a series of signalized intersections [Daniel, 1997]. However, it is not that effective in improving transit operation because of the additional passenger dwell time for transit vehicles and the variation in travel times between transit vehicles and general vehicles. Providing priority for transit vehicles in a coordinated network would result in the out of step of coordination, thereby increasing the overall delay of vehicles in the network. This also would penalize the cross street traffic and create significant delay at locations where the cross street carries significant traffic volumes [Daniel, 1997]. As a result, the impact and strategy to incorporate TSP into a coordinated network should be thoroughly considered.

Several efforts had been made in previous researches to incorporate transit signal priority into a coordinated network.

Skabardonis (2000) proposed that transit signal priority should only be granted if there is sufficient spare green time in a signal cycle. This would not result in over-saturation at a signalized intersection or loss of signal coordination. And, this would mean that little or no transit vehicles would be given priority along congested corridors or during peak hours. According to Skabardonis (2000), the spare green time was computed as:

$$G_{Spare} = \sum_{i=1}^{N} G_i * (1 - X_i)$$

For G_i = green time for phase i, X_i = degree of saturation of the critical link in phase i, N = total number of phases in a cycle.

Chatila & Swenson (2001) set the maximum green extension time to 20% (or one-fifth) of the cycle length. To return to coordination, every 5^{th} second in the cycle is skipped until the local clock (with adjusted time for green extension) and the master clock (with original reference time) are back in synchronization.

As described in Section 2.1.3.2, Duerr (2000) used a sophisticated algorithm called DARVIN (with static optimization by Genetic Algorithm and dynamic adaptation by Neural Network) to minimize the interference between transit vehicles and other general vehicles and to maintain the existing signal coordination as far as possible.

2.3.2 VEHICULAR VOLUMES

A number of studies pointed out that TSP would not be effective along a congested corridor or at a corridor with high cross street volumes. Jacobson (1993) explained this by the fact that signal priority did not provide additional capacity; therefore, it could not provide travel time savings to buses at intersections over capacity (LOS F). Jacobson (1993) further suggested that under this situation, a high occupancy vehicle (HOV) lane would be needed to provide additional capacity to the buses. Daniel (1997) supported this and stated that an HOV lane would be necessary in addition to signal priority for extremely congested conditions; yet, if an HOV lane could not be implemented, reverse progression (to provide green to a downstream intersection prior to providing green to an upstream intersection to remove the downstream queue) should be considered, particularly for intersections with short spacing and substantial queuing.

Chatila & Swenson (2000) also suggested that vehicle queuing, especially right-turning vehicles at intersections and their associated queue lengths, significantly impacts the effectiveness of TSP. Under this situation, additional time would be required to process the right-turn vehicles for the transit vehicles to enter the intersection, thus the benefits of TSP would be eliminated [Chatila & Swenson, 2000].

The researches mentioned above reported some association between vehicular volumes and the effectiveness of TSP implementation. Yet, only few studies actually performed analyses to examine the overall impacts of signal priority under different traffic saturation conditions.

Chang et al (1995) proposed an integrated system for bus preemption and adaptive signal control. In the proposed system, unconditional priority was granted to the buses over the passenger cars. The bus preemption was measured by a performance index, which included vehicle delay, bus schedule delay, and passenger delay. The authors used NETSIM to evaluate the total passenger delay under passenger car volumes of 300, 500, and 1000 Veh/hr/lane (vphpl) and mean bus headways of 120 and 180 seconds.

TOTAL DELAY FOR THE ADAPTIVE CONTROL LOGIC WITH AND WITHOUT PREEMPTION (Chang et al, 1995)

Traffic Volume (vphpl)	Mean Bus Headway (sec)	Total Passenger Delay (sec)		Percent Change
		W/o Preemption	With Preemption	
300	180	24,342	3,483	- 85%
	120	25,470	4,833	- 81.1%
500	180	34,044	18,609	- 45.3%
	120	33,303	22,020	- 33.9%
1,000	180	57,990	57,195	- 1.4%
	120	60,372	55,869	- 7.5%

Note: A negative percentage implies a reduction in total passenger delay with preemption.

The results showed that the proposed adaptive control performed especially well under light-to-moderate traffic volume, but exhibited a slight decrease in benefits at higher traffic volumes on the bus approach. This could be explained by the fact that the bus had to compete with longer private car queues for priority under congestion.

Garrow & Machemehl (1998) performed comprehensive analyses using CORSIM to simulate various green extension measures on the Gaudalupe corridor in Austin, Texas. The analyses aimed to determine whether the use of signal priority was justified and to examine the overall impact of signal priority. The tables below summarize Garrow & Machemehl (1998)'s results on the guidelines for the use of unconditional priority during off-peak hours, the negative impacts accruing on cross streets due to signal priority, and the total travel time within the arterial network under four different green extension strategies.

GUIDELINES FOR USE OF UNCONDITIONAL PRIORITY DURING OFF-PEAK HOURS (Garrow & Machemehl, 1998)

Cross street Saturation Level	Recommended Green extension / Red truncation Length
Below 0.25	Unbounded
0.25 to 0.35	20 seconds
0.35 to 0.70	10 seconds

NEGATIVE IMPACTS ACCURING ON CROSS STREET DUE TO SIGNAL PRIORITY (Assumed Headway = 10 minutes) (Garrow & Machemehl, 1998)

Cross street Saturation	Green extension = 10 sec	Green extension = 20 sec
Saturation Level = 0.8	Minimal	Moderate
Saturation Level = 0.9	Moderate	**Significant**
Saturation Level = 1.0	**Significant**	**Significant**

TOTAL TRAVEL TIME (PERSON-MINUTES) WITHIN ARTERIAL NETWORK (Assumed Bus Occupancy = 10 and Auto Occupancy = 1.2) (Garrow & Machemehl, 1998)

Person-Minutes	Case 0	Case 1	Case 2	Case 3
Auto Travel Time along arterial	4,405	4,379	4,376	4,417
Auto Travel Time along Cross street	2,899	3,193	3,023	2,985
Bus Travel Time along Arterial	108	108	96	99
Total Travel Time within Arterial Network	7,412	7,661	7,494	7,501

Note: Case 0 = Base Case with no Green Extension (GE).
Case 1 = 20-second GE for all intersections.
Case 2 = 10-second GE for saturated intersections, and 20-second GE for others.
Case 3 = No GE for saturated intersections, and 20-second GE for others.

Garrow & Machemehl (1998) reported that if the cross street saturation level was less than 0.25 (i.e., during off-peak hours), the cross street traffic could recover even with unlimited priority calls; and at this saturation level, a bus would rarely request for priority because a large portion of the time would be green for the bus approach traffic. The report also conferred that there would be severe negative impact on the cross street traffic if the cross street saturation level is 1.0 with a 10-second green extension, or if the cross street saturation level is 0.9 with a 20-second green extension. Under these situations, the cross street traffic would require 2 to 3 cycles to recover.

Balke et al (2000) proposed the "intelligent bus priority concept" that aimed to provide priority only to buses that were truly in need of priority on the basis of measurable and user-defined criteria. This aimed to ensure that the progression on the primary arterial street would not be disrupted and the normal sequence and duration of the non-coordinated phase would not be significantly altered. In this bus priority system, vehicle tracking technologies were used to estimate the arrival time of the buses and to compute whether the buses were behind schedule. Communication and control technologies were employed to examine different priority strategies, to select the most appropriate strategy subjected to wherein the cycle the buses arrived, and to adjust for the duration and sequence of the traffic signal phases. The bus priority concept was simulated with TexSIM Traffic Simulation model and the simulation was used to assess the impacts of the intelligent bus priority system on bus and non-transit vehicle travel time and average stop delay for various volume-to-capacity ratios. The tables below show the impacts of the priority system on bus and general traffic travel time and average stop delay at a v/c level of 0.5, 0.8 and 0.95.

IMPACTS OF USING INTELLIGENT PRIORITY ON BUS AND NON-TRANSIT VEHICLE TRAVEL TIME (Balke et al, 2000)

V/C Level	Direction	Travel Time		Difference in Travel Time	Percentage Change
		With TSP	W/o TSP		
Bus Travel Time					
0.5	--	259.6	345.5	-85.9	-25%
0.8	--	280.4	382.6	-102.2	-27%
0.95	--	309.4	421.3	-111.9	-27%
Non-transit Vehicle Travel Time					
0.5	Same as Bus	235.1	239.9	-4.8	-2%
	Opposite of Bus	226.5	230.8	-4.3	-2%
0.8	Same as Bus	275.2	283.1	-7.9	-3%
	Opposite of Bus	267.8	274.9	-7.1	-3%
0.95	Same as Bus	300.7	315.1	-14.4	-5%
	Opposite of Bus	293.0	301.8	-8.8	-3%

Note: A negative value implies a reduction in travel time with transit priority.

The above table illustrated that the intelligent priority system improved the bus travel time by more than 25% in the three v/c ratio of 0.5, 0.8, and 0.95; while at the same time, slightly reduced the travel time of the general traffic running parallel to the bus approach.

The authors also reported that the proposed intelligent bus priority system would have substantial negative impacts on the average stop delay of traffic traveling on the non-priority approach at v/c ratio greater than 0.95. The table below shows the impacts on average stop delay for the three v/c levels.

IMPACTS OF USING INTELLIGENT PRIORITY ON AVERAGE STOP DELAY (Balke et al, 2000)

V/C Level	Direction	Movement	Average Stop Delay (sec/veh)		Difference in Stop Delay	Percent Change
			With TSP	W/o TSP		
System Stop Delay						
0.5	All	All	27.8	27.8	0.0	+ 0%
0.8	All	All	35.5	34.8	0.7	+ 2%
0.95	All	All	52.8	47.5	5.3	+ 11%
Approach Stop Delay						
0.5	Same	Left	39.8	38.6	1.2	3%
		Through	20.7	22.1	-1.4	-6%
	Opposite	Left	40.1	29.1	1.0	3%
		Through	19.8	21.0	-1.2	-6%
	Cross Street	Left	33.1	32.5	0.6	2%
		Through	32.7	31.3	1.4	4%
0.8	Same	Left	50.6	44.5	6.1	14%
		Through	27.9	30.1	-2.2	-7%
	Opposite	Left	50.6	44.2	6.4	14%
		Through	26.8	29.1	-2.3	-8%
	Cross Street	Left	45.5	43.4	2.1	5%
		Through	38.0	35.3	2.7	8%
0.95	Same	Left	76.4	65.3	11.1	17%
		Through	33.1	36.9	-3.8	-10%
	Opposite	Left	81.8	65.4	16.4	25%
		Through	32.2	34.4	-2.2	-6%
	Cross Street	Left	79.2	68.3	10.9	16%
		Through	64.3	50.9	13.4	26%

Note: A negative value implies a reduction in stop delay with transit priority.

2.3.3 BUS HEADWAYS

Bus volumes and bus headways are factors that govern the frequency of transit priority requests. The number of request will increase when bus volume increases (or bus headway reduces).

Several previous studies agreed with Noyce et al (1997)'s proposal that large transit volumes would make TSP infeasible and can have detrimental effects on the cross street traffic operation. Daniel (1997) added to this by reporting that priority for a large bus volume could increase delay of the entire network and could penalize the cross street traffic, especially if the cross street volume was high. Daniel proposed the deployment of passive priority strategy if the priority calls were requested more than 50% of the time.

The preference of bus headways was more controversial among researches. To justify the provision of the Bus Priority System, Al-Sahili & Taylor (1996) proposed that bus headways would have to be less than 15 minutes. This would mean an increase in the number of buses and passengers, if constant passenger occupancy on each bus was assumed; consequently, this would mean an increase in the benefits (by person) of the priority system. However, some studies contradicted this preference of smaller headway;

IBI Group (2000) reported that longer headways (15 minute), combined with conditional priority to buses behind schedule and cancellation of green extension as soon as the bus clear the intersection, attributed to minimal average delay to the entire Route 123 network in the Lower Mainland, British Columbia, Canada.

Very little work had addressed the question of the optimum bus headway for preemption operation. Khasnabis & Rudraraju (1997) attempted to address this gap by examining the possible consequences of different headways for a bus preemption operation. A major bus route in Ann Arbor, Michigan was selected for the demonstration and was simulated using NETSIM. Transit priority strategies examined were green extension or red truncation, depending on the arrival time of the bus relative to the signal phase. The measure of effectiveness used in the evaluation was person-minute of delay. To account for the unequal number of vehicles likely to be processed during the base case and the priority case, a normalization procedure was used to correct for the person-minute delay between the two cases. The corrected delay (person-minute) for the preempted case was:

$$(VehicleTrip_{Base} / VehicleTrip_{\Pr eempted}) * Delay_{\Pr eempted}$$

According to Khasnabis & Rudraraju (1997), assumptions made in the simulation model were:

- Average bus occupancy: 40 persons per bus;
- Average car occupancy: 1.4 persons per car;
- Cycle length: 70 seconds;
- Preemption length: 10 seconds;
- Target direction: eastbound (from Forest to Manchester)

For the base case and the preemption case, bus headways of 15 minutes, 10 minutes and 7.5 minutes were simulated using NETSIM. The impacts of the 3 headways on person-minute delay were analyzed based on the link (approach) level, the node (intersection) level, and the route-level (main street target direction, main street both directions, cross street both directions, or main street and cross street combined). The changes in person-minute delay at the intersection-level and the route-level for the 3 headways were presented by Khasnabis & Rudraraju (1997).

CHANGES IN PERSON-MINUTES OF DELAY BETWEEN BASE AND PREEMPTION CASES, INTERSECTION LEVEL (Khasnabis & Rudraraju, 1997)

Headways	Forest/ Obser.	S. Univ. Drive	Hill Street	Austin/ Devon	Brockman	Stadium Drive	Manch./ Sheridan
15 minute	-0.9	+18.2	**-2.5**	**-3.7**	**-3.2**	-0.5	-2.1
10 minute	**-11.0**	**-0.8**	**-2.5**	+1.0	-1.0	+0.3	**-3.4**
7.5 minute	-1.9	+1.1	-0.7	-2.7	**-3.2**	**-1.5**	-0.4

Note:
- A negative value implies a reduction in person-minute of delay with bus preemption.
- Bolded value corresponds to the headway that produces the highest delay reduction for any particular intersection.

The intersection-level analysis showed that the headway that incurred the most reduction in delay varied from intersection to intersection.

CHANGES IN PERSON-MINUTES OF DELAY BETWEEN BASE AND PREEMPTION CASES, ROUTE LEVEL (Khasnabis & Rudraraju, 1997)

Headways	Main Street (EB)	Main Street (Both Directions)	Cross Street (Both Directions)	Main & Cross Street
15 minute	-4.0	-2.3	+3.2	-0.7
10 minute	**-5.0**	**-2.6**	-0.3	-2.0
7.5 minute	-1.5	-2.0	**-4.1**	**-2.7**

Note: A negative value implies a reduction in person-minute of delay with bus preemption.

The route-level analysis illustrated that 10-minute bus headway would produce the best result if reducing delay of the main street target direction or reducing delay of the main street both direction was the objective. Yet, if reduction in delay of the cross street both directions or of the combined main street and cross street was the objective, a 7.5-minute bus headway should be considered as the best alternative. However, no conclusive optimum headway was determined in the study because Khasnabis & Rudraraju (1997) claimed that the observations were tempered by limited simulation database; and, a decision to arrive at an optimal headway could be made only after repeated simulation runs for these different headway groups.

Agrawal et al (2002) also attempted to examine the impact of bus frequency in a simulation period of 30 minutes. They examined the importance of dynamic traffic assignments models in the evaluation of transit preemption strategies. Agrawal et al (2002) reported the following observations on the impact of bus frequency:

- When the number of buses rises above 30, the total system travel time of the no preemption and preemption strategies converged.
- At bus service frequency of 15, the minimum difference in total system travel time with and without preemption was observed. The authors expected that the difference would remain constant at a higher bus frequency; but this did not happen because of the vehicle route changing after preemption.
- The benefit from preemption on bus trip time was higher when there were fewer buses; and above approximately 20 buses, the benefit decreased and leveled off.

2.3.4 BUS STOP LOCATION

According to a number of previous researches, the location of bus stop can have significant impact on the efficiency on transit priority. A bus stop is a pre-specified location for passengers to board and alight from a bus. The time that is needed for the boarding and alighting is called the "Dwell time". There can be two types of bus stop locations:

- Nearside Bus Stop: Bus stop that is located upstream of a stop line. With this type of bus stop, dwell time at the bus stop should be considered when determining the extension of transit priority; or else, priority would be wasted.

- Farside Bus Stop: Bus stop that is located downstream of an intersection. Dwell time at this type of bus stop has minimal influence on the effectiveness of transit priority.

Figure 2-6 illustrates the two types of bus stops.

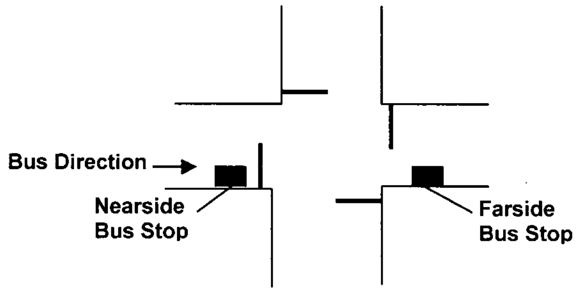

Figure 2-6 Illustration of Nearside Bus Stop & Farside Bus Stop

Among the literatures researched, there were more preferences on the employment of farside bus stop for the implementation of TSP. This is because the use of a nearside bus stop would increase the uncertainty in predicting the arrival time of a bus at an intersection due to the uncertainty in the passenger loading and unloading time [Daniel, 1997]. It was also claimed that the use of a farside bus stop would maximize the efficiency of signal priority because of the minimal influence from dwell time [Huffman et al, 1998].

Moreover, ITS America (2002) also proposed that the use of nearside bus stops presented some additional challenges when placing the bus detectors upstream of the bus stops. It pointed out that if the transit vehicles were detected upstream of a nearside bus stop, the dwell time had to be considered in the TSP timings. In addition, vehicle queuing might block the transit vehicles from getting to the nearside bus stop, resulting in additional delays and a more complex signal timing or phasing for an effective provision of priority to the transit vehicles [ITS America, 2002]. In general, ITS America (2002) suggested that a balance between the benefits of each bus stop location must be considered on a stop-by-stop basis.

However, relocation of the bus stop locations from nearside to farside would not always be feasible due to road geometric restrictions. To address the problem with nearside bus stops, Yagar (1993) suggested that signal timings for Passive Transit Priority should be set such that bus loading/unloading took place during the red phase of the bus approach, given the arrival and dwell time at each bus stop. This would reduce the delays of buses in queue and the delays of general vehicles as the buses loaded.

Skabardonis (2000) proposed alternation of nearside bus stops and farside bus stops at successive intersections. This aimed at avoiding buses from stopping both at the stop line (when the signal is red) and the bus stop at successive intersections. The idea is illustrated in Figure 2-7.

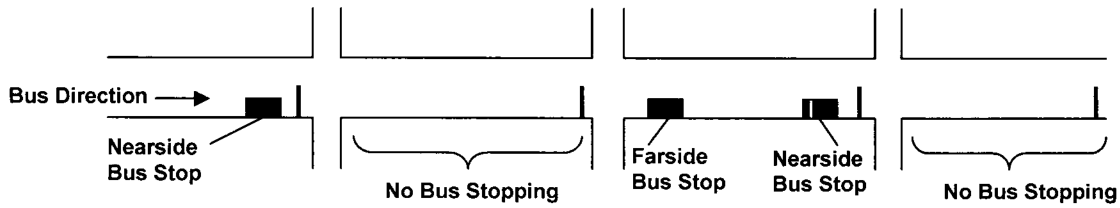

Figure 2-7 Alternating Nearside & Farside Bus Stop at Successive Intersections

Figure 2-7 shows that the bus would require no mid-block dwelling at alternating blocks. This would reduce the bus delay and would allow buses to "enjoy" the signal coordination designed for vehicles at these alternating blocks.

Garrow & Machemehl (1998) examined the effectiveness of green extension at nearside and farside bus stops by TRAF-NETSIM simulation program. The effectiveness was determined by the success rate for buses to clear an intersection during the extended green phase (i.e., avoiding a red indication). The success rate result showed that the presence of a nearside bus stop would greatly hinder the effectiveness of green extensions. This is because a significant portion of the green extension would be wasted while passengers board and alight at the nearside bus stop [Garrow & Machemehl, 1998]. On the other hand, transit signal priority is more successful when farside bus stops were used because the success of signal priority was no longer a function of the bus dwell time. The following tables presented Garrow & Machemehl (1998)'s green extension success rate results for a nearside bus stop and a farside bus stop with 10- and 20-second green extensions at bus approach saturation levels of 0.8, 0.9 and 1.0.

SUCCESS RATE OF GREEN EXTENSIONS OF NEARSIDE BUS STOP (Garrow & Machemehl, 1998)

Green Extension Length	Bus Approach Saturation Level	No. of Attempted Extensions	No. of Successful Extensions	Success Rate
10 seconds	0.8	10	2	20%
10 seconds	0.9	10	1	10%
10 seconds	1.0	10	0	0%
20 seconds	0.8	10	3	30%
20 seconds	0.9	10	3	30%
20 seconds	1.0	10	0	0%

Note: Success Rate = No. of Successful Extensions / No. of Attempted Extensions.

SUCCESS RATE OF GREEN EXTENSIONS OF FARSIDE BUS STOP (Garrow & Machemehl, 1998)

Green Extension Length	Bus Approach Saturation Level	No. of Attempted Extensions	No. of Successful Extensions	Success Rate
10 seconds	0.8	8	5	63%
10 seconds	0.9	9	6	67%
10 seconds	1.0	10	5	50%
20 seconds	0.8	8	7	88%
20 seconds	0.9	9	8	89%
20 seconds	1.0	10	6	60%

Note: Success Rate = No. of Successful Extensions / No. of Attempted Extensions.

2.3.5 PEDESTRIAN CONSIDERATIONS

The main focus of most transit signal priority studies was on its benefit and disbenefits on buses and/or vehicles. However, safety to pedestrians during the priority treatment is also a major concern [Noyce & Dunn, 1997].

Most of the current practices and researches put some consideration in pedestrian safety when implementing TSP. For example, early green or red truncation priority measure would only be allowed if the minimum requirement of the pedestrian walk and clearance time was met; and truncating of any pedestrian phase was restricted. These decision rules aim to give higher priority to pedestrians than to buses and general vehicles.

ITS America (2002) pointed out that pedestrians could have a great influence on TSP operations at a signalized intersection because the time required for a pedestrian to safely cross the street at a signalized intersection limits the time available to provide TSP. Additionally, it was believed that signal priority would not be effective in areas with large pedestrian volumes [Noyce & Dunn, 1997]. The presence of pedestrian phases could impact the effectiveness of TSP. The number of pedestrian calls, the length of crosswalks and the required clearance intervals could also impact the priority signal operation and effectiveness [Chatila & Swenson, 2001].

2.4 CHAPTER SUMMARY

This chapter summarizes the literatures reviewed on various aspects of transit signal priority (TSP): the types of TSP strategies, the evaluations of these strategies, and the considerations for the planning and implementation of TSP.

TSP strategies are most commonly categorized as Passive Priority, Active Priority or Traffic Adaptive (or Real-Time Priority). Passive priority uses a pre-determined signal timing plan that favors bus operation and does not require any monitoring or detection system of buses. Some common passive priority strategies include cycle length shortening, phase splitting, area-wide timing plans, and metering vehicles. Active priority causes alteration of the regular signal operation in response to the presence, or imminent presence, of a transit vehicle. Four common types of active priority strategies are green extension, red truncation / early green, special phase and selective strategies. Depending on the location and capabilities of the bus sensors, active priority can also be either unconditional or conditional. Unconditional active priority grants priority to all transit requests; whereas, conditional active priority provides priority only to buses that meet certain per-defined criteria, such as being behind schedule, having high passenger occupancy, or not disrupting other traffic. Traffic Adaptive Priority advances to develop signal timing plans that provide priority for transit vehicles, while incurring the least disruption to the general traffic, based on real-time flow profiles of buses and general vehicles. Documented approaches of traffic adaptive priority include a number of delay optimization models, DARVIN algorithm (employing Genetic Algorithm and Neural Network), and fuzzy logic based control algorithm.

The evaluations of TSP strategies have been widely documented. In this chapter, the evaluation is categorized into two main streams: traffic performance evaluation and economic evaluation. Traffic performance evaluation includes the assessment of bus performance, bus reliability (or schedule adherence), general traffic and cross street traffic performance, and overall traffic performance. It is observed that all documented TSP evaluation reported an improvement in general bus performance (i.e., travel time, delay, speed and reliability). This is reasonable because this is the main purpose of any TSP system. However, the improvement gained in the bus performance usually brought along deterioration in the performance of the cross street traffic. Analysis of the overall traffic performance is usually performed to account for the bus improvement and the general traffic deterioration. However, no consistent pattern of the change in the overall traffic performance is observed in the literatures reviewed. Economic evaluation of TSP projects can assess a project based on cost effectiveness analysis such as benefit to cost ratio or net benefit (i.e., benefit minus cost), or can be used to develop criteria (e.g., minimum passenger requirement or maximum initial implementation cost) needed to make a TSP project economically feasible.

Based on researches reviewed, there are some associations between the effectiveness of a TSP system and its surrounding traffic environments. Considerations that are required for a successful and effective TSP implementation have been reported in a number of studies. In this chapter, five main considerations are looked into: signal coordination, vehicular volumes, bus volumes and headways, bus stop locations, and pedestrian considerations. The generic criteria for each consideration are summarized.

Considerations for a TSP System:

Signal Coordination

- TSP would result in the out of step of signal coordination.
- Influence of TSP on the coordinated network should be kept to a minimum.

Vehicular Volumes

- TSP generally would perform well under light-to-moderate traffic volumes.
- TSP would not be effective along a congested corridor.
- TSP would not be effective at a corridor with high cross street saturation level.
- Right-turn vehicles and their associated queue lengths could significantly impact the effectiveness of TSP.
- Shorter green extension would cause less adverse impacts on cross streets at high saturation level.

Bus Volumes & Headways

- Large transit volumes would make TSP infeasible.
- Large transit volumes could have a detrimental effect on cross street traffic operation.
- An achievement of the optimum bus headway would require repeated simulation runs.

Bus Stop Locations

- Nearside bus stops would not be preferred with TSP because they could increase uncertainties of the projected bus arrival time at an intersection.
- Farside bus stops could maximize the efficiency of signal priority, as there would be less influence from dwell time at these bus stops.
- The success rate of green extension would be significantly higher for farside bus stops than for nearside bus stops.
- Alternating nearside and farside bus stops could avoid the buses from stopping at alternating blocks.

Pedestrian Considerations

- Pedestrian safety should be a major concern of bus priority treatment.
- Minimum pedestrian walk and clearance time should have higher priority than bus detection.
- TSP would not be effective in areas where large pedestrian volumes exist.
- The number of pedestrian calls, the crosswalk lengths, and the required clearance intervals could impact TSP effectiveness.

3.0 EXPERIMENTAL DESIGN

An experimental traffic micro-simulation model is set up to investigate the TSP implementation of the 98 B-Line buses traveling along the Granville Street corridor in the City of Vancouver, British Columbia, Canada. The following sections present some background of the 98 B-Line buses, the Granville Street corridor, and the experimental design of this research.

3.1 AVAILABLE DATA

This section describes the actual traffic elements and environments of the TSP case study evaluated in this research. The following sections provide descriptions of the 98 B-Line buses, the Granville Street corridor on which the 98 B-Line buses run, and the actual signal logic deployed for the TSP application.

3.1.1 98 B-LINE BUSES

The 98 B-Line Rapid Transit Project is one of the major Intelligent Transportation System (ITS) Projects supported by TransLink, the transit authority of the Greater Vancouver Regional District (GVRD). The 98 B-Line is an express bus route that runs between Downtown Vancouver and Downtown Richmond to meet the increasing demand for quicker and more efficient transit service between the two city centers. The 98 B-Line buses pass through three distinctive traffic environments:

- Downtown Vancouver: Downtown Vancouver is the main business core of the region and is the highest commuter attractor in the GVRD. The 98 B-Line buses have to meander on mixed traffic streets and to travel through intersections with equally high traffic volumes from all approaches.

- Granville Street corridor: This corridor is one of the busiest traffic and transit corridors in the GVRD. The 98 B-Line buses run straight through this mixed traffic corridor with comparatively less traffic from the cross street approaches, except at Broadway where the 99 B-Line buses (another rapid transit route) runs.

- Downtown Richmond: The 98 B-Line buses run in the northbound and southbound directions through exclusive bus lanes on the median lanes of the No.3 Road, which is one of the busiest arterials in the City of Richmond.

Figure 3-1 illustrates the route map of the 98 B-Line buses. The empty circles represent the locations of the 98 B-Line bus stops along the route.

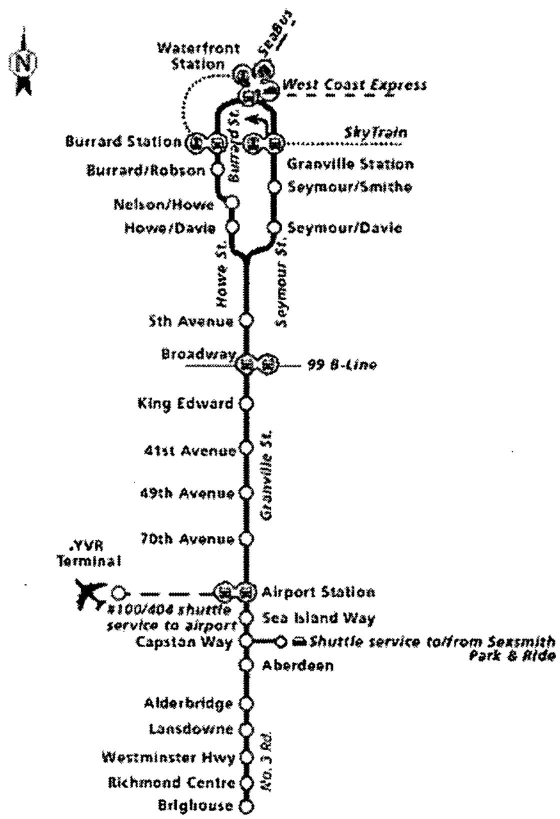

Figure 3-1 **Route Map of the 98 B-Line Buses *(Sources: TransLink website)***

The 98 B-Line will be the first rapid transit route with full-time deployment of Transit Signal Priority (TSP) system in the GVRD. According to the City of Vancouver, the TSP system is expected to be fully deployed in the fall of 2002. All 98 B-Line buses are equipped with a Global Positioning System (GPS) on board for the real-time tracking of the B-Line bus locations. This vehicle tracking system can provide information on the real-time bus arrival time to the transit riders as well as can dissipate the real-time location and schedule adherence information to the transit control center for TSP requests.

For the real-time detection of the 98 B-Line buses, transponders are installed on all 98 B-Line buses. These transponders transmit coded infrared signals on the identification and schedule adherence information to the road-side check-in and check-out detectors, or the "Wayside Unit" [Novax website]. The check-in detectors are for TSP request; while the check-out detectors are for TSP call cancellation or termination.

Figure 3-2 and Figure 3-3 show the vehicle transponder and the Wayside unit, developed by Novax Industries Corporation, for the TSP system of the 98 B-Line Rapid Transit Project.

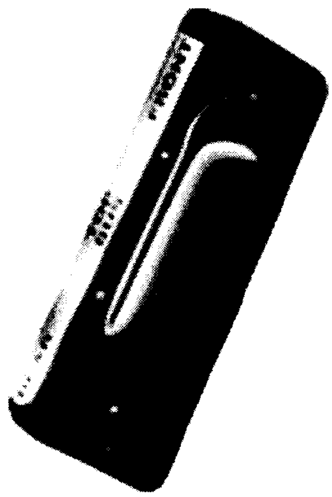

Figure 3-2 Vehicle Transponder (Source: Novax website)

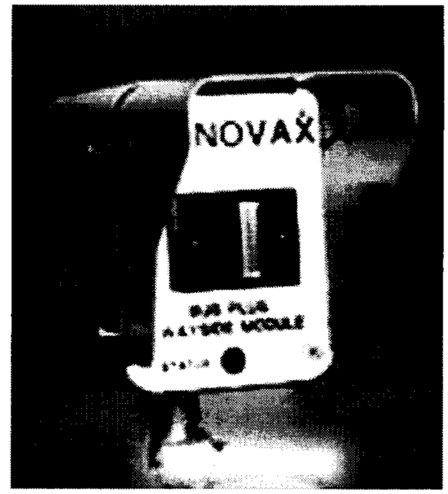

Figure 3-3 Roadside Detector, or Wayside Unit (Source: Novax website)

The actual locations of the 98 B-Line bus check-in detectors along Granville Street are obtained from the IBI Group, the consulting firm responsible for the design of the 98 B-Line TSP systems. The distance between the check-in detectors and the intersection are estimated as the minimum of either the minimum approach distance or the maximum clearance distance based on the average B-Line bus speed and the maximum green extension deployed. According to the IBI Group, the average B-Line bus speed is assumed to be 25 km/hr and the maximum green extension is assumed to be 15 seconds. The locations of the detectors are also constrained by the availability of a pole upstream of the intersections for the detector installations. The actual check-in detector locations, selected by Novax Industries Corporation and provided by the IBI Group, are listed in Appendix A-1.

A site survey was performed to obtain the actual locations of the 98 B-Line bus stops along Granville Street. Along the studied section of Granville Street, five 98 B-Line bus stops are placed on each Granville Street approach. All the B-Line bus stops are farside bus stops (i.e., located downstream of the intersections), except for the B-Line bus stop on the northbound approach at the intersection of Granville Street and Broadway where a nearside bus stop is placed and where TSP will not be implemented. The main reason for placing a nearside bus stop at the intersection is the high transit stop demand that already exists at the intersection in the northbound direction. The actual locations of the B-Line bus stops are shown in Appendix A-2.

3.1.2 GRANVILLE STREET

In this research, an experimental corridor is developed based on a case study of the Granville Street corridor in the City of Vancouver. The Granville Street corridor is chosen because it is where the 98 B-Line bus buses are running in a mixed-traffic condition without any maneuverings (i.e., turn-makings). This matches the focus of this research.

The Granville Street corridor is one of the busiest traffic and transit corridors in the City of Vancouver. It is a 6-lane major arterial that runs in the north-south direction, connecting to the Granville Street Bridge to the north and the Arthur Laing Bridge to the south. It is also designated as part of a provincial highway (i.e., Highway 99) that runs between the US-Canada border to the south and north of British Columbia. The speed limit of the Granville Street corridor is 50 km/hr.

There is a high commuter traffic in the morning peak period in the northbound direction as most people are destined to the Downtown Vancouver and the business districts on Broadway. During the afternoon peak period, the direction of the commuter traffic is in the southbound direction as the travelers leave the business districts. Appendix A-3 shows the normalized weekday traffic count along Granville Street for the AM peak period (7:00 – 9:00 a.m.), PM peak period (4:00 – 6:00 p.m.) and in 24 hours, provided by the City of Vancouver.

The Granville Street section studied stretches between Broadway and 70th Avenue. The entire section is approximately 6.5 km in length, intersected by ten major cross streets running in the east-west direction. These ten major intersections are controlled by either fixed-time or traffic-actuated signals. These major intersections are:

- Granville Street and Broadway;
- Granville Street and 12th Avenue;
- Granville Street and 16th Avenue;
- Granville Street and 25th Avenue;
- Granville Street and 33rd Avenue;
- Granville Street and 41st Avenue;
- Granville Street and 49th Avenue;
- Granville Street and 57th Avenue;
- Granville Street and 59th Avenue; and
- Granville Street and 70th Avenue.

The morning peak traffic condition on Granville Street will be evaluated for this research. The morning peak hour traffic counts at the aforementioned major intersections for the year of 2000, provided by the City of Vancouver, are shown in Appendix A-4. The year 2000 data are used because the year 2001 data are skewed due to the 4-month transit strike in the Greater Vancouver and the year 2002 data was not yet available when the modeling finished.

There are 3 lanes in the northbound and southbound approaches along Granville Street. At the intersections of Granville Street and 41st Avenue and Granville Street and 70th Avenue, additional dedicated left-turn lanes are provided on both Granville Street approaches. As of March 2001, the City of Vancouver implemented left-turn restrictions during the peak periods at most major intersections along Granville Street. Appendix A-5 lists all left-turn restrictions applied along the corridor.

Along most parts of the Granville Street section, the curb lane on Granville Street permits on-street parking except in the northbound direction during the morning peak period and in the southbound direction during the afternoon peak period. And the northbound and southbound rightmost lanes at the south end of the Granville Street section are designated as bus and High Occupancy Vehicle (HOV) lanes during the peak periods. During the morning peak period, the northbound HOV lane is reserved for buses and bicycles; whereas, the southbound HOV lane is reserved for buses and vehicles with more than 2 occupants during the afternoon peak period. The parking restrictions along Granville Street are summarized in Appendix A-6.

The adjacent land use on the Granville Street corridor comprises a mix of business, commercial and residential land uses. The business and commercial land uses are concentrated on the north end and the south end of the corridor; meanwhile, the rest is mostly for residential use. Figure 3-4 illustrates the land use patterns along the Granville Street corridor.

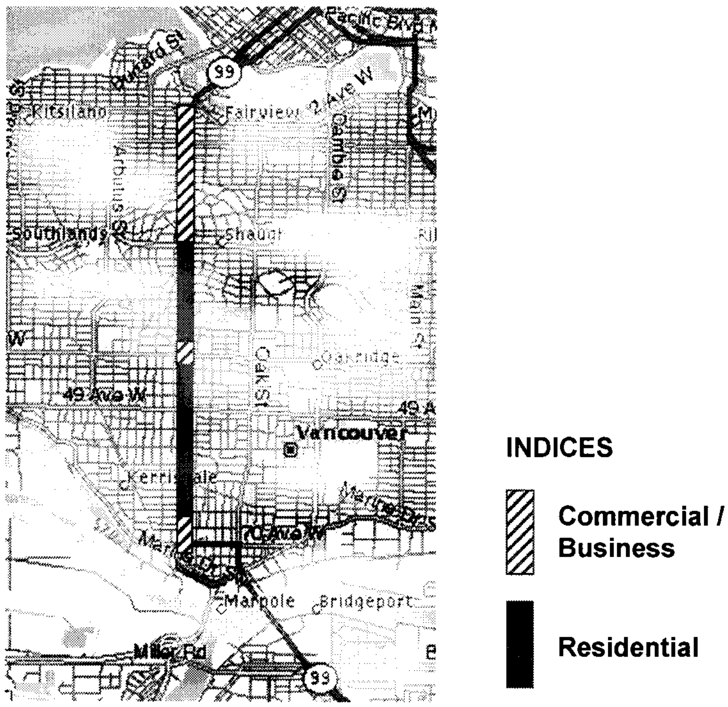

Figure 3-4 Illustration of Land use Pattern on Granville Street

3.1.3 SIGNAL CONTROL LOGIC

According to the year 2000 data from the City of Vancouver, the 98 B-Line bus route traverses nineteen signalized intersections along the Granville Street section from Broadway to 70th Avenue. Among them are ten full traffic signals and nine pedestrian-actuated signals (or half signals). The locations, along with the types of signal control, are given in Table 3-1.

Table 3-1 Type of Signal Control for Signalized Intersections on Granville Street

Intersection	Type of Signal Control	TSP Implementation
Granville Street and Broadway	Fixed-time 3-phased signal	No
Granville Street and 10th Avenue	Pedestrian signal	Yes
Granville Street and 12th Avenue	Fixed-time 2-phased signal	Yes
Granville Street and 13th Avenue	Pedestrian signal	Yes
Granville Street and 14th Avenue	Pedestrian signal	Yes
Granville Street and 16th Avenue	Fixed-time 3-phased signal	Yes
Granville Street and 25th Avenue	Fixed-time 2-phased signal	Yes
Granville Street and 27th Avenue	Pedestrian signal	No
Granville Street and 33rd Avenue	Fixed-time 2-phased signal	Yes
Granville Street and 37th Avenue	Pedestrian signal	No
Granville Street and 41st Avenue	3-phased actuated NS-LT signal	Yes
Granville Street and 45th Avenue	Pedestrian signal	No
Granville Street and 49th Avenue	Fixed-time 2-phased signal	Yes
Granville Street and 57th Avenue	Semi-actuated signal	Yes
Granville Street and 59th Avenue	Semi-actuated signal	Yes
Granville Street and 63rd Avenue	Pedestrian signal	No
Granville Street and 64th Avenue	Pedestrian signal	Yes
Granville Street and 68th Avenue	Pedestrian signal	Yes
Granville Street and 70th Avenue	Fixed-time 3-phased signal	Yes

According to the City of Vancouver, coordination is maintained for the general traffic on three different Granville Street sections: North of 16th Avenue, from 25th Avenue to 59th Avenue, and from 64th Avenue to the South end of Granville Street. A fixed cycle length of 75 seconds is deployed along the Granville Street corridor. The offsets and the details of signal phases, provided by the City of Vancouver, are summarized in Appendix A-7.

According to the City of Vancouver, the maximum green extension (or Max-Timer) proposed for the B-Line buses on Granville Street is 14 seconds. While the maximum red truncation at each intersection is determined by the minimum walk time specified by the City of Vancouver. TSP will be implemented at most of these signalized intersections except five intersections. These locations along with the reasons for no TSP implementation are listed below:

- Granville Street and Broadway: TSP will not be implemented at this intersection because of the existing heavy traffic and transit demand on Broadway.

- Granville Street and 27th Avenue: At this pedestrian signal, higher priority would be given to the pedestrians than to the 98 B-Line buses because there are no other legal pedestrian crossings at its vicinity.

- Granville Street and 37th Avenue: TSP will not be implemented at this intersection because 37th Avenue is part of the major bicycle route. Consequently, higher priority will be given to cyclists and pedestrians than to the 98 B-Line buses.

- Granville Street and 45th Avenue: At this pedestrian signal, higher priority would be given to the pedestrians than to the 98 B-Line buses because there are no other legal pedestrian crossings at its vicinity.

- Granville Street and 63rd Avenue: At this pedestrian signal, higher priority is given to pedestrians than to the 98 B-Line buses because of the high pedestrian demand at the intersection.

3.2 EXPERIMENT

Based on the available traffic data and signal control information in the Granville Street network, a VISSIM simulation model is developed to model the TSP implementation of the 98 B-Line buses on the Granville Street corridor under different traffic conditions. The following sub-sections describe the VISSIM simulation software, the studied traffic parameters, and the measures of effectiveness for the evaluations.

3.2.1 VISSIM

VISSIM is a microscopic, time-step and behavior-based simulation model of urban traffic and public transit operations developed in Germany [VISSIM, 2000]. The program can analyze traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals and transit stops.

VISSIM has a number of features that make it a useful tool for modeling urban traffic, transit operation and transit priority:

1. To model a signal operation, VISSIM has a user-programmable traffic signal controller that operates separately from the traffic simulation, with a limited interface [Janos & Furth, 2002]. The signal operation can be fixed-time, vehicle-actuated or user-defined. The user-defined signal operation is especially useful to test different strategies of transit signal priority because of the flexibility in the signal logics it allows. The user-defined signal controller is coded with VAP that is a C-like programming language that offers traffic related functions (e.g., detector calls, switching of signal phases, and transit phasing) [PTV website]. An add-on module VisVAP, a graphical flow chart editor, is available for easier control logic data entry and error checking.

2. To model a non-signalized operation, non-signalized priority rules (or yielding rules) can be set according to the user-defined minimum headway and minimum gap acceptance [PTV website]. This allows the coding of user-defined gaps for permissive left-turn and right-turn-on-red (RTOR).

3. To model a bus detector and a bus communication, VISSIM features transit detectors that can communicate with the traffic control system, indicating the line, direction, load, priority and delay of the transit vehicles. In addition, the bus detectors can work in both mixed traffic and on an exclusive lane or median [Janos & Furth, 2002].

4. To model dwelling at bus stops, VISSIM could track the load on each bus, generate passenger arrivals at the stops following a Poisson distribution, and determine the passenger alighting based on a fixed or user-supplied proportion of the load at each stop [Janos & Furth, 2002].

For the output presentations, VISSIM allows user-customized output files of measures of effectiveness such as vehicle number, mean speed, travel time, delay, queue lengths, number of stops, and time-space diagram [PTV website]. In addition, VISSIM provides a variety of animation capabilities, e.g., displaying traffic situations for different scenarios as printouts and visualizing vehicle movements in 2- and 3-dimensional animations.

3.2.2 TRAFFIC PARAMETERS

A VISSIM simulation model is developed to investigate the individual impact of twelve traffic and transit parameters on TSP impact and TSP effectiveness. These parameters and their definitions are given in Table 3-2.

Table 3-2 List and Definitions of Studied Traffic Parameters

Traffic Parameter	Definition
1. Granville Street Volume	➢ Through volume traveling on Granville Street.
2. B-Line Bus Headway	➢ The average time difference between two successive 98 B-Line buses.
3. Cross Street Volume	➢ Through volume on a cross street.
4. Left-turn Volume	➢ Left-turn volume made from Granville Street to the cross street.
5. Opposing-through Volume	➢ Through volume on Granville Street that the left-turn traffic has to yield to during the permissive left-turn phase.
6. Right-turn Volume	➢ Right-turn volume made from Granville Street to the cross street.
7. Pedestrian Volume	➢ Volume of pedestrians traveling in the direction conflicting with the right-turn traffic.
8. Bus Stop Location	➢ The bus stop location with respect to the intersection. Two scenarios are considered: farside (downstream) bus stop and nearside (upstream) bus stops.
9. Bus Check-in Detector Location	➢ Distance of the 98 B-Line bus check-in detectors from the intersection stop bar.
10. TSP Strategy	➢ Deployment of green extension and/or red truncation.
11. Recovery Strategy	➢ Restriction of TSP in successive cycles to control the disturbance to the cross street traffic. Two scenarios are considered: no successive TSP calls allowed and successive TSP calls allowed.
12. Signal Coordination	➢ Implementation of signal coordination with TSP application.

Each of these traffic parameters is varied individually to isolate its impact on the implementation of TSP. For some experiments, impacts of more than one traffic parameter are examined when one parameter can influence the impact of another parameter. The followings show examples of these traffic parameters:

- Left-turn volume's impact on TSP application under different opposing-through volumes will be analyzed. The opposing-through volume is a major factor influencing the dissipation of the left-turn traffic at an intersection when permissive left turn phase is provided.

- Right-turn volume's impact on TSP application under different volume of pedestrians that travels in the direction conflicting with the right-turn traffic. The pedestrian volume is a major factor hindering the dissipation of the right-turn traffic at an intersection.

- The locations of check-in detector can cause different impact on TSP application under different scenarios of bus stop locations: farside bus stops and nearside bus stops.

After grouping, nine groups of traffic parameters are considered for TSP application:

1. Granville Street volume scenarios;

2. B-Line bus headway scenarios;

3. Cross street volume scenarios;

4. Left-turn and opposing-through volume scenarios;

5. Right-turn and pedestrian volume scenarios;

6. Bus stop and bus check-in detector location scenarios;

7. TSP strategy scenarios;

8. Recovery strategy scenarios; and

9. Signal coordination scenarios.

3.2.3 MEASURES OF EFFECTIVENESS

Nine groups of traffic parameters, as described in Section 3.2.2, are analyzed for the impact of TSP and the effectiveness of TSP and green extension, whichever is/are applicable.

3.2.3.1 Impact of TSP

TSP aims to improve the performance of B-Line buses, i.e., to reduce the B-Line bus travel time and delay; however, it may also increase the cross street delay. As discussed in Chapter 2, the impacts of TSP might vary under different traffic conditions.

In this research, the Impact of TSP measures the change in the performances of B-Line buses (i.e., B-Line buses travel time or delay) and cross streets (i.e., cross street delay) under different traffic conditions when TSP is implemented.

TSP Impact on B-Line Bus Performance: The improvement (or reduction) in the average travel time or delay of B-Line buses on Granville Street when TSP is implemented. The factors considered for this evaluation are: Granville Street volume, B-Line bus headway, bus stop and detector location, TSP strategy, and recovery strategy.

TSP Impact on Cross Street Delay: The change in the average delay of the cross street traffic at an intersection where TSP is implemented. The experiments evaluated are B-Line bus headways and cross street v/c ratios.

Each of the nine traffic parameter groups listed in Section 3.2.2 is varied individually to capture its individual influence on the TSP impacts. Table 3-3 shows the traffic performance(s) evaluated for each traffic parameter group. Details of the scenarios will be presented in Section 4.2.

Table 3-3 List of Evaluations Performed for TSP Impact

Traffic Parameter Group	Change in B-Line Bus Performance	Change in Cross Street Performance
Granville Street Volume	✓	
Bus Headway	✓	✓
Cross Street Volume		✓
Bus Stop & Detector Location	✓	
TSP Strategy	✓	
Recovery Strategy	✓	✓

3.2.3.2 Effectiveness of TSP

The Effectiveness of TSP measures the influence of a traffic parameter on the change in B-Line bus or general traffic performance when TSP is implemented. In other words, this measures how a change in a traffic parameter's value would influence the effectiveness of TSP, when TSP is implemented. Traffic parameters considered for this evaluation are:

- Left-turn and opposing-through volume,
- Right-turn and pedestrian volume, and
- Signal coordination.

3.2.3.3 Effectiveness of Green Extension

The Effectiveness of green extension measures the influence of a traffic parameter on the green extension success rate and the checkout detector effectiveness, which are defined as:

Green Extension Success Rate: The green extension success rate measures the usefulness of the green extensions to the B-Line buses. This value is calculated as the number of B-Line buses checking out during the green extension phase divided by the total number of green extensions granted, expressed in percentage.

Checkout Detector Effectiveness: A checkout detector is used to provide earlier termination of a green extension if a B-Line bus clears the intersection before the maximum green extension (or Max-Timer) is reached. This aims to reduce the unnecessary delay to the cross street traffic after the bus clears the intersection. As its name implies, the checkout detector effectiveness measures the usefulness of a checkout detector to terminate a green extension earlier before the Max-Timer is reached. This value is calculated as the number of green extensions ended before the Max-Timer is reached divided by the total number of green extensions granted, expressed in percentage. It should be noted that the checkout detector effectiveness would always be less than or equal to the green extension success rate. The two values would be the same when no buses check out with the maximum green extension or during the clearance interval (i.e., yellow interval).

Each applicable traffic parameters is studied individually to obtain its impact on TSP effectiveness. These parameters include:

- Granville Street Volume;
- B-Line bus headway;
- Bus stop and detector location;
- TSP strategy; and
- Recovery strategy.

3.3 CHAPTER SUMMARY

This chapter provides descriptions of the TSP case study studied in this research and describes the attempts of this research.

In this research, the Transit Signal Priority (TSP) application of the 98 B-Line rapid transit buses along Granville Street in the City of Vancouver is used as a case study. The Granville Street corridor, where the 98 B-Line buses run, is one of the busiest traffic and transit corridors in the GVRD. Along the Granville Street corridor, the 98 B-Line buses are running in a mixed traffic condition with no maneuvering (i.e., turning), which matches the evaluation focus of this research. The investigation focuses on the TSP application of the northbound (i.e., peak commuter direction) B-Line buses during the morning peak period on the coordinated Granville Street corridor, with 75-second cycle length and offsets specified by the City of Vancouver. Active TSP strategy is deployed for the 98 B-Line buses, on which transponders are installed to transmit the real-time identification and schedule adherence information to the roadside infrared check-in and check-out detectors. Both green extension and red truncation are deployed in the TSP strategy of the 98 B-Line buses, with a maximum green extension of 14 seconds and the red truncation lengths determined by the minimum walk time of pedestrians crossing Granville Street, suggested by the City of Vancouver.

VISSIM, a micro-simulation software, is used to simulate the TSP operation on the Granville Street corridor. The individual influence of twelve traffic parameters on the impacts and effectiveness of TSP are studied. The traffic parameters investigated include: Granville Street (or bus approach traffic) volume, bus headway, cross street volume/capacity ratio, left-turn and opposing-through volume, right-turn and pedestrian volume, bus stop and bus check-in detector location, TSP strategy (green extension and red truncation), recovery strategy (successive TSP strategy and non-successive TSP strategy) and signal coordination.

These traffic parameters are tested for their influences on the impacts of TSP, the effectiveness of TSP and the effectiveness of green extension. The impact of TSP compares the traffic performance under different traffic scenarios with and without TSP implementation. The effectiveness of TSP measures how a change in the value of a traffic parameter would influence the effectiveness and impacts of a TSP application. Meanwhile, the effectiveness of green extension has two measures of effectiveness: (i) green extension success rate, which expresses the rate at which a bus may clear the intersection successfully when a green extension is granted; and (ii) checkout detector effectiveness, which measures the rate at which the check-out detector may be useful, i.e., when a bus checks out before the maximum green extension elapsed.

4.0 MODELING

This chapter presents the modeling process of this research. The following sections provide details of the simulation models used, the scenarios for the experiments, and the challenges encountered and assumptions made in the experiments.

4.1 NoTAC MODEL

A simulation model, named "NoTAC" model", is developed using VISSIM to model the TSP implementation for the 98 B-Line buses on the Granville Street section from Broadway to 70^{th} Avenue.

The "**NoTAC** model" models the Granville Street network with major assumptions of **No** **T**urnings on Granville Street, no **A**ctuation from pedestrians, and no turning from the **C**ross streets. The purpose of using the "NoTAC model" is to isolate the impact of an individually studied traffic parameter by getting rid of the impact from unrelated factors such as fluctuation in vehicle additions and removals, turning movement blockages or pedestrian actuations, which may affect the impact of the studied parameter from one simulation run to another.

The following sections describe the network geometry, the traffic input and the signal logic used in the "NoTAC model".

4.1.1 NETWORK GEOMETRY

The geometric layout of the "NoTAC model" is a modification of a simulation model available at the University of British Columbia. Actual geometric layout, number of lanes and their assignments on the Granville Street network are coded in the model. The network has three major corridors running in the north-south direction and ten major arterials running in the east-west direction. Minor streets are also coded in the model, yet it is assumed that no traffic is assigned to these minor streets, where only little traffic would be generated or absorbed and where actual traffic counts were not available from the City of Vancouver.

To reduce the impact from unrelated factors other than that from the studied traffic parameter, the network is modified such that no right-turn and no left-turn movements are allowed on Granville Street and from the cross streets onto Granville Street. However, all the existing left-turn bays are kept in the network for the analyses of scenarios with turning movements.

It is also assumed that the corridor gradient, the bus exclusive lanes and the on-street parking be not considered in the model to eliminate their impact on the traffic performance when analyzing the selected traffic parameters.

Figure 4-1 pictures the layouts of the major arterials in the "NoTAC model" and the locations of the traffic signals coded in the model. It should be noted that only the relative locations of major corridors and traffic signals are shown and they are not shown in scale.

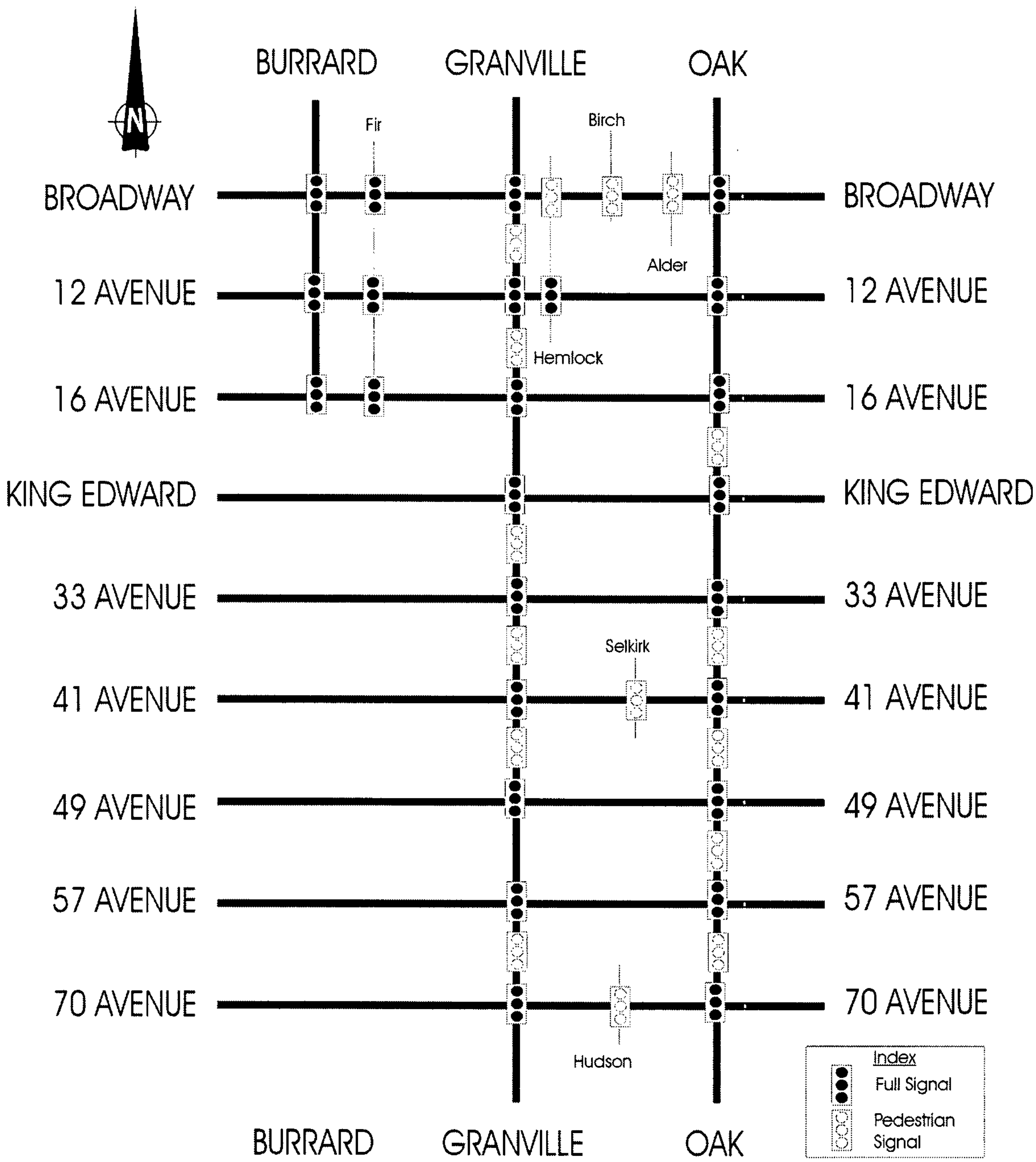

Figure 4-1 Geometrical and Signal Layouts of the "NoTAC model"

4.1.2 TRAFFIC INPUT

Six traffic groups are included in the "NoTAC model". The groups and their assumed average traveling speeds are summarized in Table 4-1. Details of the traffic groups are described in the sub-sections that follow.

Table 4-1 Defined Average Speeds of Traffic Groups in the "NoTAC model"

Traffic Group	Average Speed (km/hr)
Pedestrian	5
General vehicle	50
Heavy vehicle	35
Regular bus	45
Trolley bus	45
B-Line bus	50

4.1.2.1 General Traffic and Pedestrians

Actual morning peak hour traffic counts for year 2000 are coded in the "NoTAC model", except along the Granville Street corridor where no turnings are assumed. The actual northbound and southbound entering volumes onto Granville Street during the morning peak hour are 2,009 Veh/hr and 995 Veh/hr respectively. Based on these actual volumes, default northbound and southbound entering volumes of 2,000 Veh/hr and 1,000 Veh/hr respectively are assumed in the "NoTAC Model". Since no turnings are allowed on Granville Street and from the cross streets onto Granville Street, the northbound and southbound volumes would remain constant along the entire corridor.

A 2% heavy vehicle demand is assumed on most major arterials in the network, which include:

- North-south arterials: Granville Street, Burrard Street, and Oak Street.
- East-west arterials: Broadway, 16th Avenue, 25th Avenue, 41st Avenue, 49th Avenue (EW), and 70th Avenue.

4.1.2.2 Regular Buses

In the "NoTAC model", regular buses and trolley buses can only run on the rightmost (or curb) lane on an arterial to reflect the real situation. The actual routes of the regular buses and trolley buses, as in Year 2000, are coded in the "NoTAC model".

4.1.2.3 B-Line Buses

All B-Line buses in the "NoTAC model" are allowed to run on the rightmost and the center lanes on the B-Line bus routes. This allows the B-Line buses to pass the stopping regular or trolley buses at bus stops. The actual B-Line bus headway of 10 minutes, as provided by TransLink in Year 2000, is used.

To replicate the impact of TSP on the B-Line bus performance, actual B-Line bus check-in detectors locations and actual bus stop locations are coded in the "NoTAC model". The actual locations of the check-in detectors and the bus stops are described in Section 3.1.1 and are shown in Appendix A-1 and Appendix A-2 respectively.

4.1.3 SIGNAL CONTROL LOGIC

The following sections describe the TSP logic deployed and the programming tool used for the coding of signal timing logics of the "NoTAC model".

4.1.3.1 TSP Strategy for the "NoTAC model"

A TSP strategy consisting of green extension and red truncation is used for the experiments for this research. The default TSP strategy deploys:

<u>14-second maximum green extension:</u>

- This proposed value of the maximum green extension is to be implemented on the Granville Street Corridor.
- No attempt was made to further increase the 14-second maximum green extension to generate higher impact of TSP because the value is limited by the 18-second green time for the cross street approaches at the intersection of Granville Street and 57th Avenue. This value allows at least 4 seconds of green time for the general traffic on 57th Avenue.
- The actual length of green extension granted would vary with the time required by the B-Line buses to check out, to a maximum of 14 seconds.

<u>3-second minimum pedestrian walk time:</u>

- This value is slightly less than the minimum walk time (i.e., 5 seconds) currently used by the City of Vancouver.
- After consultation with the City of Vancouver, a 3-second minimal walk time is considered acceptable.
- The actual walk time given to the pedestrians crossing Granville Street would depend on the time at which the B-Line bus checks in, ranging from 3 second to the maximum walk time.
- The maximum red truncation for each signalized intersection on Granville Street is obtained based on the minimum pedestrian walk time. The maximum red truncations are listed in Table 4-2 and can be calculated as:

$$Maximum\_Red\_Truncation = Green - FDW - Minimum\_Walk\_Time$$

Where "Green" = the green time for the cross street approaches; "FDW" = flash don't walk for the EW pedestrians who travel across Granville Street; and "Minimum_Walk_Time" = the minimum walk time for the EW pedestrians.

Table 4-2 Maximum Red Truncations Deployed for the "NoTAC model"

North-south Street	East-west Street	Maximum Green (sec)	FDW (sec)	Maximum Red Truncation (sec)
Granville St.	**10 Ave**	17	11	**3**
Granville St.	**12 Ave**	26	14	**9**
Granville St.	**13 Ave**	16	10	**3**
Granville St.	**14 Ave**	19	11	**5**
Granville St.	**16 Ave**	21	13	**5**
Granville St.	**25 Ave / King Edward**	27	10	**14**
Granville St.	**33 Ave**	24	10	**11**
Granville St.	**41 Ave**	25	15	**7**
Granville St.	**49 Ave**	24	11	**10**
Granville St.	**57 Ave**	19	11	**5**
Granville St.	**59 Ave / Park**	23	15	**5**
Granville St.	**64 Ave**	19	10	**6**
Granville St.	**68 Ave**	19	10	**6**
Granville St.	**70 Ave**	25	16	**6**

Non-successive TSP Recovery Strategy:

- A proposed non-successive TSP recovery strategy is to be implemented on the 98 B-Line buses.
- A non-successive TSP recovery strategy does not allow the provision of TSP calls (either green extension or red truncation) in two successive cycles.
- This strategy aims to reduce the negative effect on the cross street traffic.

Coordination is maintained:

- As proposed by the City of Vancouver, TSP on Granville Street will be implemented in a coordinated network.
- Coordination parameters provided by the City of Vancouver, as presented in Section 3.1.3, is used in the signal timing logic. It should be noted that no attempts have been made to check the optimality of the offsets for coordination on Granville Street.
- For the signal logic programmed, when a green is extended for the bus approaches, the green time for the cross street traffic in the following cycle would

be shortened accordingly to maintain coordination; that is, if the bus approach green was extended for 10 seconds, the cross street approach green would be shortened by 10 seconds in the following cycles. And if the shortening of the cross street green time did not allow enough flash don't walk time for the pedestrians to cross safely, the pedestrian phase for that cycle would be skipped.

- Red truncation is called when there is enough spare green time from the cross street phase. This criterion, as suggested by Skabardonis (2000), guarantees the maintenance of coordination along a TSP corridor. In this research, the spare green time would be determined as follows:

When a B-Line bus checks in before the minimum walk time is reached:

$$Spare\_Green = Maximum\_Green - Minimum\_Walk - FDW$$

When a B-Line bus checks in after the minimum walk time and before the flash don't walk is given:

$$Spare\_Green = Remaining\_Green - FDW$$

Where "Maximum_Green" = the maximum green time of the cross street phase, "Minimum_Walk" = the minimum walk time specified in the TSP strategy; "Remaining_Green" = the remaining green time of the cross street phase at the moment a B-Line bus checks in; and "FDW" = the flash don't walk interval of the pedestrians crossing.

Based on the above equations, red truncation is only granted when the calculated spare green time is a positive value. In other words, no red truncation would be allowed after the start of the Flash Don't Walk of the pedestrian (crossing Granville Street) phase. In addition, the actual red truncation granted would equal the value of the spare green time, to a maximum value of the maximum red truncation shown in Table 4-2.

4.1.3.2 Programming of Signal and TSP Strategy

The regular signal logics and TSP signal logics presented in Section 4.1.3.1 are programmed using VisVAP (or Visual VAP). VisVAP is a graphical flow chart editor that allows signal logics to be defined using easy flow-chart data entry methods. Constants, expressions and subroutines can be defined. The graphical flow chart is transformed into a programming language code, VAP language, which is similar to the C-programming language but with additional traffic related functions such as detector calls, switching of signal phases, and transit phases [PTV website]. The VAP language is understood by VISSIM.

Figure 4-2 illustrates an user-interface of VisVAP.

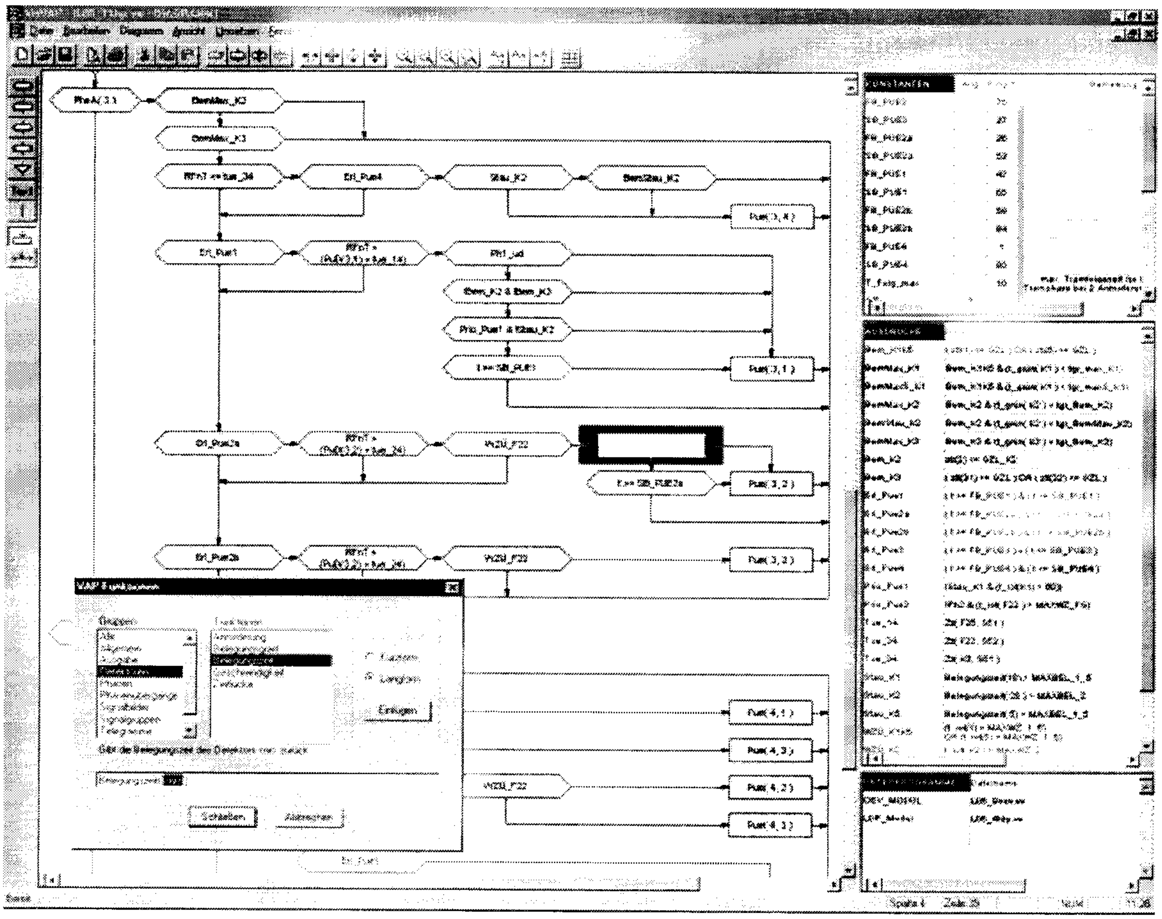

Figure 4-2 VisVAP Flow Chart Editor for Traffic Responsive Signal Control Logic (Sources: PTV website)

4.1.4 SIMULATION AND CALIBRATION

The total simulation time is 1 hour and 15 minutes including a 15-minute normalization period at the beginning to fill the network with vehicles and a 1-hour simulation period to collect data for the analyses. The 1-hour simulation period would allow 4 to 5 B-Line buses to complete a full trip on each direction in the default "NoTAC model", even under moderate-to-high congestion level. No statistics are gathered during the 15-minute normalization period. Each micro-simulation run represents a random experiment; therefore, each experiment performs five different random seeds to account for the stochastic traffic input of VISSIM. This is required to ensure the validity and stability of the results.

As with every modeling exercise, a calibration process of the base network is performed. A geometric network calibration is performed by looking at the VISSIM graphical user interface for any unusual behavior of the traffic, which may be due to the inexact coding of the network construction or traffic signal logics. In addition, calibration is performed to reduce the fluctuation in results due to randomness and the influences from unrelated factors other than the studied parameter.

Comparisons of the calibrated network and the inputted traffic conditions on Granville Street volume, left-turn volume and right turn volume are performed and are shown in Appendices B-1, B-2 and B-3, respectively. The purpose of this calibration is to see how the simulated traffic condition matches the inputted traffic parameters in the model.

It should be noted that this research only focuses on the relative comparison of the TSP impacts and effectiveness between different traffic scenarios; therefore, calibration between the simulation model and the actual 2000 traffic environment is not vital for this research.

4.1.5 CHALLENGES AND ASSUMPTIONS

This section presents the challenges encountered during the processes of data collection, modeling, scenario development and results acquisition in this research. The assumptions made to cope with these challenges are also presented.

Data Collection:

Challenge #1:

The most recent traffic volume data cannot be used for the research. It is because the Year 2002 data was not yet available when the model was developed and the Year 2001 data was not appropriate for the research because the count program of year 2001 was undertaken during a 4-month bus strike, in which the traffic conditions might have been skewed and no 98 B-Line bus data could be obtained.

Assumption for Challenge #1:

- It is assumed that the TSP application of the 98 B-Line buses was implemented under the Year 2000 traffic environment. Traffic and transit information are also based on the Year 2000 data. Therefore, the new changes that occurred after Year 2000 on Granville Street are not considered. The recent changes that are not considered in this research include the addition of the new left-turn restrictions at most major signalized intersections along Granville Street, the installation of a new pedestrian signal at the intersection of Granville Street and 11^{th} Avenue, and a shorter B-Line bus headway of 5 to 8 minutes during the AM peak period.

Modeling:

Challenge #2:

The investigation of the isolated impact of a traffic parameter can hardly be captured using the base "Granville Street model", which models the actual traffic operations and intersection turning movements along the Granville Street corridor. This is because the usage of the base "Granville Street model" would generate too much fluctuations in the results on the B-Line bus and general traffic performances due to many unrelated factors such as turning movement blockages, pedestrian or vehicle actuations, and change in Granville Street volume from turnings made to and from the cross streets.

Assumptions for Challenge #2:

- A "NoTAC model" is developed to analyze the individual impact of the traffic parameters. It is assumed that no turning is allowed anywhere on Granville Street, no actuation from pedestrians and vehicles is allowed along Granville Street, and no turnings are allowed onto Granville Street from the cross streets. Therefore, the "NoTAC model" is used to reduce the impact from unrelated factors that may influence the B-Line bus performance or the cross street performance.

- In addition, other actual traffic environments (e.g., on-street parking, gradient on Granville Street, and bus and carpool lanes) are not considered in the model to eliminate their impacts on the traffic performance when investigating a specific traffic parameter.

Scenario Development:

Challenge #3:

When examining TSP impact at an approach of a signalized intersection, the default 10-minute B-Line bus headway only gives a few number of TSP calls at the intersection (i.e., around 2 to 3 calls during the 1-hour simulation period at an intersection). This number of TSP calls may not representative enough to illustrate the impact of TSP when comparing different traffic scenarios at one intersection.

Assumptions for Challenge #3:

- To cope with the lack of TSP calls with the 10-minute B-Line bus headway during the 1-hour simulation period, two options are initially proposed: (i) to increase the simulation period from 1 hour to 2 hours and (ii) to use a smaller B-Line bus headway in the 1-hour simulation period. The latter option was chosen because the former option (i.e., increasing the simulation period) would be more time-consuming in model modification and simulation. As a result, a 4-minute B-Line bus headway is assumed for all scenarios that analyze TSP impact at an approach of just one intersection. These scenarios include the cross street volume scenarios, the left-turn and opposing-through volume scenarios, the right turn and pedestrian volume scenarios, and the bus stop and detector location scenarios.

- To further increase the number of TSP calls at the intersection, successive TSP is assumed to be allowed for these scenarios.

Results Acquisition:

Challenge #4:

Some fluctuations and randomness in the VISSIM results are observed from one simulation run to another and from one scenario to another. As explained by a representative from VISSIM, VISSIM may produce some variability in results when modeling a large network with high traffic volume, which is the case for the "NoTAC model".

Assumption for Challenge #4:

- The results from five simulation runs are averaged using a common statistical method called "Trimmed Average". It is assumed that the trimmed averaged result would represent the average of the results from the 5 simulation runs. Trimmed Average is performed by excluding the highest and the lowest results of the runs, then averaging the remaining. This aims to reduce the effect of randomness on the simulation results and to get a more representative result from the runs. For example, if the 5 simulation runs produced B-Line bus travel time of 12.5 minutes, 12.8 minutes, 12.9 minutes, 13.1 minutes and 13.6 minutes, the maximum (i.e., 13.6 minutes) and the minimum (i.e., 12.5 minutes) of the results will be removed, and the trimmed average of the B-Line bus travel time would be the average of only 12.8 minutes, 12.9 minutes and 13.1 minutes, which is 12.9 minutes.

Challenge #5:

Some result inconsistency is observed when measuring the B-Line bus performance on an approach at an intersection in the "NoTAC model", which makes the comparison of B-Line bus approach delay between scenarios impossible. The inconsistent results are attributed to a high uncertainty in the cycle time at which a B-Line bus would arrive at an intersection, when different scenarios are considered. This fluctuation is attributed by the inconsistent pattern of B-Line bus arrivals from the upstream intersections when different scenarios are studied; and it directly impacts the approach delay of the B-Line buses. This problem is observed when considering experiments that study the approach delay of a B-Line bus.

Assumption for Challenge #5:

- An "isolated-intersection model" is developed for the analyses of scenarios that study the approach delay of the B-Line buses at one intersection. This model successfully removes all the fluctuation and inconsistency in the approach results because any fluctuations of vehicle arrival from the upstream intersections are removed when no upstream intersections are included in the simulation model. This model is used in experiments that study the approach delay of the B-Line buses; these experiments are the left-turn and opposing-through volume, the right turn and pedestrian volume, and the bus stop and bus detector locations scenarios.

4.2 SIMULATION SCENARIOS

TSP application is examined by individually varying the twelve selected traffic parameters described in Section 3.2.2. A default "NoTAC model" is developed and the default parameters of the model are described in Section 4.1 and summarized in Table 4-3 below.

Table 4-3 Default Parameters of the "NoTAC model"

Granville Street volume	2,000 Veh/hr (northbound) and 1,000 Veh/hr (southbound).
Coordination parameters	Granville Street coordinated with 75-second fixed cycle length and offsets specified by the City of Vancouver *.
Turning on Granville Street	Not allowed.
Turning from cross streets	Not allowed.
B-Line Bus headway	10 minutes.
Bus Stop Locations	Farside bus stops (actual locations).
Bus Detector Locations	Approximately 100 meters from intersections (actual locations).
TSP strategy	14-second maximum green extension and 3-second minimum walk time for Granville Street pedestrians.
Recovery Strategy	No successive TSP calls are allowed.

* The detail of the signal timing plan and offset plans of all signalized intersections along Granville Street are shown in Appendix A-7.

To capture the individual impact of a traffic parameter, only one traffic parameter is changed at a time while keeping all the other parameters fixed as shown in Table 4-3. The default values of the traffic parameters are used for the analyses unless otherwise specified. The following sections detail the scenarios studied for the nine sets of experiments.

4.2.1 GRANVILLE STREET VOLUME SCENARIOS

The B-Line bus performance is examined for six Granville Street volume scenarios. The considered Granville Street volumes are: 500, 1,000, 1,500, 2,000, 2,500, and 2,700 Veh/hr.

These Granville Street volumes represent Granville Street v/c ratios ranging from 0.2 to 1.0 (i.e., at capacity). The v/c ratios are calculated by the volume-capacity ratio equation suggested in the 1994 Highway Capacity Manual Model for a signalized intersection. The capacity of the Granville Street corridor is estimated to be the average of the capacities of the North-South (i.e., bus approach) phases at the ten major signalized intersections along the Granville Street corridor. The calculation of the capacity and the volume-capacity ratios are shown in Appendix C-1. The Granville Street volumes, along with their corresponding calculated v/c ratios, are given in Table 4-4.

Table 4-4 Major Volume and Corresponding v/c Ratios

Major Volume (Veh/hr)	Major v/c Ratio
500	0.18
1,000	0.37
1,500	0.55
2,000	0.74
2,500	0.92
2,700	0.99

4.2.2 BUS HEADWAY SCENARIOS

The B-Line bus headway is varied to assess the performance of the B-Line buses running in the morning peak direction (i.e., the northbound direction) on Granville Street. In addition, the impact of TSP on the average cross street delay of the eastbound approach of 70th Avenue (with default v/c ratio of 0.6) is also assessed for different B-Line bus headways. The eastbound approach of 70th Avenue is selected because:

- It is observed from the simulation that the intersection of Granville Street and 70th Avenue has the highest numbers of TSP calls granted, thereby making the TSP impact more obvious when comparing different B-Line bus headway scenarios;
- The eastbound approach of 70th Avenue does not have any bus traffic nor bus stop, thereby limiting the unnecessary delay from bus dwelling; and
- Vehicle arrivals on this approach are not influenced by any upstream signalized intersection, thereby allowing randomness in vehicle arrival at the intersection.

Five B-Line bus headways are studied to examine the impact of TSP on B-Line bus travel time and cross street delay. The marginal headways are selected to be 2 minutes on the lower end and 20 minutes on the upper end. The 2-minute headway is the smallest headway implemented among researches and the 20-minute headway represents the off-peak headway of the B-Line buses on Granville Street corridor. The B-Line bus headway scenarios studied are: 2, 5, 10, 15, and 20 minutes.

4.2.3 CROSS STREET VOLUME SCENARIOS

For the same reasons mentioned in Section 4.2.2, the eastbound approach of 70th Avenue (i.e., one of the cross streets along Granville Street) is studied for this experiment.

Five cross street v/c ratios are tested to examine the impact of TSP on cross street delay. These cross street v/c ratio scenarios examined are: 0.25, 0.50, 0.80, 0.90, and 1.00.

The entering volumes on the eastbound approach of 70th Avenue for the cross street v/c ratio scenarios are calculated using the volume-capacity equation from the 1994 Highway Capacity Manual Model for a signalized intersection. The calculations are shown in Appendix C-2. The entering volumes on 70th Avenue for the v/c ratios are given in Table 4-5.

Table 4-5 Scenarios of Cross Street Volume on the 70th Avenue (Eastbound)

Cross Street v/c Ratio	Entering Volume (Veh/hr)
0.25	295
0.50	590
0.80	944
0.90	1,062
1.00	1,180

4.2.4 LEFT-TURN VOLUME SCENARIOS

For this experiment, the intersection of Granville Street and 41st Avenue is chosen as the studied location. The intersection is selected because of the availability of a left-turn exclusive lane on both Granville Street approaches, which can be used to evaluate the influences of left-turn lane and left-turn phase. Additionally, the left-turn volume is applied only to the northbound approach of the intersection.

It was observed that the 10-minute default B-Line bus headway brings about only a small number of TSP calls at the studied intersection. As a result, three adjustments are made to the default model: (i) the northbound B-Line buses are operated at 4-minute headways; (ii) the northbound B-Line buses are allowed to request for TSP calls in successive cycles; and (iii) only northbound B-Line buses can request for TSP. The use of smaller B-Line bus headway and the allowance of successive TSP calls can increase the number of TSP calls at the intersection, thereby producing more obvious impacts of TSP under different left-turn scenarios. In addition, the provision of TSP only to the northbound B-Line buses neglects the impact of TSP calls requested by the southbound buses, which is not the focus of this experiment analysis and may cause unnecessary fluctuation in the traffic signal plans.

Moreover, some fluctuations in the B-Line bus arrival times in a cycle are observed for different scenarios, which make the comparison of the B-Line bus approach delays under different scenarios difficult. This could be attributed to the randomness in the generation and dissipation of general traffic and B-Line buses from the upstream intersections. To reduce this fluctuation, an "isolated intersection model" is used for this analysis to remove the impact from the upstream intersections on the B-Line bus arrival time. The deployment of an "isolated-intersection model" is considered reasonable because the left-turns and the evaluation are only applied to one intersection.

The left-turn volume scenarios examined are determined based on the maximum left-turn data on the Granville Street corridor, provided by the City of Vancouver. Based on the Year 2000 traffic count data, the maximum left-turn volumes at an intersection with protected left-turn phase and permissive left-turn phase are 174 Veh/hr and 54 Veh/hr respectively. Based on these values, the left-turn (LT) volumes considered are: 25, 50, 100, 150, and 200 Veh/hr.

The opposing-through volume that travels in the southbound direction on Granville Street controls the throughput of northbound left-turn traffic. Therefore, the opposing-through volume is set to different values to investigate its impact on left-turn dissipation and TSP application. To isolate only the impact of opposing-through volume on left-turn throughputs, it is assumed that no pedestrians are crossing in the direction conflicting with the left-turn movement. The opposing-through volume scenarios examined are 1,000 Veh/hr, 1,500 Veh/hr and 2,000 Veh/hr, which represent opposing-through v/c ratios of 0.37, 0.55 and 0.74 respectively.

The combinations of various left-turn and opposing-through volumes are also tested under three different left-turn conditions to study the impacts of left-turn lane and left-turn phase on the B-Line bus performance. These left-turn conditions are:

1. Permissive left-turn phase with shared left-turn-through lane;
2. Permissive left-turn phase with exclusive left-turn lane; and
3. Protected left-turn phase with exclusive left-turn lane.

4.2.5 RIGHT-TURN VOLUME SCENARIOS

Similar to the left-turn volume experiment in the previous section, the intersection of Granville Street and 41st Avenue is studied for this experiment.

For reasons identical to those given in Section 4.2.4, an "isolated-intersection model" is deployed for this experiment. And similar to the left-turn volume experiment, three adjustments are made to the default model for this experiment: (1) the northbound B-Line buses are operated at 4-minute headways; (2) the northbound B-Line buses can request for successive TSP calls; and (3) only the northbound B-Line buses can request for TSP. Justifications of these are given in Section 4.2.4.

Moreover, volume of pedestrians traveling in direction conflicting with the right-turn traffic is a critical factor that controls the dissipation of the right-turn traffic. As a result, the pedestrian volume is set to different values to investigate its impact on right-turn dissipation and TSP application. For each pedestrian volume scenario, it is assumed that the directional splits of pedestrians would be 50%-50%, that is, the same number of pedestrians is traveling in the northbound and the southbound directions. For example, if there were 50 pedestrians, then 25 pedestrians would be crossing in the northbound direction and 25 pedestrians would be crossing in the southbound direction.

According to the Year 2000 traffic count data provided by the City of Vancouver, the maximum right-turn volume and the maximum pedestrian volume counted along Granville Street are 232 Veh/hr and 143 Ped/hr respectively. Based on these counts, the right-turn (RT) and pedestrian volume scenarios assessed are:

RT Volume (Veh/hr): 50, 150, and 250.
Pedestrian Volume (Ped/hr): 50 and 150.

4.2.6 BUS STOP AND BUS DETECTOR LOCATION SCENARIOS

In this experiment, the effects of the bus stop and bus detector locations are studied through two sets of experiments: (i) Bus stop location experiment, and (ii) Bus detector location experiment.

An "isolated-intersection model" is again deployed for these experiments to get rid of any impact on the B-Line bus approach delay from the upstream intersections, as explained in Section 4.2.4. Moreover, similar to the left-turn and right turn volume experiments, three adjustments are made to the default model: (i) the northbound B-Line buses are operated at 4-minute headways; (ii) the northbound B-Line buses can request for successive TSP calls; and (iii) only the northbound B-Line buses can request for TSP. Justifications of these are described in Section 4.2.4. Furthermore, the intersection of Granville Street and 41st Avenue is selected for the experiments.

For the bus stop location experiment, two bus stop scenarios are tested:

- Farside Bus Stop Scenario: A B-Line bus stop is placed on the farside (or downstream) of a signalized intersection. The bus stop is located 48 meters downstream from the intersection stop bar, as is actually placed at the intersection of Granville Street and 41st Avenue.

- Nearside Bus Stop Scenario: A B-Line bus stop are placed on the nearside (or upstream) of a signalized intersection. This bus stop is assumed to be placed 50 meters upstream of the intersection stop bar. This distance is estimated based on the actual B-Line bus stop distance on the farside of the intersection of Granville Street and 41st Avenue.

The two bus stop location scenarios are examined and compared under different Granville Street traffic volumes: 500, 1000, 1500, 2000, and 2500 Veh/hr, which represent Granville Street v/c ratios ranging from 0.2 to 0.95.

For the bus detector location experiment, seven B-Line bus check-in detector locations are analyzed under the two bus stop location scenarios described above. The bus stop and detector scenarios are listed in Table 4-6 and illustrated in Figure 4-3 and Figure 4-4.

Table 4-6 Bus Stop & Detector Location Scenarios

Bus Stop Location	Detector Location from Downstream Stop Bar (meters)					
Farside	50	100	150	200	250	300
Nearside	75	100	150	200	250	300

It should be noted that, for this experiment, the nearside bus stop is placed between the check-in detectors and the intersection; therefore, given the assumed nearside bus location, the closest check-in detector used for the nearside bus stop scenario is placed 75 meters upstream from the intersection and 25 meters upstream from the bus stop.

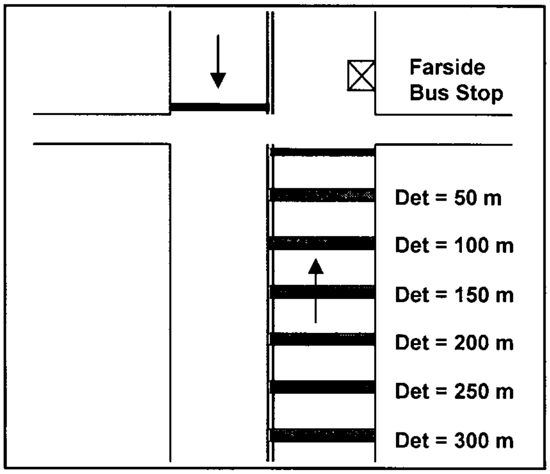

Figure 4-3 Bus Stop and Detector Layouts for the Farside Bus Stop Scenario

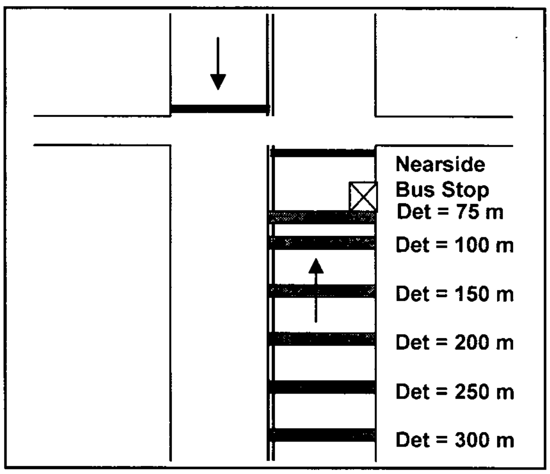

Figure 4-4 Bus Stop and Detector Layouts for the Nearside Bus Stop Scenario

4.2.7 TSP STRATEGY SCENARIOS

Active transit signal priority (TSP) is considered for this experiment. Active TSP requires the usage of check-in detectors for real-time detection of the B-Line buses to trigger a request for TSP. The TSP strategies examined in this experiment consists of one or both of two commonly used active TSP strategies:

- Green Extension: This strategy is applied when a bus checks in during green. The green time for the bus approach will be extended for a detected bus if the bus cannot check out from the intersection before the end of the green time. If the green time is extended, the green extension will continue until either the bus checks out (i.e., clear the intersection) or the maximum green time (or Max-Timer) is reached.

- Red Truncation: This strategy is applied when a bus checks in during red. The green time for the non-bus approach or approaches will be shortened, thus allowing the green time for the bus approach to start earlier. For this experiment, the maximum red truncation length is determined by a pre-specified minimum walk time provided for the pedestrians crossing Granville Street (or the bus approach). The maximum length of the red truncation is calculated as:

$$Maximum\_Red\_Truncation = Green - FDW - Minimum\_Walk\_Time$$

Where "Green" = the green time for the non-bus approach; "FDW" = flash don't walk for the EW pedestrians who travel eastbound and westbound (i.e., across Granville Street); and "Minimum_Walk_Time" = the minimum walk time for the EW pedestrians.

In addition, the default no-successive TSP recovery strategy is assumed for this experiment. And the TSP is granted only when there is enough spare green time for the TSP call, as described in Section 4.1.3.1.

In this research, the impacts of TSP on the B-Line bus and cross street performances are studied under different combinations of maximum green extension and minimum pedestrian walk time, which determines the length of the maximum red truncation. The maximum green extensions and minimum walk times examined are:

Maximum Green Extension: 0, 5, 10, and 14 seconds.
Minimum Walk Time: 3 seconds, and maximum walk time (i.e., no red truncation).

4.2.8 RECOVERY STRATEGY SCENARIOS

In this experiment, the influences of two recovery strategies on TSP application are studied:

- No-Successive-TSP Recovery Strategy: TSP calls are not allowed in two successive. In other words, when a TSP is granted at one cycle, TSP will not be granted again in the following cycle even when a B-Line bus is detected. This strategy aims to disallow interruptions to the cross street traffic in two successive cycles.

- Successive-TSP Recovery Strategy: TSP can be conferred whenever a B-Line bus is detected.

Two analyses are performed for the two recovery strategy described immediately above. These analyses are:

- Comparison of TSP's improvement on the B-Line bus travel time with and without the allowance of successive TSP calls, for various B-Line bus headway scenarios (i.e., 2-min, 5-min, 10-min, 15-min, and 20-min).

- Comparison of the impact of TSP on the cross street performance with and without the allowance of successive TSP calls, for various cross street v/c ratios. To investigate the impact of successive TSP calls, 2-minute B-Line bus headway is assumed because successive TSP calls would be requested more frequently at a small B-Line bus headway.

4.2.9 SIGNAL COORDINATION SCEANRIOS

To investigate the impact of signal coordination on TSP effectiveness, two coordination scenarios are compared:

- TSP Application with Signal Coordination: The signal coordination is based on the default signal coordination parameters provided by the City of Vancouver, as described in Section 3.1.3. Under this scenario, the signal coordination is given a higher priority than a TSP request, i.e., a TSP request will only be granted if signal coordination can be maintained. And to maintain the coordination of the signals, the green time of the cross street approaches would be shortened accordingly when a TSP (green extension or red truncation) is granted.

- TSP Application with No Signal Coordination: No signal coordination is maintained along the Granville Street corridor. In this scenario, the traffic signal plans are only actuated by the TSP calls from the B-Line buses. Moreover, the cycle lengths would fluctuate with the lengths of green extension or red truncation conferred to the B-Line buses. Furthermore, the green time for the cross street approaches would be maintained after a green extension is conferred. Consequently, successive TSP calls are allowed for this scenario because a TSP call would not impact the cross street green time.

4.3 CHAPTER SUMMARY

This chapter presents the modeling process of this research, focusing on the modeling and scenarios for the experiments as well as the challenges and assumptions made during the experiments.

As described in Section 3.0, the purpose of the research is to capture the individual influence of the selected traffic parameters on the impacts and effectiveness of TSP application. A simulation model, named "NoTAC model", is developed using VISSIM for the evaluation of TSP application of the 98 B-Line buses on Granville Street. The "**NoTAC** model" has the assumptions of **No** **T**urning on Granville Street, no **A**ctuation from pedestrians, and no turning from the **C**ross Streets. In addition, the "NoTAC model" neglects the actual gradient of the Granville Street corridor, the actual bus exclusive lanes on the south end of the corridor, and the actual on-street parking on both Granville Street approaches. The usage of this model aims to reduce the fluctuation in results due to unrelated factors, which may affect the impact of the studied traffic parameters.

Nine sets of experiments are performed to study nine traffic parameter groups' influence on TSP application. To capture the isolated impact of a single traffic parameter, only one parameter is varied at a time while keeping all other variables fixed. The scenarios examined for each traffic parameter group are summarized in Table 4-7 below.

Table 4-7 Summary of Traffic Parameter Scenarios

	Traffic Parameter	Scenarios
#1	Granville Street Volume	500, 1000, 1500, 2000, 2500, 2700 Veh/hr
#2	B-Line Bus Headway	2, 5, 10, 15, 20 Minutes
#3	Cross Street v/c Ratio	0.25, 0.50, 0.80, 0.90, 1.00
#4	Left-turn Volume	25, 50, 100, 150, 200 Veh/hr
	Opposing-through Volume	1000, 1500, 2000 Veh/hr
#5	Right-turn Volume	50, 150, 250 Veh/hr
	Pedestrian Volume	50, 150 Ped/hr
#6	Bus Stop Location	Farside (downstream) Bus Stop, Nearside (upstream) Bus Stop
	Bus Detector Location	Farside bus stop: 50, 100, 150, 200, 250, 300 meters Nearside bus stop: 75, 100, 150, 200, 250, 300 meters
#7	TSP Strategy	Combinations of Maximum Green Extension: 5, 10, 14 sec and minimum pedestrian walk time: Maximum walk time, 3 sec
#8	Recovery Strategy	Non-successive TSP, Successive TSP
#9	Signal Coordination	With signal coordination, no signal coordination

Table 4-8 summarizes the major challenges encountered and assumptions made in the data collection, modeling, scenario development and result acquisition processes.

Table 4-8 Summary of Challenges and Assumptions

CHALLENGES	ASSUMPTIONS
1. The most recent traffic data cannot be used for the research.	➢ It is assumed that the TSP of the 98 B-Line buses was implemented under the Year 2000 traffic environment.
2. The individual influence of a traffic parameter on TSP application cannot be captured by simulating the actual Granville Street traffic condition, which has too many influences from unrelated traffic variables such as turning movements and pedestrian actuations.	➢ A "NoTAC model" is developed for the evaluation. The model assumes no turnings onto or from Granville Street, no pedestrian actuation, and no considerations of gradient, bus and HOV lane, and on-street parking.
3. When examining the TSP application at a single signalized intersection, the default 10-minute B-Line bus headway and non-successive TSP strategy only give a small number of TSP calls, thereby cannot provide representative results on the impact of TSP when comparing different traffic scenarios.	➢ A 4-minute B-Line bus headway and successive TSP strategy are assumed for all scenarios that analyze TSP application at a single signalized intersection.
4. Some fluctuations and randomness in the VISSIM results are observed from one simulation run to another.	➢ It is assumed that the "trimmed-averaged" results would represent the average results from the five simulation runs, aiming to reduce the randomness of the results.
5. Some inconsistency in the results is observed when measuring the performance of an approach at a single intersection in a large VISSIM network.	➢ An "isolated-intersection model" is used for the experiments that study the approach performance of the B-Line buses.

5.0 RESULTS AND ANALYSES

Nine sets of experiments, described in Section 4.2, are performed to provide a comprehensive investigation of twelve traffic parameters' influences on the impacts and effectiveness of TSP applications. These experiments include:

- Granville Street Volume;
- B-Line Bus Headway;
- Cross Street v/c Ratios;
- Left-turn Volume and Opposing-through Volume;
- Right-turn Volume and Pedestrian Volume;
- Bus Stop and Bus Check-in Detector Location;
- TSP Strategy;
- Recovery Strategy; and
- Signal Coordination.

Table 5-1 summarizes the analyses performed for these scenarios in this chapter.

Table 5-1 Analyses Summary for Selected Traffic Parameters

Traffic Parameter	TSP Impact On			TSP Effectiveness	Green Extension Effectiveness
	B-Line Bus	Cross Street	Entire Corridor		
Granville Street Volume	✓				✓
B-Line Bus Headway	✓	✓			✓
Cross Street v/c Ratios		✓			
Left-turn & Opposing-through Volume				✓	
Right-turn & Pedestrian Volume				✓	
Bus Stop & Detector Location	✓				✓
TSP Strategy	✓				✓
Recovery Strategy	✓	✓	✓		✓
Signal Coordination			✓	✓	

5.1 GRANVILLE STREET VOLUME

The 98 B-Line buses are running in a mixed-traffic condition on Granville Street, which is one of the busiest traffic and transit corridors in the City of Vancouver. The mixed and heavy traffic condition on Granville Street increases the interaction between B-Line buses and the general traffic that runs parallel to them. This section assesses the impacts of TSP on the B-Line bus performance and the green extension effectiveness under different Granville Street volumes (or bus approach traffic volumes). This experiment is studied on a corridor basis. Details of the Granville Street volume scenarios are described in Section 4.2.1.

5.1.1 GRANVILLE STREET VOLUME IMPACT ON B-LINE BUS PERFORMANCE

Figure 5-1 shows the comparison of travel time of B-Line buses along the Granville Street corridor with and without TSP implementation, under different Granville Street v/c ratios.

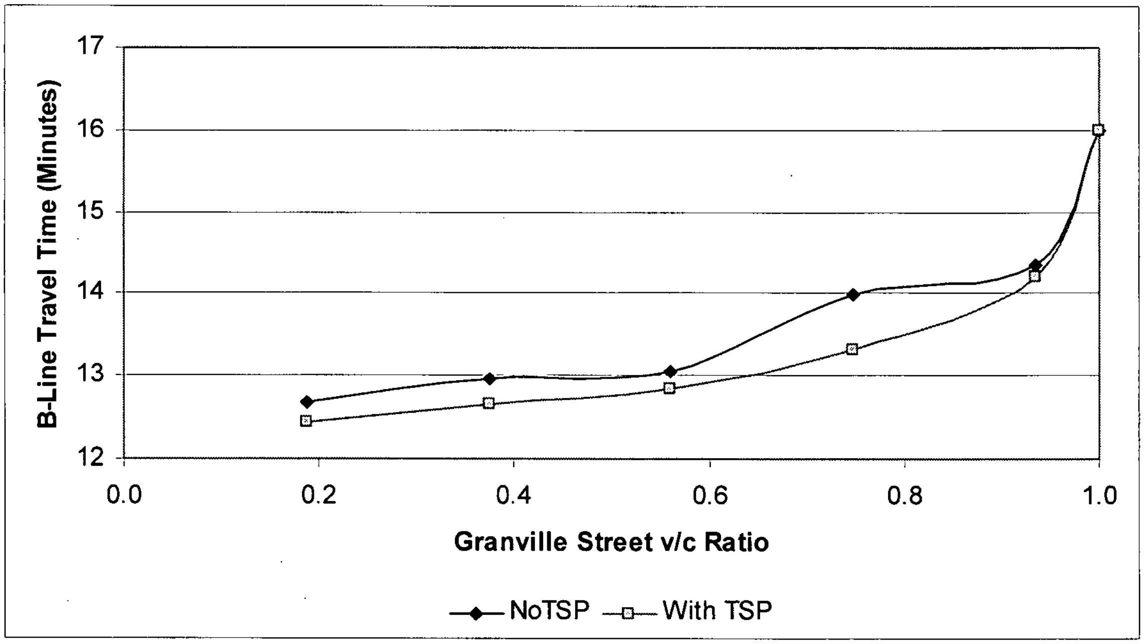

Figure 5-1 Granville Street v/c Ratio Impact on B-Line Bus Travel Time

The result indicates that the travel time of B-Line buses running along the Granville Street corridor would increase with the Granville Street v/c ratios. It also shows that the B-Line bus travel time along Granville Street could be improved with TSP. These improvements are shown in Figure 5-2.

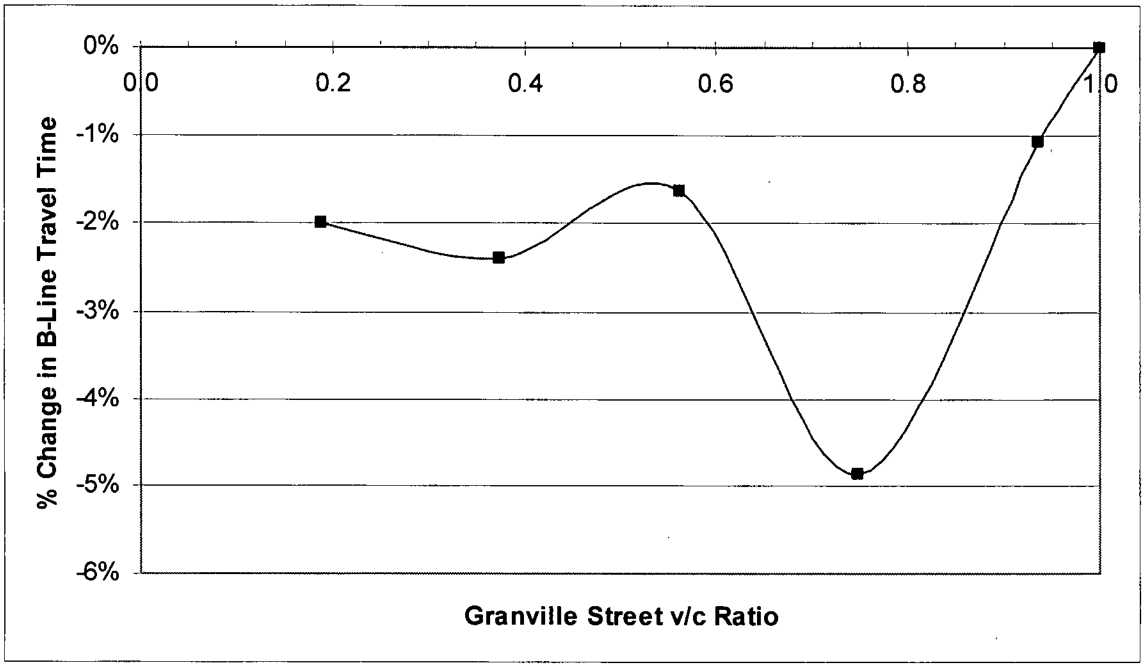

Figure 5-2 Granville Street v/c Ratio Impact on B-Line Bus Travel Time Improvement (With TSP)

Figure 5-2 shows the impacts of TSP on the B-Line bus travel time under various Granville Street (or bus approach traffic) v/c ratios:

- Granville Street v/c ratio <= 0.6: TSP's improvement in the B-Line bus travel time stays at around 2%. In this range of v/c ratios, the B-Line buses do not encounter too much traffic delay, thereby constraining TSP's improvement on the B-Line bus performance.

- Granville Street v/c ratio between 0.6 and 0.9: TSP's improvement in the B-Line bus travel time rises to almost 5%. In this v/c ratio range, the B-Line buses encounter higher traffic delay; consequently, TSP can improve the B-Line bus performance more significantly.

- Granville Street v/c ratio from 0.9 to 1.0: TSP's improvement in B-Line bus travel time is minimal. This shows that TSP only improves the B-Line bus travel time minimally at traffic conditions approaching capacity (i.e., v/c ratio = 1.0) because the congested traffic would hinder the B-Line bus movement.

  This agrees with the findings of Jacobson (1993) that TSP could not provide travel time saving to buses at intersections operating above capacity because TSP could not provide additional capacity.

5.1.2 GRANVILLE STREET VOLUME IMPACT ON GREEN EXTENSION EFFECTIVENESS

Figure 5-3 shows the green extension success rate of the B-Line buses when different Granville Street v/c ratios are considered.

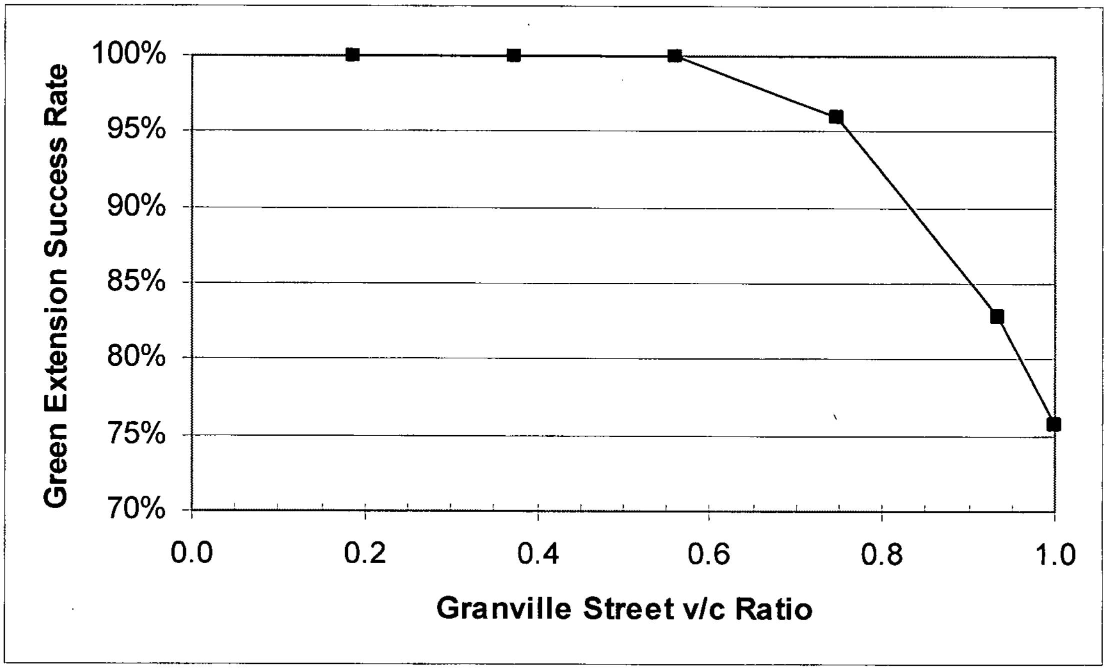

Figure 5-3 Granville Street v/c Ratio Impact on Green Extension Success Rate

Figure 5-3 shows the following findings:

- At Granville Street v/c ratio at or below 0.55 (Granville Street volume of 1,500 Veh/hr), all B-Line buses can check out successfully during the green extension phase.
- At Granville Street v/c ratio beyond 0.55, the rate at which a B-Line bus can check out successfully during the green extension phase would gradually reduce with an increase in the Granville Street v/c ratio. This is because high congestion on Granville Street lengthens the time required by the B-Line buses to enter the intersection after checking in and makes them less likely to clear the intersection even when green extension is granted.
- At capacity (i.e., 2,700 Veh/hr) on Granville Street, the green extension success rate of the B-Line buses drops to almost 75%.

The checkout detector effectiveness of the B-Line buses under different Granville Street v/c ratios is also examined. Figure 5-4 shows the results.

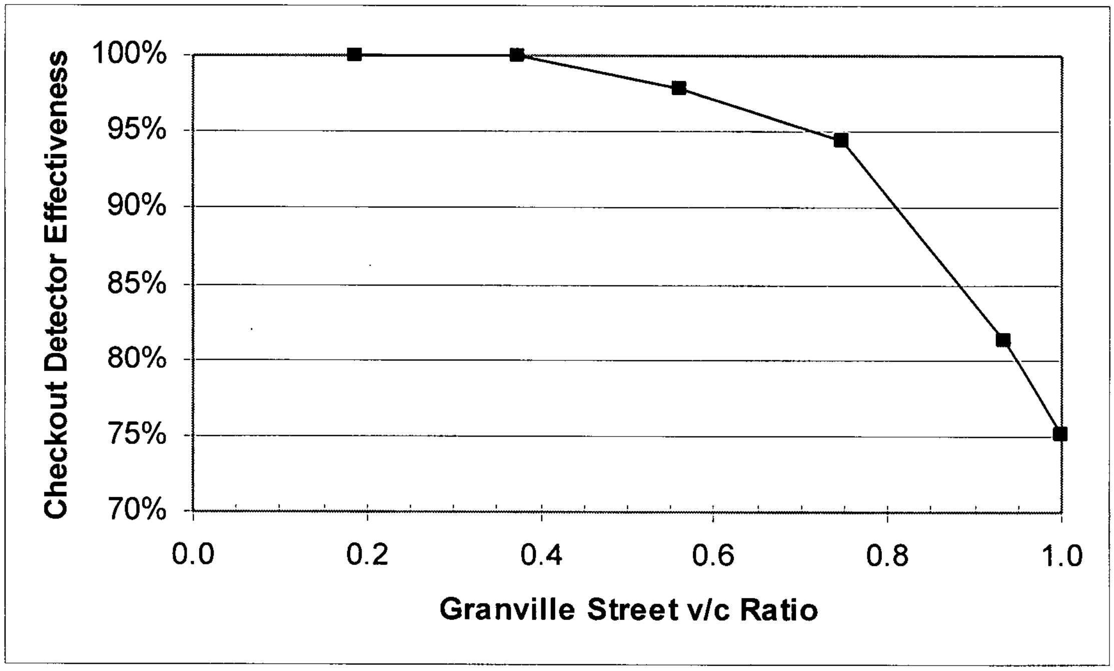

Figure 5-4 **Granville Street v/c Ratio Impact on Checkout Detector Effectiveness**

Figure 5-4 indicates the following findings:

- At Granville Street v/c ratio below 0.4 (i.e., 1,000 Veh/hr), the checkout detectors are capable of terminating the green extension before the maximum green extension (or Max-Timer) elapsed.

- The checkout detector effectiveness experiences slight reduction from 100% to 95% between the Granville Street v/c ratios of 0.4 (i.e., 1,000 Veh/hr) and 0.75 (i.e., 2,000 Veh/hr). This is because the moderate-to-heavy Granville Street traffic lengthens the time for the B-Line buses to enter the intersection after checking in; thereby increasing the chance that a Max-Timer be required.

- Beyond Granville Street v/c ratio of 0.75 (i.e., 2,000 Veh/hr), the checkout detector effectiveness experiences further reduction, from around 95% at v/c ratio of 0.75 to 75% at capacity. The more congested traffic condition further lengthens the B-Line bus travel time; thereby more significantly increasing the chance that a Max-Timer be required.

5.2 B-LINE BUS HEADWAY

A number of previous studies reported that TSP could have different influences on traffic performance under different bus headways (i.e., different TSP request frequencies). This section assesses the TSP impact on the B-Line buses and cross street performances when the B-Line buses are operating at different headways. This experiment is studied on a corridor basis. Details of the B-Line bus headway scenarios are described in Section 4.2.2.

5.2.1 B-LINE BUS HEADWAY IMPACT ON B-LINE BUS PERFORMANCE

Figure 5-5 illustrates the travel time of B-Line buses along the Granville Street corridor when TSP is implemented under different B-Line bus headways.

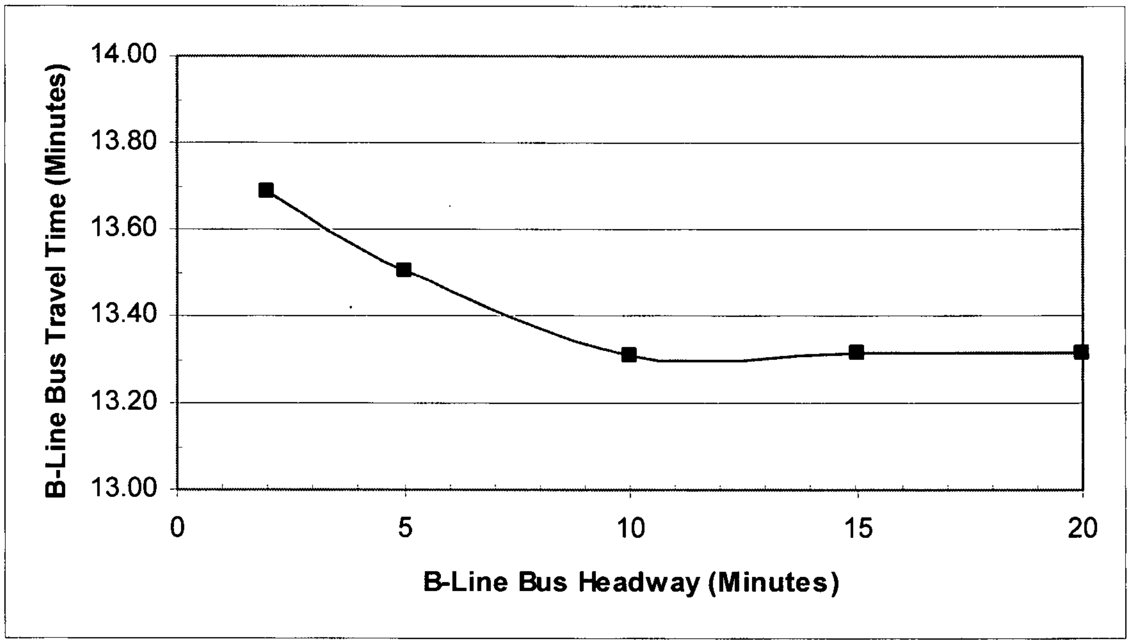

Figure 5-5 B-Line Bus Headway Impact on B-Line Bus Travel Time (With TSP)

Figure 5-5 shows that when the B-Line buses are operating at headways between 10 minutes and 20 minutes, the travel time of B-Line buses along the Granville Street corridor stays constant at around 13.3 minutes, when TSP is implemented. At B-Line bus headways smaller than 10 minutes, the B-Line bus travel time gradually increases to 13.7 minutes. This could be attributed to a higher B-Line bus volume in the network that increases the B-Line bus delays.

Additionally, the TSP improvement on B-Line bus travel time under different B-Line bus headways is shown in Figure 5-6.

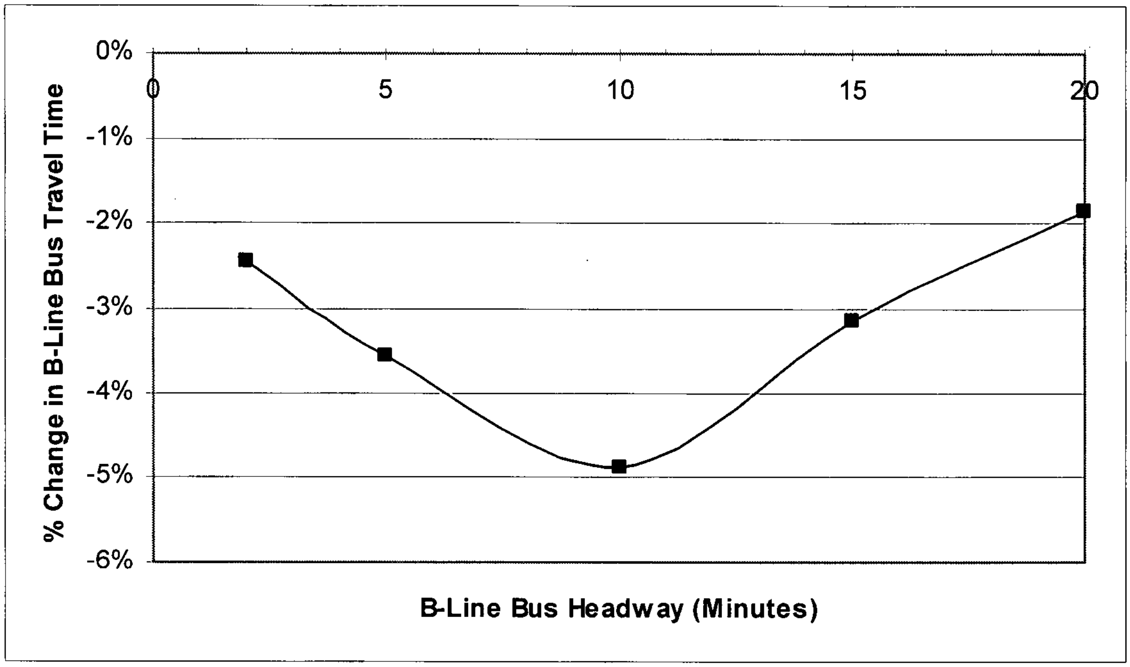

Figure 5-6 B-Line Bus Headway Impact on B-Line Bus Travel Time Improvement (With TSP)

Based on the results shown in Figure 5-6, the following observations are made:

- The 10-Minute B-Line bus headway would be considered as the optimal headway at which TSP would bring the highest improvement to the B-Line bus travel time.
- At B-Line bus headway greater than the optimal headway (i.e., > 10 minutes), TSP's improvement on the B-Line bus travel time reduces as the B-Line bus headway increases. This is because an increase in the B-Line bus headway would trigger fewer TSP requests from the B-Line buses, thereby limiting the benefits of TSP on the B-Line buses.
- At B-Line bus headway below the optimal headway (i.e., < 10 minutes), the improvement of TSP on the B-Line bus travel time reduces because smaller B-Line bus headway (or larger B-Line bus volume) would increase the B-Line bus delay.

The plot on Figure 5-6 agrees with the findings of Agrawal et al's (2002) that the benefit from TSP on the bus trip time is higher with fewer buses (or longer bus headway). However, it does not agree with their proposal that the TSP benefit on the bus trip time would decrease and level off beyond a certain bus frequency. According to their study, this threshold is at a bus frequency of 20 buses for a simulation period of 30 minutes.

5.2.2 B-LINE BUS HEADWAY IMPACT ON CROSS STREET PERFORMANCE

Figure 5-7 illustrates the average cross street delay on the eastbound approach (with base v/c of 0.6) at the intersection of Granville Street and 70th Avenue when TSP is implemented. The reasons of the selection of this cross street approach are given in Section 4.2.3. Meanwhile, Figure 5-8 shows the percentage change in the average cross street delay on the approach when TSP is implemented.

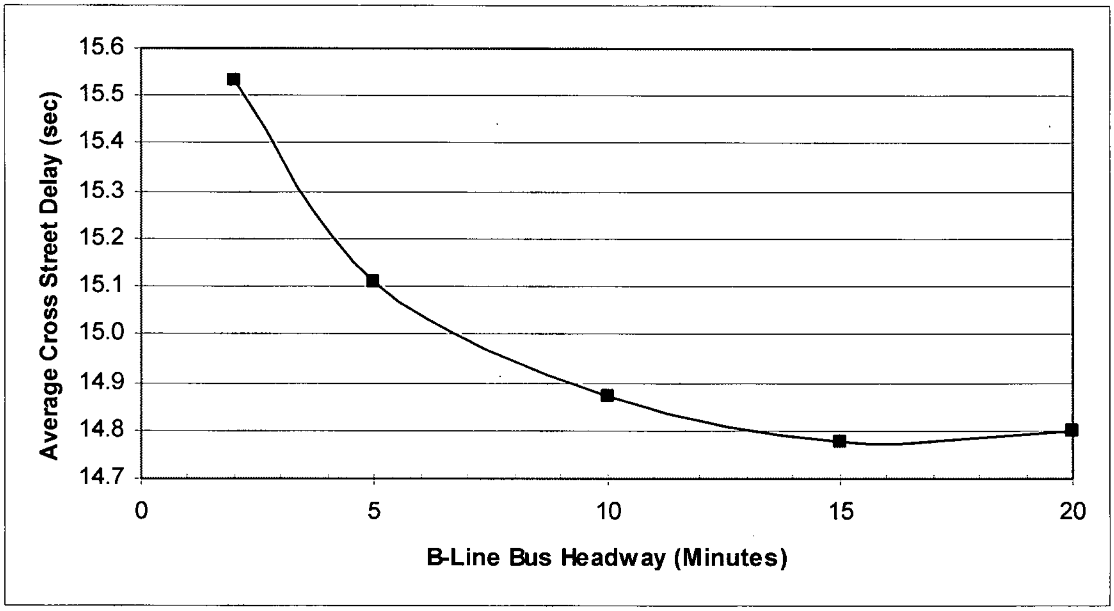

Figure 5-7 B-Line Bus Headway Impact on Cross Street Delay (with TSP)

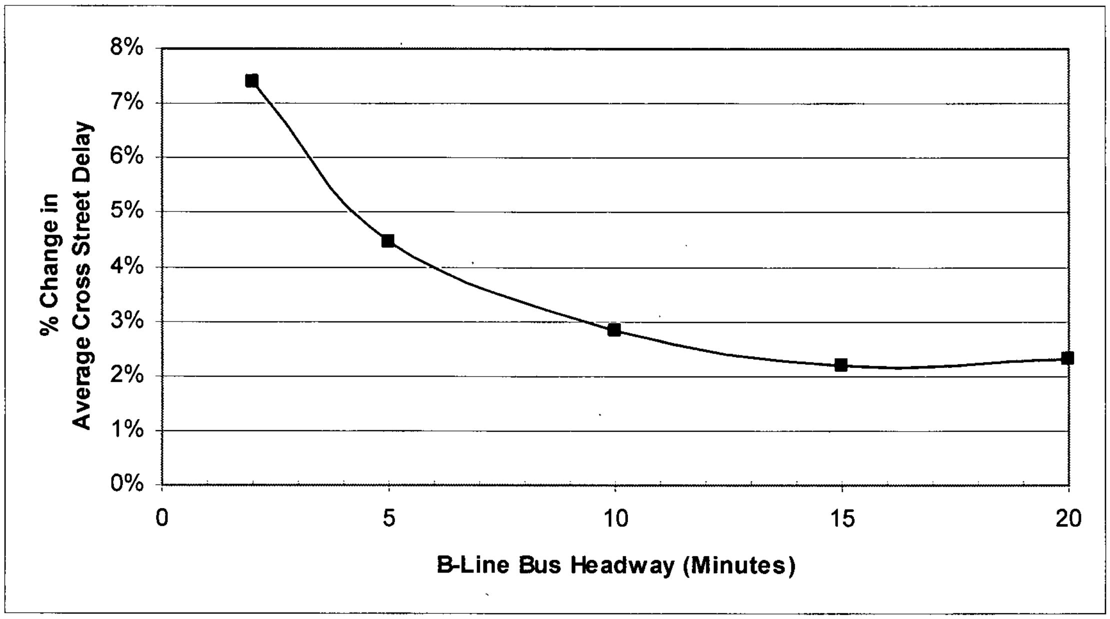

Figure 5-8 B-Line Bus Headway Impact on Cross Street Delay Increase with TSP

Figure 5-7 and Figure 5-8 show that, when TSP is implemented, the average cross street delay increases with a decrease in the B-Line bus headway, especially at B-Line bus headways below 5 minutes. This result supports the proposal by Daniel (1997) that a large volume of transit vehicles (or small bus headway) could penalize the cross street traffic, particularly if the cross street volume was high.

It should be noted that the very slight increase in cross street delay at a 20-minute B-Line bus headway could be attributed to the randomness in the simulation results, which has been reduced by averaging the trimmed results but cannot be eliminated totally.

5.2.3 B-LINE BUS HEADWAY IMPACT ON GREEN EXTENSION EFFECTIVENESS

This section analyzes the impact of B-Line bus headway on the effectiveness of green extension. Figure 5-9 and Figure 5-10 plot the impact of B-Line bus headway on the success rate of green extension and the effectiveness of checkout detectors.

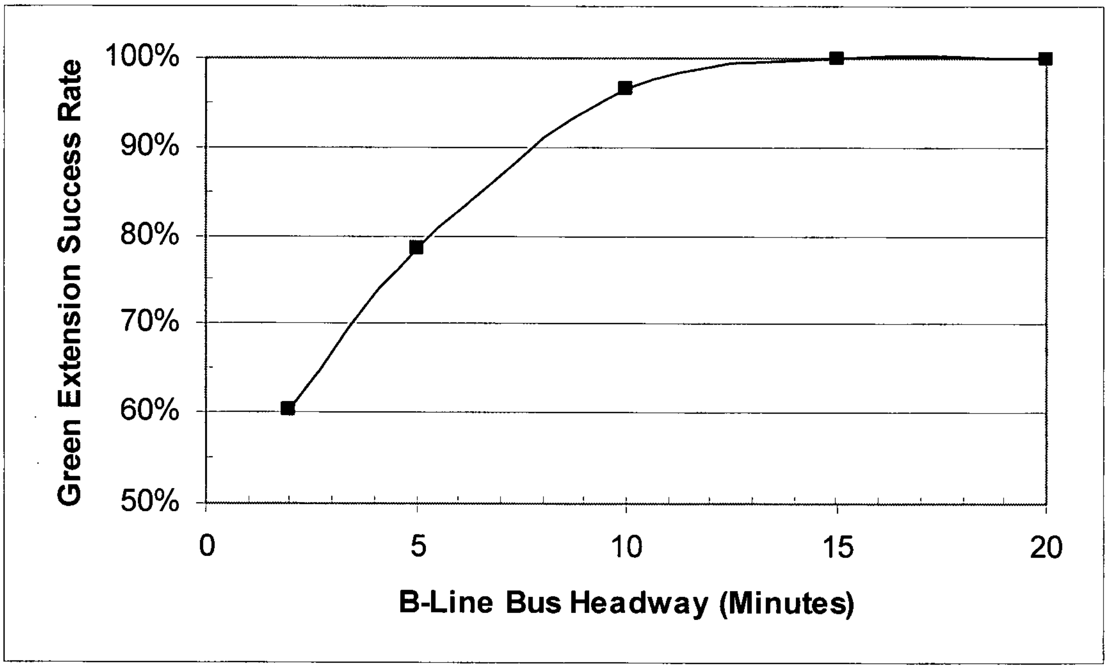

Figure 5-9 B-Line Bus Headway Impact on Green Extension Success Rate

Figure 5-9 indicates that at B-Line bus headways at or above 15 minutes, the B-Line buses would always checkout an intersection during the green extension phase. Meanwhile, the green extension success rate would drop at smaller B-Line bus headways.

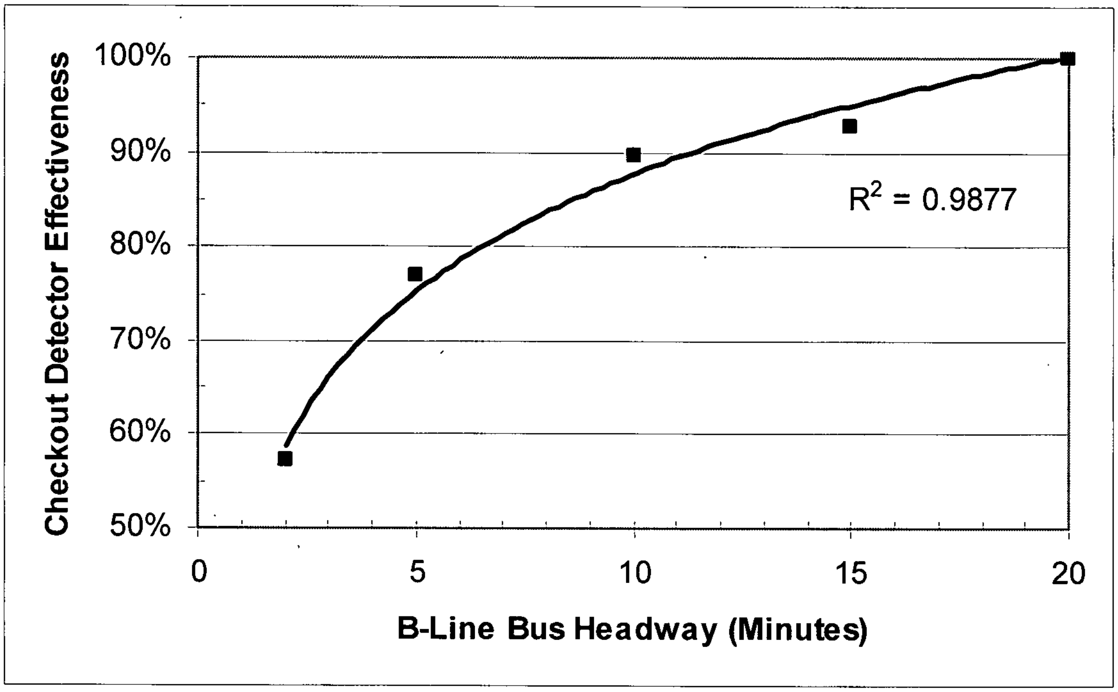

Figure 5-10 B-Line Bus Headway Impact on Checkout Detector Effectiveness

Figure 5-10 shows that the checkout detector effectiveness is greatest at a higher B-Line bus headway, i.e., 20-minute. The trend also shows that as the B-Line bus headway reduces (or B-Line bus volume increases), the checkout detector effectiveness would decrease and the reduction in checkout detector effectiveness would experience more significant increase.

5.3 CROSS STREET VOLUME

The implementation of TSP usually incurs adverse impact on the cross street traffic because the green time of the cross street is often being traded off for a longer green time for the bus approaches, especially when signal coordination and the signal cycle length has to be maintained. As a result, it is very important to consider the impact of TSP on cross street delay. In this analysis, the impacts of TSP on cross street delay are assessed for different cross street v/c ratios. This experiment is studied on an approach basis. The details of the cross street v/c ratio scenarios are described in Section 4.2.3.

5.3.1 CROSS STREET VOLUME IMPACT ON CROSS STREET PERFORMANCE

Figure 5-11 to Figure 5-15 illustrate the cross street average cycle delay trends under different cross street v/c ratios with and without TSP application. The vertical solid line represents the time at which a green extension is granted and the vertical dotted line represents the time at which a red truncation is called. The numerical value on top of each vertical line represents the length of green extension or red truncation conferred to the B-Line bus approach. The circle identifies the maximum number of recovery cycles required for each cross street v/c ratio scenario.

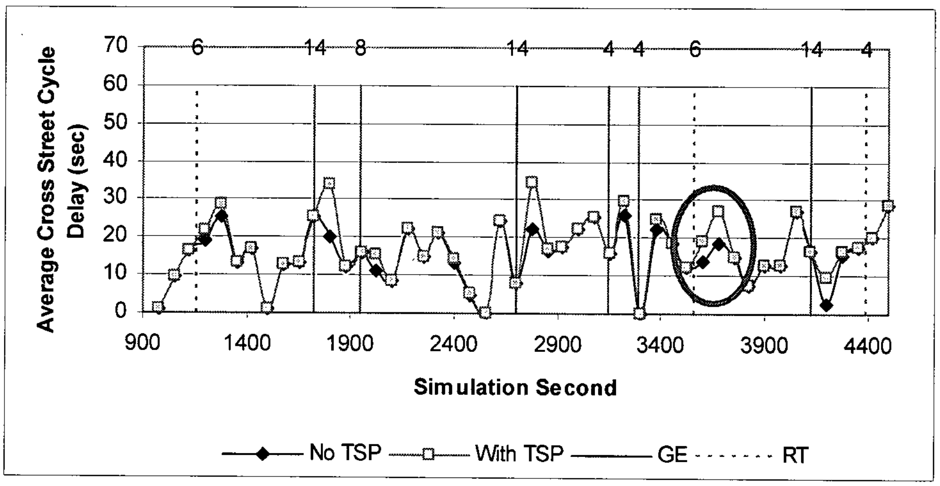

Figure 5-11 Average Cross Street Cycle Delay at v/c Ratio = 0.25 (with and without TSP)

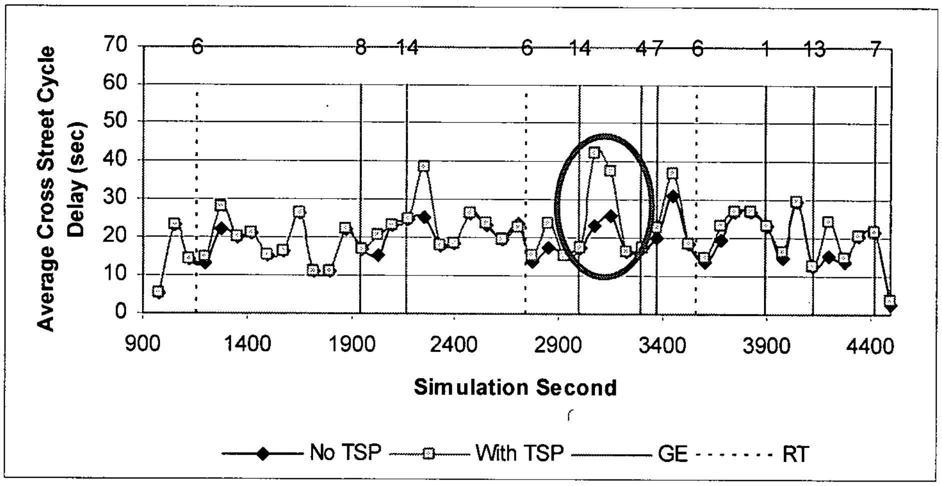

Figure 5-12 Average Cross Street Cycle Delay v/c Ratio = 0.50 (With and Without TSP)

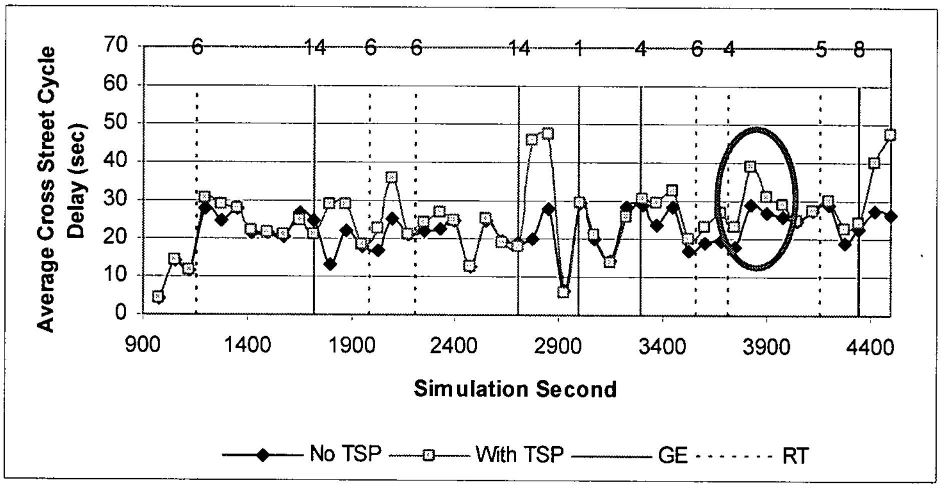

Figure 5-13 Average Cross Street Cycle Delay at v/c Ratio = 0.80 (With and Without TSP)

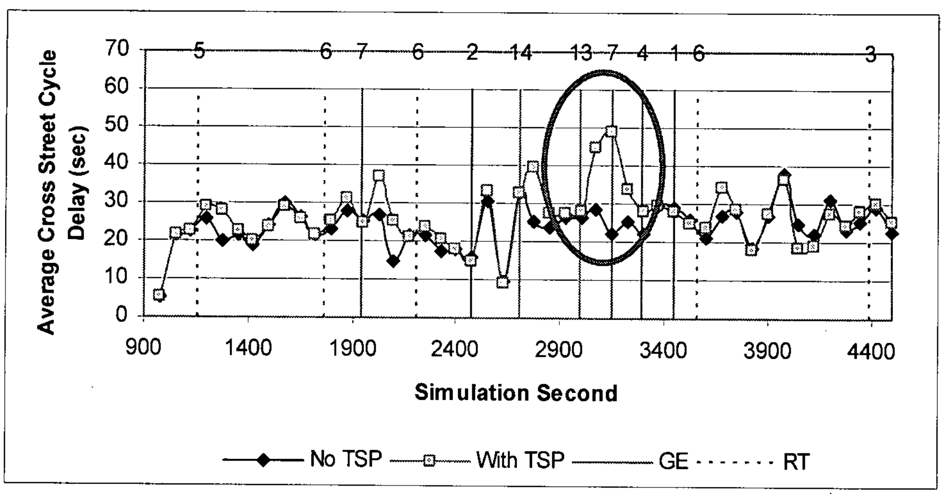

Figure 5-14 Average Cross Street Cycle Delay at v/c Ratio = 0.90 (With and Without TSP)

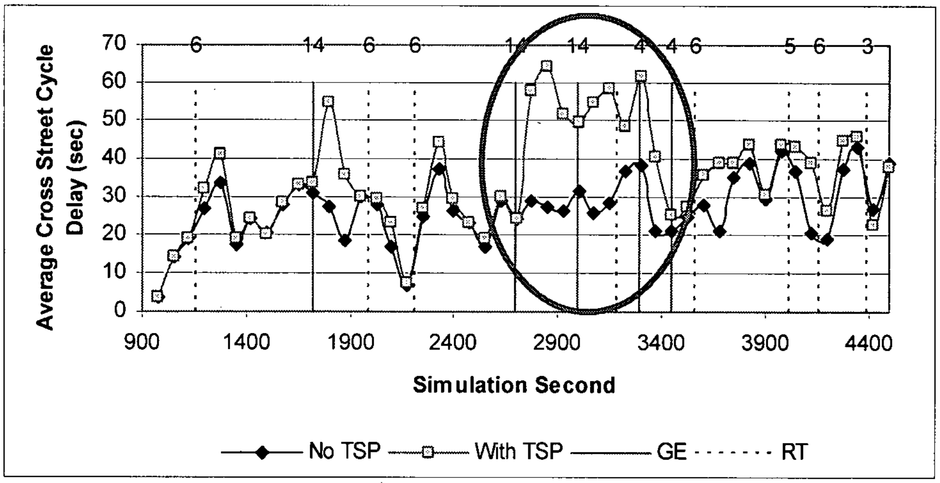

Figure 5-15 Average Cross Street Cycle Delay at v/c Ratio = 1.0 (With and Without TSP)

Table 5-2 summarizes the number of cycles needed for the cross street recovery for different cross street v/c ratio scenarios.

Table 5-2 Cross Street Recovery Cycles at Different Cross Street v/c Ratios

	v/c = 0.25	v/c = 0.50	v/c = 0.80	v/c = 0.90	v/c = 1.0
# Recovery Cycles	2-3	2-3	3-4	3-6	4-11

Table 5-3 shows the maximum cross street delay observed during a TSP call for different cross street v/c ratios.

Table 5-3 Maximum Cross Street Delay with TSP at Different Cross Street v/c Ratios

	v/c = 0.25	v/c = 0.50	v/c = 0.80	v/c = 0.90	v/c = 1.0
Maximum Delay (sec)	35	42	47	49	64

Figure 5-11 to Figure 5-15 illustrate the following findings:

- TSP impact on the cross street performance is minimal at low cross street v/c ratios. The cross street delay needs 2 to 3 cycles to recover. And at a low cross street v/c ratio, TSP only brings about minimal increase in the cross street delay.
- TSP has moderate impact on the cross street performance at a cross street v/c ratio of 0.8, and it has more significant impact on the cross street performance above cross street v/c ratios above 0.9. This suggests that the increases in the number of cross street recovery cycles and the cross street delay are more significant at a higher cross street v/c ratio.

The results obtained from this experiment agree with the proposal of Daniel (1997) that TSP provision would penalize cross street traffic. Additionally, Garrow & Machemehl (1998) also reported the impact of TSP on cross streets. Table 5-4 shows a comparison of their results to that obtained from the 98 B-Line experiment.

Table 5-4 Comparison of TSP Impact on Cross Street Performance (Garrow & Machemehl, 1998 vs. No Successive TSP)

Reported by	Garrow & Machemehl (1998)		98 B-Line Experiment (2002)
Cross Street v/c Ratio	**GE = 10 seconds**	**GE = 20 seconds**	**GE = 14 seconds + RT**
0.25	N/A	N/A	Minimal
0.50	N/A	N/A	Minimal
0.80	Minimal	Moderate	Moderate
0.90	Moderate	Significant	Significant
1.00	Significant	Significant	Significant

Note: "N/A" represents results that were not reported. "GE" represents Green Extension and "RT" represents red truncation. This 98 B-Line experiment uses a 4-minute B-Line bus headway for the analysis.

Based on the above analysis, the result from the 98 B-Line experiment agrees with that reported by Garrow & Machemehl (1998). Both experiments show that TSP would have moderate impact on cross streets at a v/c ratio of 0.80 and would have significant impact at v/c ratios above 0.90.

5.4 LEFT-TURN VOLUME

The impact of left-turn traffic on the effectiveness of TSP at a signalized intersection is studied. Different combinations of left-turn volume and opposing-through volume scenarios are analyzed. And their impacts are studied under three left-turn conditions:

i. Shared through left-turn (TH-LT) lane with permissive left-turn phase.
ii. Exclusive left-turn (LT) lane with permissive left-turn phase.
iii. Exclusive left-turn (LT) lane with protected-permissive left-turn phase.

This experiment is studied on an intersection basis; and the details of the left-turn volume scenarios are described in Section 4.2.4. In this experiment, the TSP effectiveness is measured by the change in B-Line bus delay when TSP is applied; in other words, an increase in the B-Line bus delay would mean a reduction in the TSP effectiveness (i.e., a reduction in TSP's capability to improve the performance or delay of the B-Line buses).

5.4.1 LEFT-TURN AND OPPOSING-THROUGH VOLUME IMPACT ON TSP EFFECTIVENESS

In this analysis, the scenario of no left-turn traffic, a condition that would lead to the highest effectiveness of TSP implementation, is used as a benchmark for the comparison of the TSP effectiveness under different left-turn conditions. Since more left-turn impact is expected when the left-turn traffic are using a shared through-left-turn lane and a permissive left-turn phase, the impacts of various left-turn and opposing-through traffic volume scenarios are studied under this left-turn condition. Figure 5-16 shows the percentage increase in the average B-Line bus delay, relative to the no left-turn scenario, for different left-turn (LT) volumes and opposing-through (OppTH) v/c ratios when TSP is implemented.

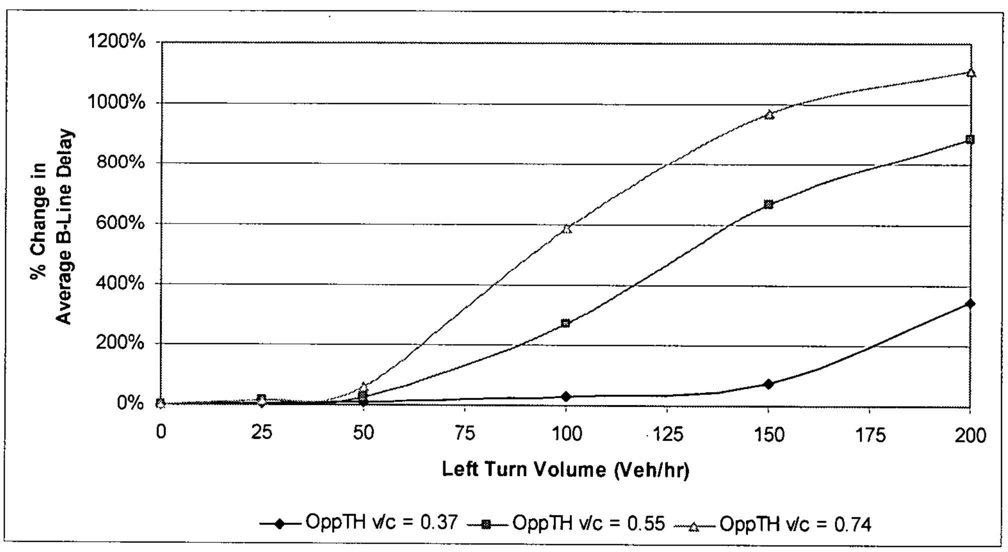

Figure 5-16 Left-Turn and Opposing-Through Traffic Impact on TSP Effectiveness (Shared TH-LT Lane and Permissive LT Phase)

Figure 5-16 shows that the average delay of B-Line buses would increase with an increase in left-turn traffic when TSP is implemented. This is because an increase in left-turn traffic traveling on a shared through-left-turn (TH-LT) lane would encourage more traffic to use the center and the rightmost lanes, where the B-Line buses are traveling. This would result in an increase in the B-Line bus delay because the B-Line buses would have to compete with increased traffic traveling on the same lane. Moreover, the v/c ratio of the opposing-through volume can impact the delay of the B-Line buses, especially when the left-turn traffic is heavy. It is because the dissipation of the left-turn traffic during the permissive left-turn phase is controlled by the availability of an adequate gap of the opposing-through traffic. As a result, the application of TSP needs to be carefully considered at intersections with high left-turn and opposing-through volume, when only shared TH-LT lane and permissive left-turn phase can be provided. This result agrees with the findings reported by Abdulhai et al (2002) that the banning of left-turn on King Street would improve the transit cycle time by 13%.

It should be noted that, for this analysis, the scenarios with high left-turn and high opposing-through volumes are not realistic, but are examined to show the theoretical trend of the change in B-Line bus delay and to compare with other left-turn lane and left-turn phase conditions. A protected left-turn phase is usually provided when the product of the left-turn volume and opposing-through volume exceeds 50,000 [Roess et al, 1998], which most of these scenarios have exceeded.

5.4.2 LEFT-TURN LANE IMPACT ON TSP EFFECTIVENESS

In this section, the left-turn lane impact on TSP effectiveness is studied. Figure 5-17, Figure 5-18 and Figure 5-19 show the impact of left-turn lane on the percentage increase in B-Line bus delay (i.e., percentage deterioration in TSP effectiveness) for opposing-through v/c ratios of 0.37 (1,000 Veh/hr), 0.55 (1,500 Veh/hr) and 0.74 (2,000 Veh/hr) respectively, when TSP is implemented.

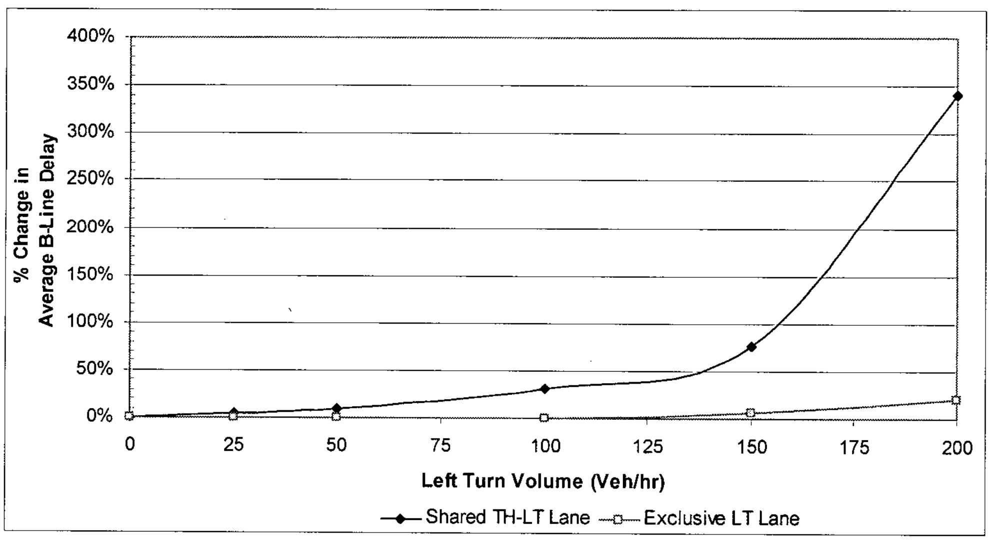

Figure 5-17 Left-Turn Lane Impact on TSP Effectiveness (Opposing-through v/c = 0.37 or 1,000 Veh/hr)

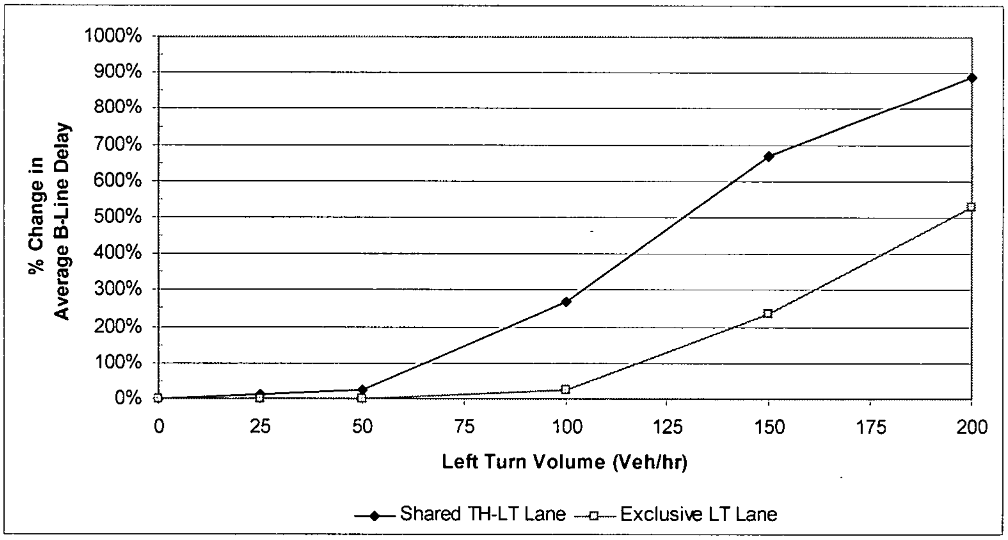

Figure 5-18 Left-Turn Lane Impact on TSP Effectiveness (Opposing-through v/c = 0.55 or 1,500 Veh/hr)

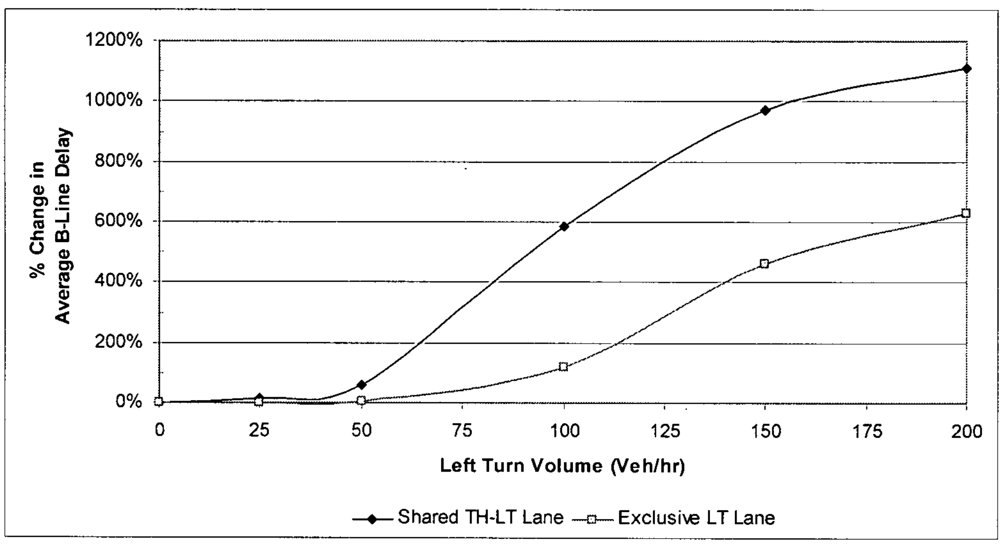

Figure 5-19 Left-Turn Lane Impact on TSP Effectiveness (Opposing-through v/c = 0.74 or 2,000 Veh/hr)

The above results illustrate, when a permissive left-turn phase is deployed, the TSP effectiveness would be significantly improved with a provision of an exclusive left-turn lane. It is observed from the three opposing-through v/c scenarios that an exclusive left-turn lane would begin to lose its effectiveness at a left-turn and opposing-through volume cross-product of around 100,000.

5.4.3 LEFT-TURN PHASE IMPACT ON TSP EFFECTIVENESS

In this section, the impact of left-turn phase on the effectiveness of TSP is analyzed. Two left-turn phasing schemes are considered: permissive left-turn phase and protected-permissive left-turn phase. Figure 5-20, Figure 5-21 and Figure 5-22 show the impact of left-turn phase on the percentage increase in B-Line bus delay (i.e., percentage deterioration in TSP effectiveness) for opposing-through v/c ratios of 0.37 (1,000 Veh/hr), 0.55 (1,500 Veh/hr) and 0.74 (2,000 Veh/hr) respectively, when TSP is implemented.

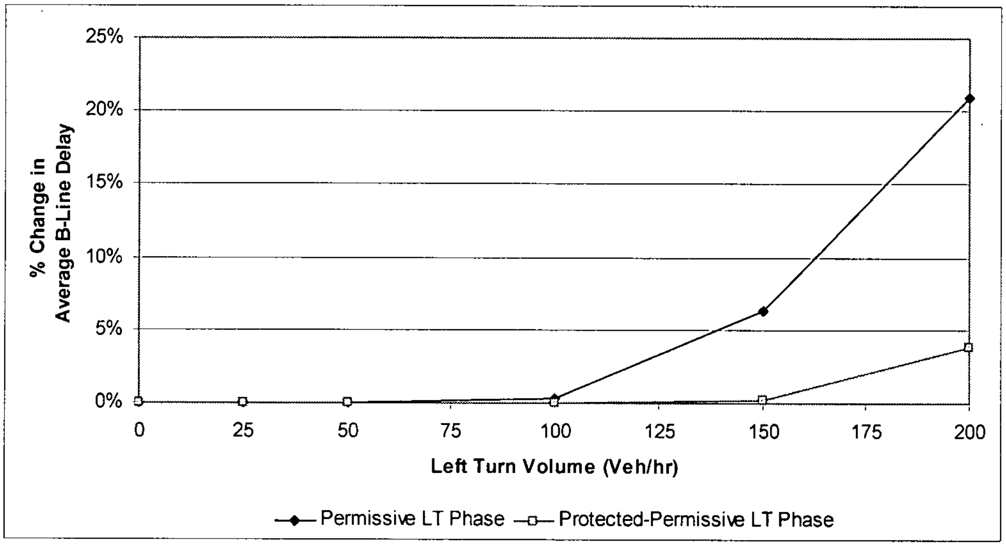

Figure 5-20 Left-Turn Phase Impact on TSP Effectiveness (Opposing-through v/c = 0.37 or 1,000 Veh/hr)

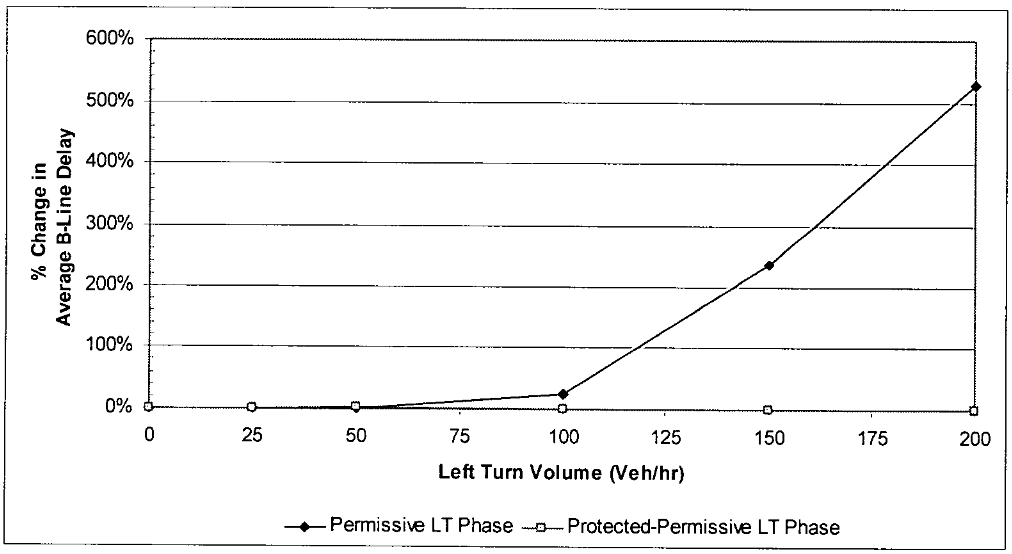

Figure 5-21 Left-Turn Phase Impact on TSP Effectiveness (Opposing-through v/c = 0.55 or 1,500 Veh/hr)

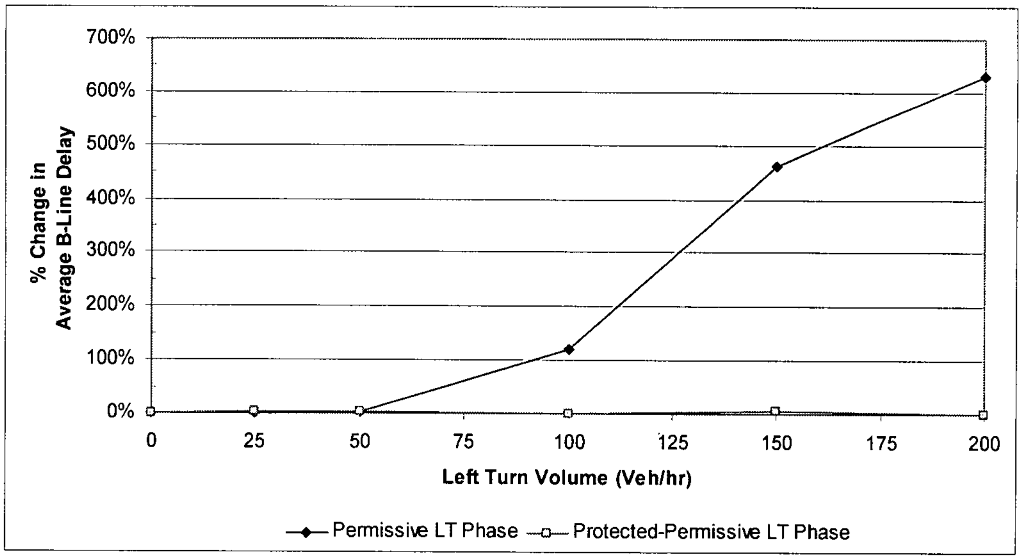

Figure 5-22 Left-Turn Phase Impact on TSP Effectiveness (Opposing-through v/c = 0.74 or 2,000 Veh/hr)

The above figures illustrate that left-turn traffic would have a minimal influence on the B-Line bus performance (or TSP effectiveness) when both a protected left-turn phase and an exclusive left-turn lane are used. This result demonstrates the need for a protected left-turn phase and an exclusive left-turn lane at a signalized intersection with high left-turn and opposing-through volume, in order to maintain the highest effectiveness of a TSP application.

5.5 RIGHT-TURN VOLUME

This section examines the impact of right-turn volume on the effectiveness of TSP. Since the throughput of the right-turn traffic is highly dependent on the pedestrian traffic that travels in the direction conflicting with the right-turn traffic, combinations of different right-turn and pedestrian volumes at an intersection are considered. Additionally, the impact of right-turn lane on the TSP effectiveness is also examined. This experiment is studied on an intersection basis and the details of the right-turn volume scenarios are described in Section 4.2.5.

Similar to the left-turn experiment, the TSP effectiveness is measured by the change in B-Line bus delay when TSP is implemented; in other words, an increase in delay of the B-Line buses would mean a reduction in the TSP effectiveness (i.e., a reduction in TSP's capability to improve the performance or delay of the B-Line buses).

5.5.1 RIGHT-TURN AND PEDESTRIAN VOLUME IMPACT ON TSP EFFECTIVENESS

In this analysis, the scenario of no right-turn traffic, a condition that would lead to the highest effectiveness of TSP implementation, is used as a benchmark for comparison of the effectiveness of TSP under different right-turn conditions. Figure 5-23 shows the percentage change in the average B-Line bus delay relative to the no right-turn scenario. This results is obtained when a shared through-right-turn (TH-RT) lane is used.

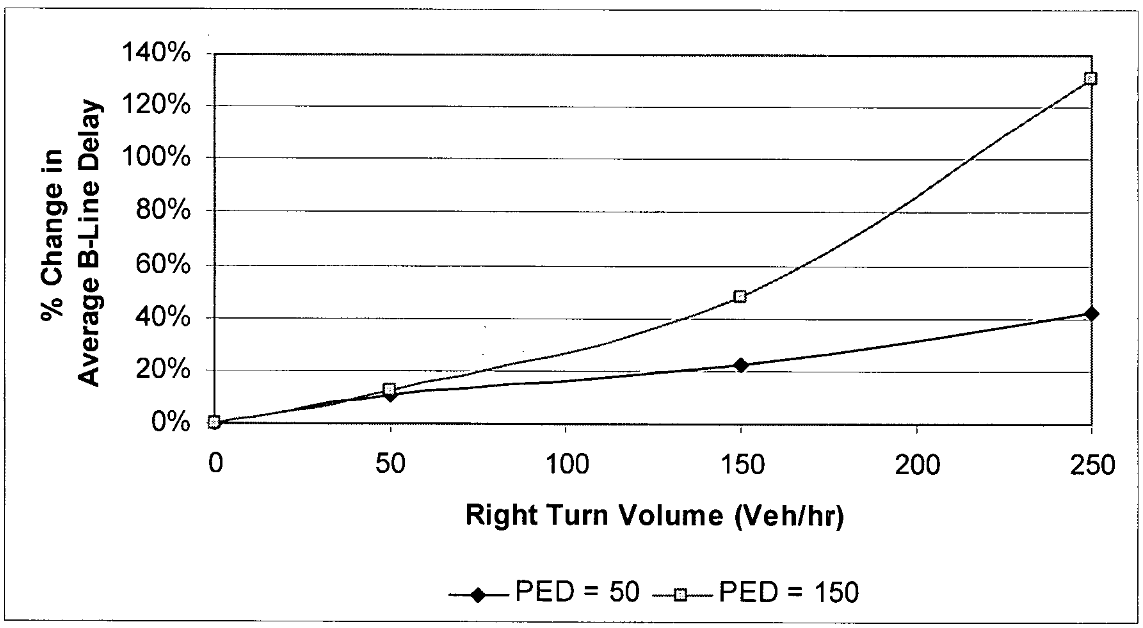

Figure 5-23 Right-Turn and Pedestrian Traffic Impact on TSP Effectiveness (Shared TH-RT Lane)

Figure 5-23 illustrates that an increase in right-turn traffic would increase the average delay of the B-Line buses, thus lowering the effectiveness of TSP. This is because an increase in right-turn traffic would hinder the movements of the B-Line buses, which travels on the rightmost lane where the right-turn vehicles make their turns. It is also shown that the effectiveness of TSP would further decrease as the pedestrian volume increases. This is because the pedestrian volume would directly affect the dissipation of the right-turn traffic, which has to yield to the crossing pedestrians before they make their turns. This concludes that careful consideration should be made when applying TSP at an intersection with heavy right-turn and pedestrian traffic.

The above result is in agreement with the findings by Chatila & Swenson (2000) that vehicle queuing, especially right turning vehicles at intersection and their associated queue length, significantly impacted the effectiveness of TSP. They suggested that under this situation, additional time would be required to process the right-turn vehicles for the transit vehicles to enter the intersection, thereby reducing the benefits of TSP [Chatila & Swenson, 2000].

5.5.2 RIGHT-TURN LANE IMPACT ON TSP EFFECTIVENESS

Additionally, the influence of a right-turn lane on TSP effectiveness is studied. Figure 5-24 and Figure 5-25 show this influence for the pedestrian volume scenarios of 50 pedestrians/hour and 150 pedestrians/hour respectively.

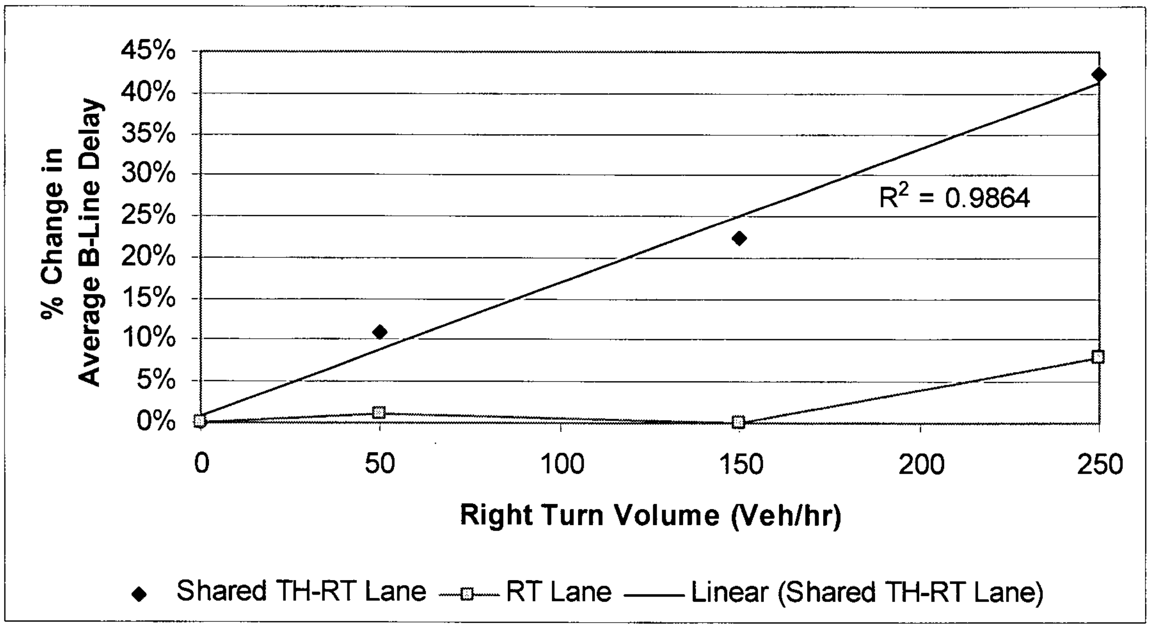

Figure 5-24 Right-Turn Lane Impact on TSP Effectiveness (Pedestrian Volume = 50 Pedestrians/hour)

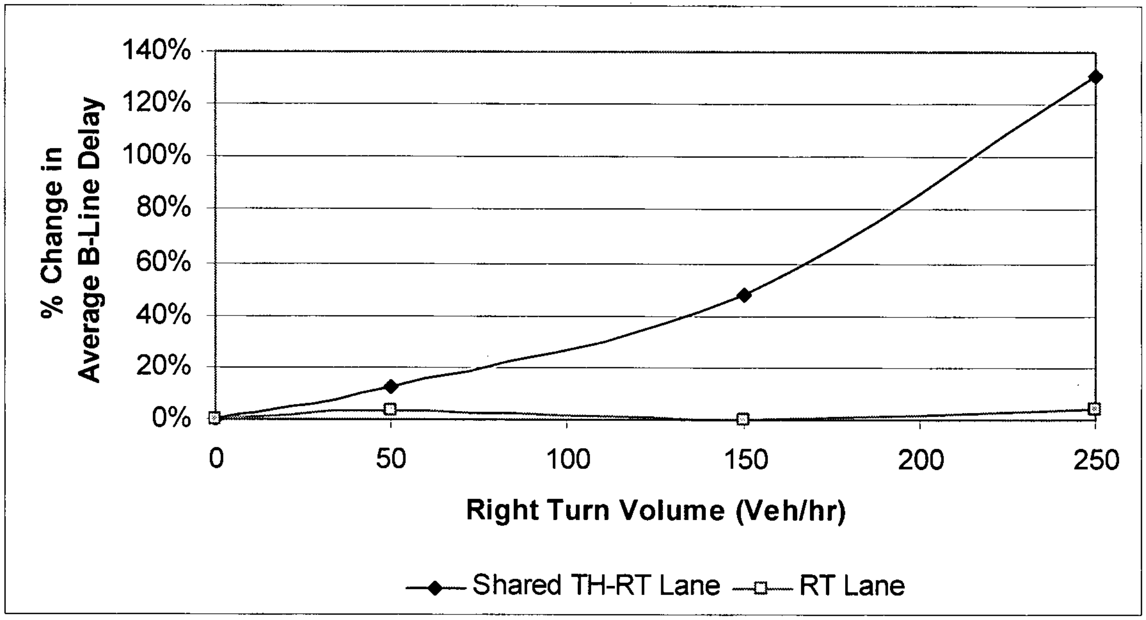

Figure 5-25 Right-Turn Lane Impact on TSP Effectiveness (Pedestrian Volume = 150 Pedestrians/hour)

Figure 5-24 and Figure 5-25 clearly show that when an exclusive right-turn lane is used, an increase in right-turn volume would only incur very minimal impact on the B-Line bus performance and the effectiveness of TSP would be maintained even with heavy right turn volume. As a result, for the highest effectiveness of TSP, it would be ideal to use an exclusive right-turn lane at a signalized intersection with heavy right-turn traffic. And the length of the exclusive right-turn lane should be long enough to accommodate the right-turn traffic queue.

5.6 BUS STOP AND DETECTOR LOCATION

Previous studies reported that the location of a bus stop would influence the green extension success rate of the transit vehicles. In this research, the influence of the bus stop location (i.e., farside bus stop versus nearside bus stop) on the effectiveness of TSP is compared under different Granville Street v/c ratios. In addition, the influence of the bus check-in detector location on TSP effectiveness is also examined. These experiments are studied on intersection bases; and the bus stop and bus check-in detector location scenarios used for the experiments are detailed in Section 4.2.6.

5.6.1 BUS STOP LOCATION IMPACT ON B-LINE BUS PERFORMANCE

In this section, the impact of the bus stop location on TSP effectiveness (or on delay of the B-Line buses) is studied. The impact of converting a farside bus stop to a nearside bus stop is also analyzed.

Figure 5-26 compares the average B-Line bus delay for a farside bus stop and a nearside bus stop under different Granville Street v/c ratios, when TSP is implemented. The B-Line bus delay values express only the traffic delays of the B-Line buses, i.e., the B-Line bus dwell time delays have been excluded.

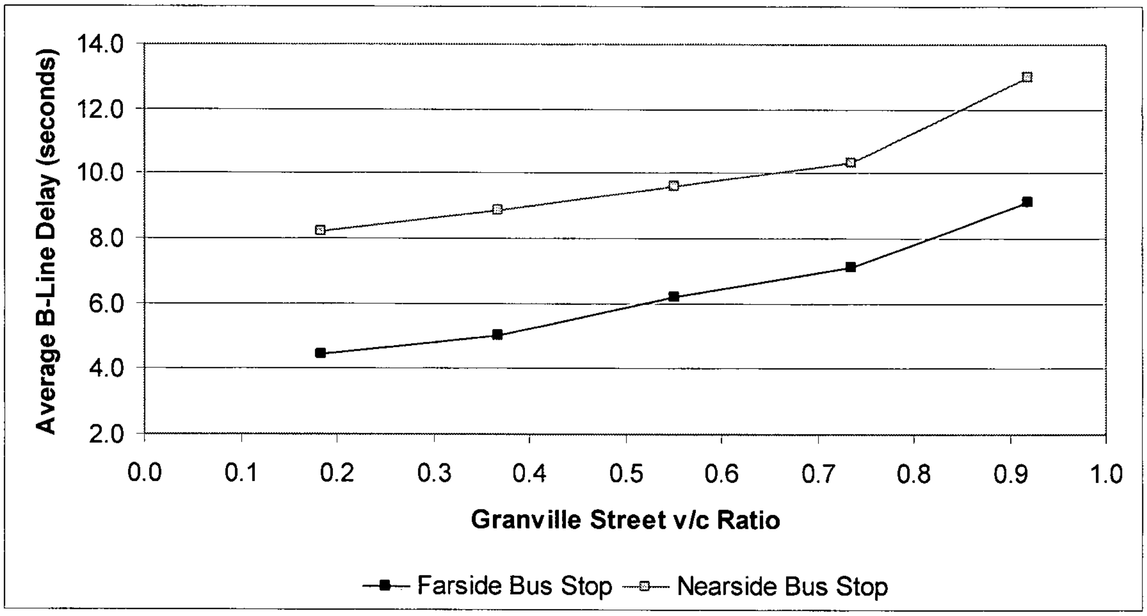

Figure 5-26 Bus Stop Location Impact on Average B-Line Bus Delay

Figure 5-26 shows that a nearside bus stop would cause higher delay to the B-Line buses than a farside bus stop would. This is because a significant portion of the green extension would be wasted while the passengers are boarding and alighting at a nearside bus stop, thereby lowering the green extension success rate of the B-Line buses. This lengthens the B-Line bus waiting time at a signal and causes higher delay to the B-Line buses.

The results shown in Figure 5-26 are in agreement with a number of researches that preferred a farside bus stop more for a TSP application. As explained by Daniel (1997), the use of a nearside bus stop with green extension or red truncation would increase in the uncertainty in predicting the arrival time of a bus at an intersection because of the uncertain passenger loading and unloading time. And Huffman et al (1998) also believed that the usage of a farside bus stop would maximize the efficiency of signal priority because there would be less influence from the dwell time at a farside bus stop.

Further analysis is performed to study the impact on B-Line bus delay when a farside bus stop is converted to a nearside bus stop. **Figure 5-27** illustrates the impact.

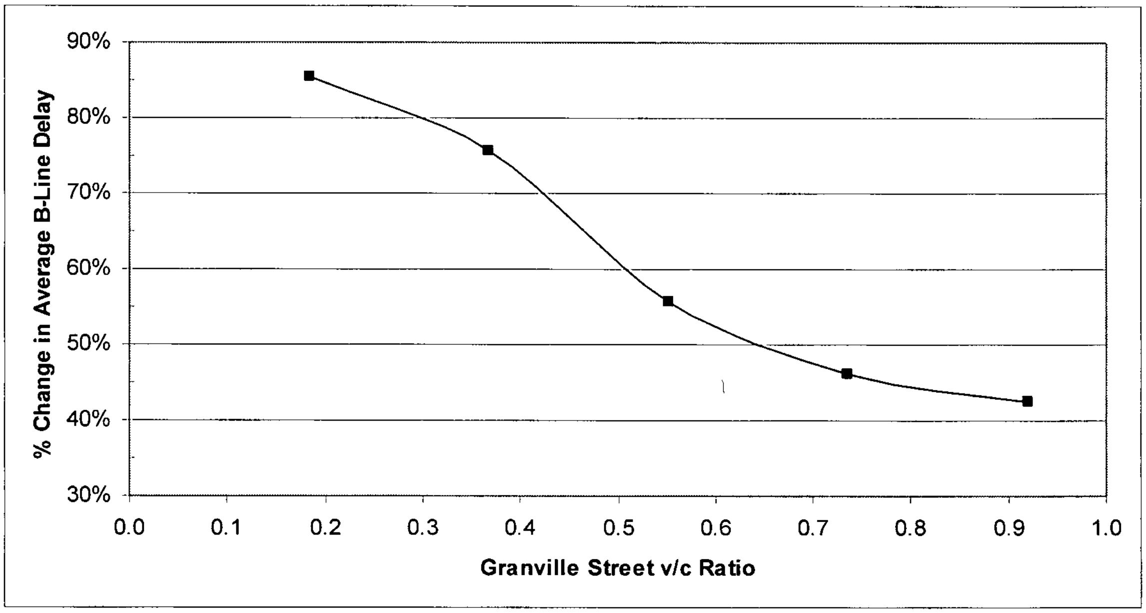

Figure 5-27 Nearside Bus Stop Impact on TSP Effectiveness

Figure 5-27 illustrates that the average B-Line bus delay would increase when a farside bus stop is converted to a nearside bus stop. This increase in the average B-Line bus delay would reduce as the Granville Street v/c ratio increases. This is because, as the Granville Street v/c ratio increases, the B-Line bus delay would be more influenced by the traffic delay from the heavier Granville Street traffic than by the bus stop location.

5.6.2 BUS DETECTOR LOCATION IMPACT ON B-LINE BUS PERFORMANCE

Figure 5-28 shows the influence of the B-Line bus check-in detector location on the average B-Line bus delay with the usage of a farside bus stop and a nearside bus stop, when TSP is implemented. The B-Line bus delay values express only the traffic delays of the B-Line buses, i.e., the B-Line bus dwell time delays have been excluded.

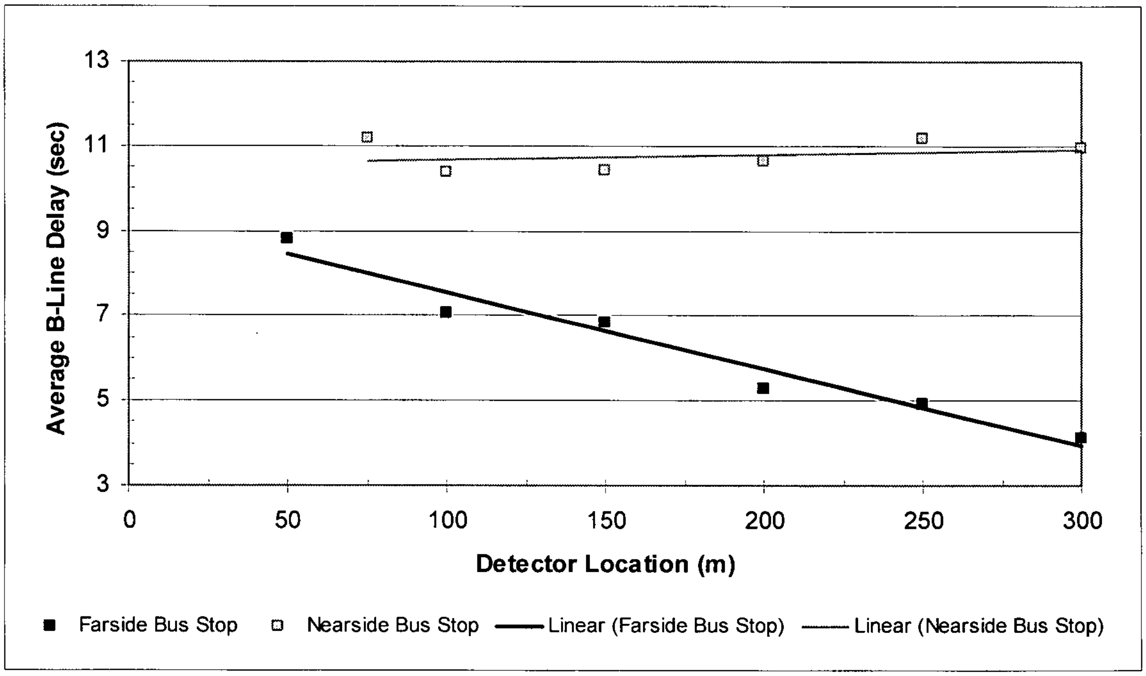

Figure 5-28 Detector Location Impact on Average B-Line Bus Delay (Comparison of Farside Bus Stop versus Nearside Bus Stop)

Based on the analysis, the following observations are made:

- As discussed earlier in Section 5.6.1, the B-Line buses perform better with a farside bus stop than with a nearside bus stop.
- The delay of the B-Line buses is less sensitive to the check-in detector location when a nearside bus stop is placed. This is because the performance of the B-Line buses would be more influenced by the dwell time at the nearside bus stop than by the location at which the buses are detected.
- The B-Line bus delay is more sensitive to the B-Line bus check-in detector location when a farside bus stop is placed.
- Locating the check-in detectors further from the intersection stop bar would improve the delay of the B-Line buses. When a B-Line bus checks in during red, placing the bus check-in detectors further from an intersection could allow an earlier request for a red truncation, thereby allowing the queuing vehicles at the intersection to be dissipated earlier. On the other hand, when a B-Line bus checks in during green, placing the bus check-in detectors further from the

intersection stop bar could allow a green extension to be requested more in advance. This would increase the chances that a green extension be called, especially if the B-Line bus checks in almost at the end of the green time. However, the check-in detector should be placed within the clearance distance of the B-Line buses such that the buses can enter the intersection after checking in for the maximum green extension given.

- A reduction in TSP effectiveness is expected when placing the check-in detector beyond the clearance distance of the B-Line buses, which is 200 meters from the intersection stop bar in this experiment. The 200 meters is calculated based on an average B-Line bus traveling speed of 50 km/hr (or 13.9 m/s) and a maximum green extension of 14 seconds. However, this expectation is not observed in Figure 5-28. This could be explained by the fact that the clearance distance of 200 meters is calculated based on the assumption that the B-Line buses would check in right at the end of the green phase. However, it is observed from the simulations that, given a 40-second bus approach green time in a 75-second signal cycle, the B-Line buses rarely check in right at the end of the green phase; therefore, the allowable green time window for a B-Line bus is actually the sum of the remaining green time in the phase after the bus checks in and the maximum green extension of 14 seconds. Consequently, most B-Line buses could check out without much difficulty even if the check-in detectors are placed further than clearance distance of the B-Line buses.

5.6.3 BUS STOP AND DETECTOR LOCATION IMPACT ON GREEN EXTENSION EFFECTIVENESS

Figure 5-29 and Figure 5-30 show the influence of the bus stop and bus detector location on the green extension success rate and checkout detector effectiveness of the B-Line buses.

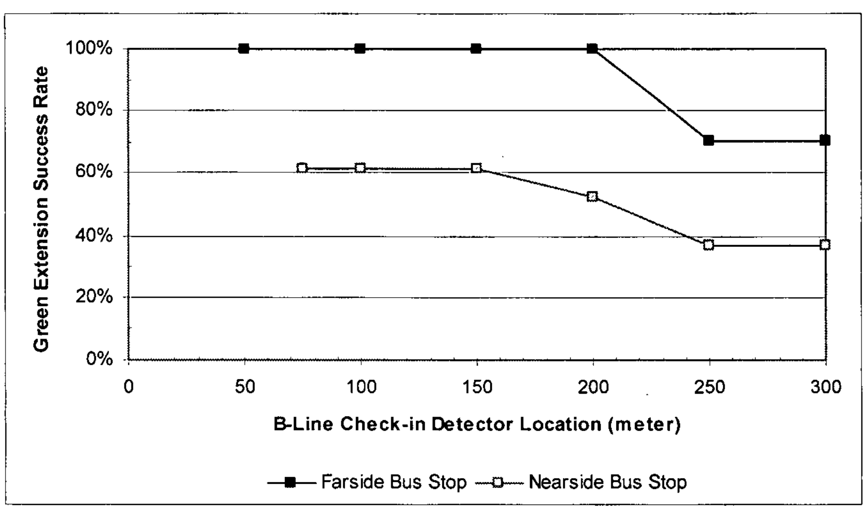

Figure 5-29 Check-in Detector Location Impact on Green Extension Success Rate

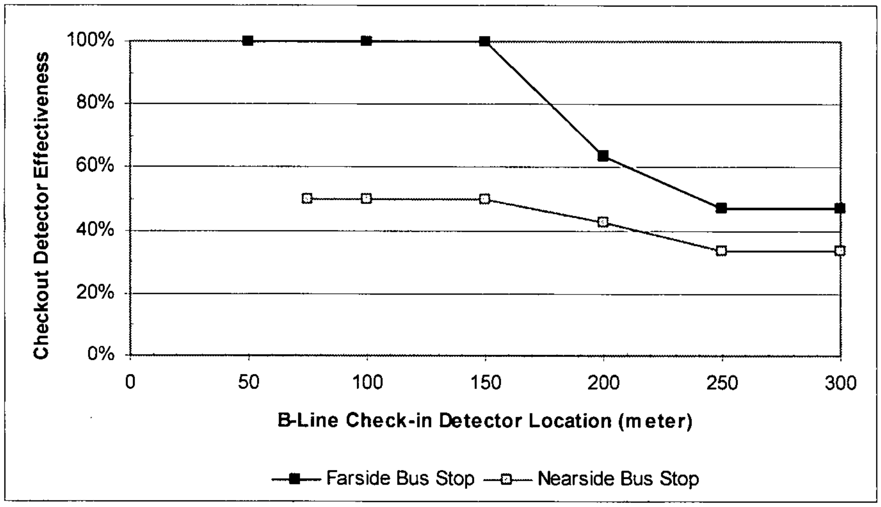

Figure 5-30 Check-in Detector Location Impact on Checkout Detector Effectiveness

Figure 5-29 and Figure 5-30 show the following results:

- A farside Bus Stop gives a higher success rate of green extension and checkout detector effectiveness than a nearside bus stop does. This is because a nearside bus stop is placed in between the B-Line bus check-in detectors and the intersection, for which the dwell time at the bus stop would lengthen and fluctuate the time required for the bus to clear the intersection after checking in.

  This supports the results obtained by Garrow & Machemehl (1998) that the effectiveness of green extension would be higher for a farside bus stop than for a nearside bus stop. Their green extension success rate results ranged from 50% to 89% for a farside bus stop and varied from 10% to 30% for a nearside bus stop, under different green extension lengths and bus approach saturation levels described in Section 2.3.4. Garrow & Machemehl (1998) explained this by the fact that the presence of a nearside bus stop would waste a significant portion of the green extension while the passengers board and alight at the bus stop.

- The green extension success rate and checkout detector effectiveness decreases would drop when the check-in detectors are placed beyond the clearance distance of the B-Line buses. This is because the further a bus detector is placed, the longer time is required for a B-Line bus to enter the intersection (i.e., check out) after checking in.

Additionally, the number of green extension (GE) calls granted and the number of GE failure (i.e., the number of B-Line bus that cannot checkout the intersection during the green extension phase) for the Farside Bus Stop and the Nearside Bus Stop scenarios are compared. The comparisons are shown in Table 5-5.

Table 5-5 Count of GE Calls and GE Failures for Farside and Nearside Bus Stop

Detector Location	Total # of GE		# of GE Failure	
	Farside	Nearside	Farside	Nearside
50 m	2	--	0	--
75 m	--	6	--	2
100 m	3	6	0	2
150 m	3	6	0	2
200 m	4	7	0	3
250 m	6	9	2	6
300 m	6	9	2	6

Note:

- "GE" represents green extension; and
- The closest detector to the intersection is placed 50 meters and 75 meters for the farside bus stop scenario and nearside bus stop scenario respectively.

It is observed from the above table that a higher number of green extensions calls and green extension failures are called with a nearside bus stop. This is because the use of a nearside bus stop would waste a significant portion of the green time provided to the B-Line buses; therefore, more B-Line buses would require a green extension to clear the intersection. In addition, the numbers of green extension calls and green extension failures are higher when the B-Line bus check-in detectors are placed further from the intersection stop bar. This is because placing the detectors further from the intersection would lengthen the B-Line bus traveling time from the check-in detectors to the intersection. In general, the results from this analysis show that the number of green extension calls and green extension failures would increase when a nearside bus stop is placed or when the bus check-in detector is placed further from an intersection with a farside bus stop.

5.7 TSP STRATEGY

In this section, the impact of TSP strategies on the B-Line bus performance and the green extension effectiveness are assessed. This experiment is studied on a corridor basis and the details of the TSP strategy scenarios are described in Section 4.2.7.

5.7.1 TSP STRATEGY IMPACT ON B-LINE BUS PERFORMANCE

Figure 5-31 and Figure 5-32 shows the influence of the maximum green extension on the average B-Line bus travel time along the Granville Street corridor, for two minimum walk time scenarios: (i) minimum walk time equals the maximum walk time (i.e., no red truncation is granted) and (ii) minimum walk time of 3 seconds (the corresponding lengths of the maximum red truncation are shown in Section 4.2.7).

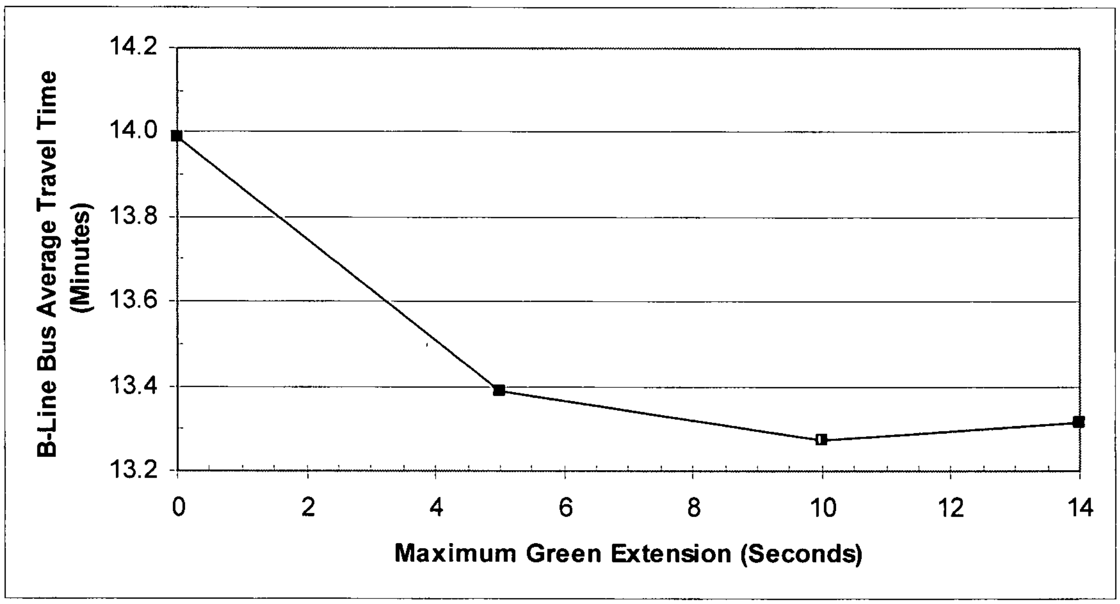

Figure 5-31 TSP Strategy Impact on Average B-Line Bus Travel Time (No Red Truncation)

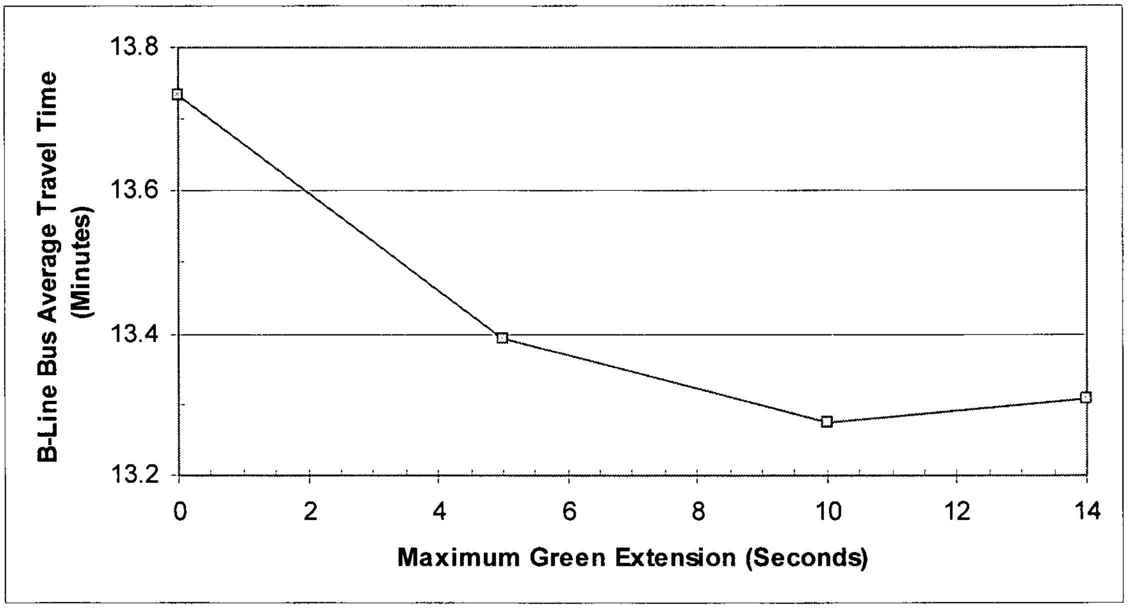

Figure 5-32 TSP Strategy Impact on Average B-Line Bus Travel Time (Minimum Walk Time = 3 seconds)

Figure 5-31 and Figure 5-32 demonstrate the following impacts of TSP strategies on the B-Line bus performance:

- In general, TSP improves the average B-Line bus travel time more significantly when a longer maximum green extension is deployed. This is because a longer maximum green extension would provide a longer green time window for the B-Line buses to clear the intersection after checking in.

- Beyond the maximum green extension of 10 seconds, the effectiveness of TSP levels off because it is observed from the simulations that green extensions over 10 seconds are seldom called.

It should be noted that an addition of red truncation to a green extension strategy only has minimal impact on the B-Line bus performance. This could be attributed to the small number of TSP calls granted for this experiment with a 10-minute B-Line bus headway and non-successive TSP recovery strategy (i.e., TSP calls are restricted in successive cycles).

5.7.2 TSP STRATEGY IMPACT ON GREEN EXTENSION EFFECTIVENESS

The impact of TSP strategy on the green extension effectiveness is also assessed. Figure 5-33 and Figure 5-34 illustrate the impact of TSP strategy on the green extension success rate and the checkout detector effectiveness of the B-Line buses respectively. The definitions of green extension success rate and checkout detector effectiveness are given in Section 3.2.3.3.

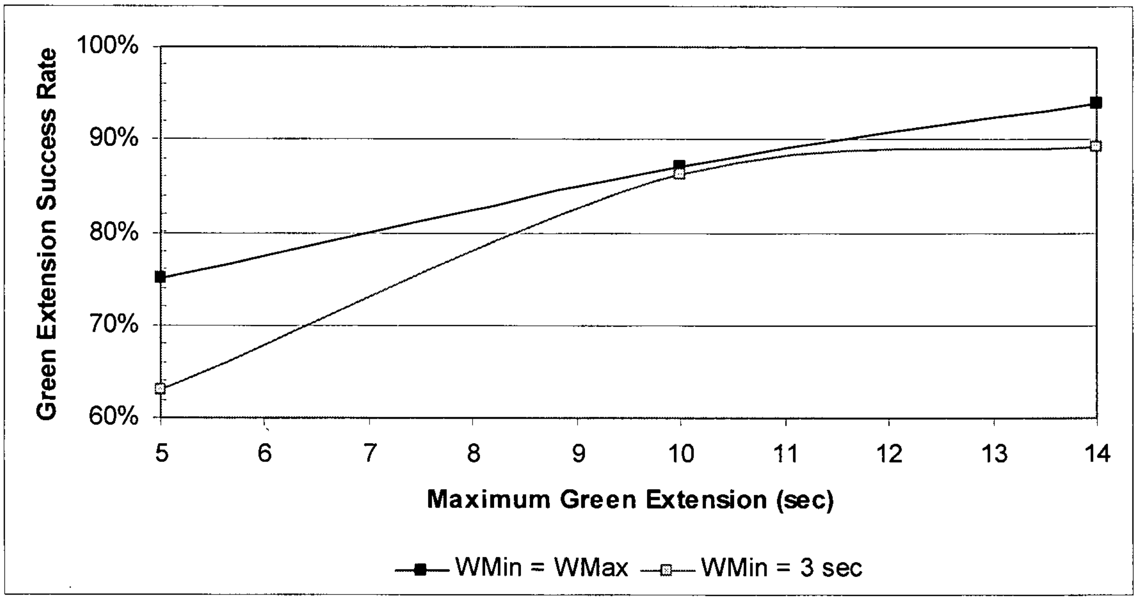

Figure 5-33 TSP Strategy Impact on Green Extension Success Rate

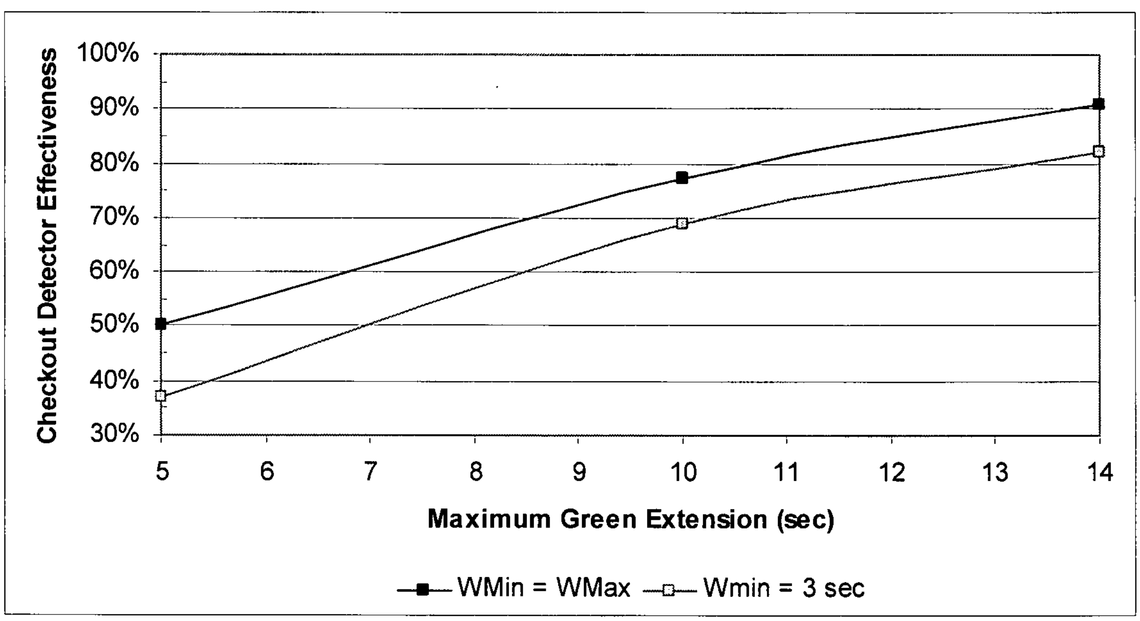

Figure 5-34 TSP Strategy Impact on Checkout Detector Effectiveness

Figure 5-33 and Figure 5-34 show the following results:

- The number of green extension successes (i.e., the number of B-Line buses that check out successfully during the green extension period) increases when a higher maximum green extension (or Max-Timer) is deployed. This is because a longer Max-Timer for the B-Line buses would provide a longer green time window for the B-Line buses to clear the intersection after checking in, thereby increasing the chance that a bus checks out successfully during the green extension phase.

- The usefulness of a checkout detector (i.e., the number of times a checkout detector is used to provide early termination of a green extension phase) increases when a higher maximum green extension (or Max-Timer) is deployed. This is because a higher Max-Timer would increase the chance that a B-Line bus checks out before the Max-Timer is reached.

- The success of a green extension would be slightly reduced when red truncation is also allowed. The provision of both red truncation and green extension in a TSP strategy would increase the number of TSP calls because the B-Line buses could request for a TSP call when they check in either during the green time or the red time. However, this would also increase the chance that a green extension be requested after a TSP call in the preceding cycle. Since the usage of successive TSP strategy (i.e., allowance of TSP calls in successive cycles) is restricted for this experiment, the green extension effectiveness would tend to decrease because green extension request following another TSP calls in the preceding cycles would not be granted.

5.8 RECOVERY STRATEGY

A recovery strategy could be applied to control the frequency and successiveness of TSP calls. This section considers the impact of TSP on the B-Line bus and cross street performances under two recovery strategies: (i) with successive TSP allowed and (ii) no successive TSP allowed, i.e., no TSP calls are allowed in two successive cycles. Details of the recovery strategy scenarios are described in Section 4.2.8.

5.8.1 RECOVERY STRATEGY IMPACT ON B-LINE BUS PERFORMANCE

This experiment is studied on a corridor basis. Figure 5-35 shows a comparison of the improvement of TSP on the B-Line buses travel time along the Granville Street corridor when non-successive TSP and successive TSP recovery strategies are deployed, under 5 different B-Line bus headways.

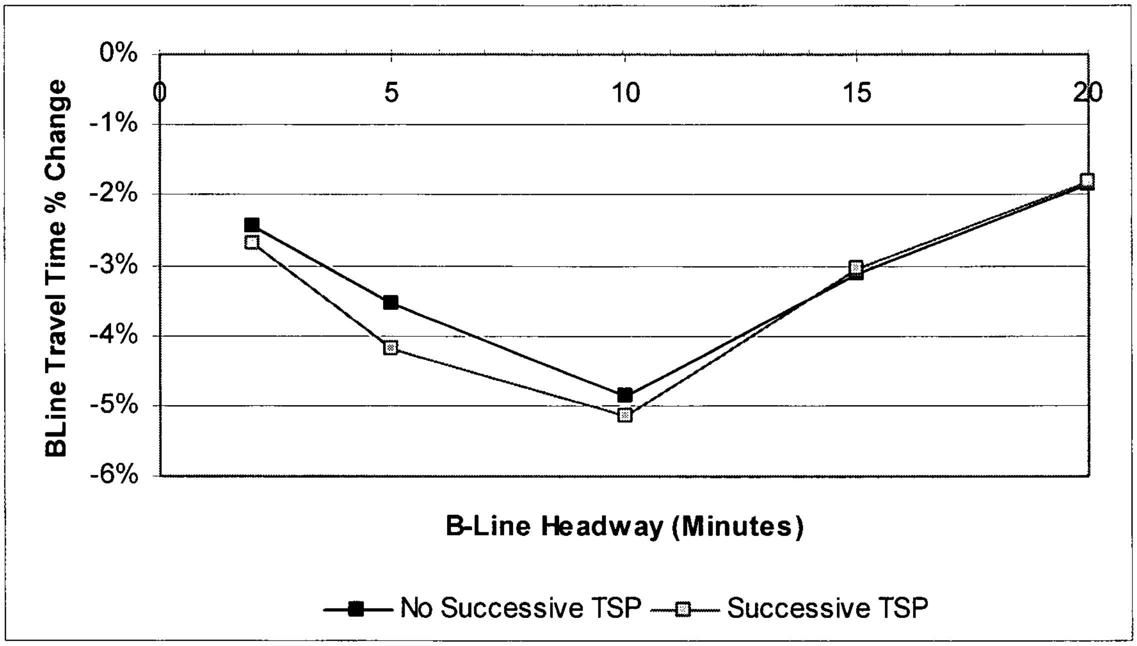

Figure 5-35 Recovery Strategy Impact on TSP Effectiveness

Figure 5-35 shows that:

- The allowance of successive TSP does not impact the improvement of B-Line bus travel time at B-Line bus headways above 15 minutes. This is because a longer B-Line bus headway, or lower B-Line buses arrival frequency, rarely causes two buses arriving in successive cycles.

- The allowance of successive TSP has higher impact on the B-Line bus travel time improvement at B-Line bus headways at or below 10 minutes. This is because a smaller B-Line bus headway would trigger a higher number of TSP calls in successive cycles. Therefore, the allowance of TSP calls in successive cycles with low B-Line bus headways could increase the effectiveness of TSP, thus improving the performance of B-Line buses.

- The 10-minute B-Line bus headway could be the threshold B-Line bus headway below which the allowance of successive TSP strategy could make further improvement (or reduction) in the B-Line bus travel time.

- Successive TSP has the highest impact on B-Line bus performance at a B-Line bus headway of 5 minutes. The impact reduces at a B-Line bus headway of 2 minutes, attributed to a higher bus volume that increases the B-Line bus delay in the network.

5.8.2 RECOVERY STRATEGY IMPACT ON CROSS STREET PERFORMANCE

In this section, the impact of recovery strategy on the cross street delay is investigated. The eastbound approach of 70th Avenue is examined for this experiment. Figure 5-36 to Figure 5-43 show the cross street average cycle delay trends with and without the allowance of successive TSP calls, for cross street v/c ratios of 0.25, 0.50, 0.80 and 0.90.

The even numbered figures (i.e., Figure 5-36, Figure 5-38, Figure 5-40, and Figure 5-42) illustrate the comparisons of the cross street delay trends between the "No TSP" scenario and the "Non-Successive TSP" scenario. Meanwhile, the odd numbered figures (i.e., Figure 5-37, Figure 5-39, Figure 5-41, and Figure 5-43) show the comparisons of the cross street delay trends between the "No TSP" scenario and the "Successive TSP" scenario.

On the figures, the vertical solid line represents the time at which a green extension is granted and the vertical dotted line represents the time at which a red truncation is called. The numerical value on top of each line represents the length of green extension or red truncation conferred to the B-Line buses. And the circle highlights the cycles in which the impact of successive TSP strategy is most noticeably shown, for each cross street v/c ratio scenario.

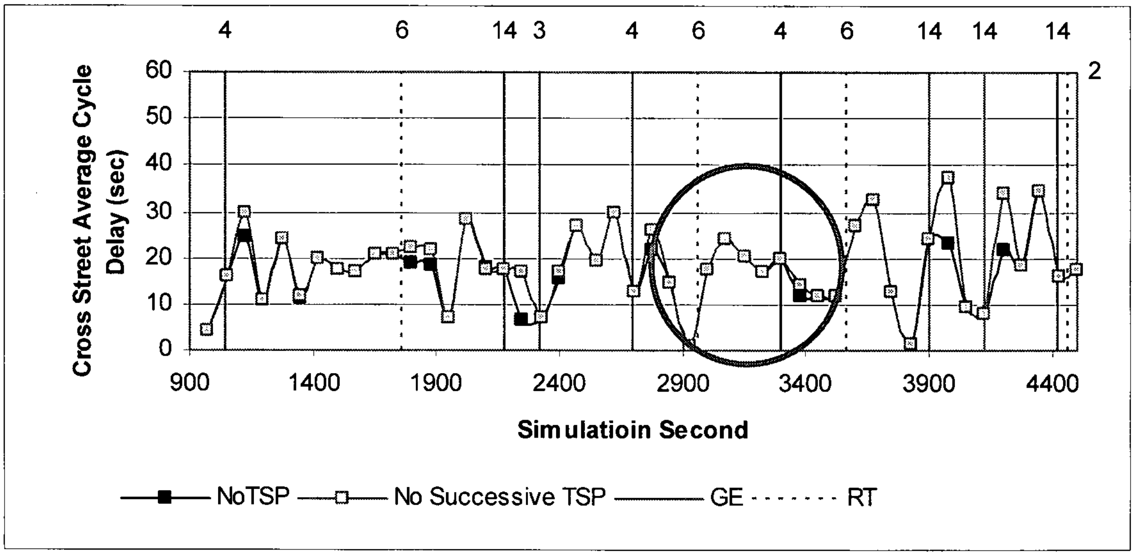

Figure 5-36 Non-Successive TSP Impact on Cross Street Performance (v/c = 0.25)

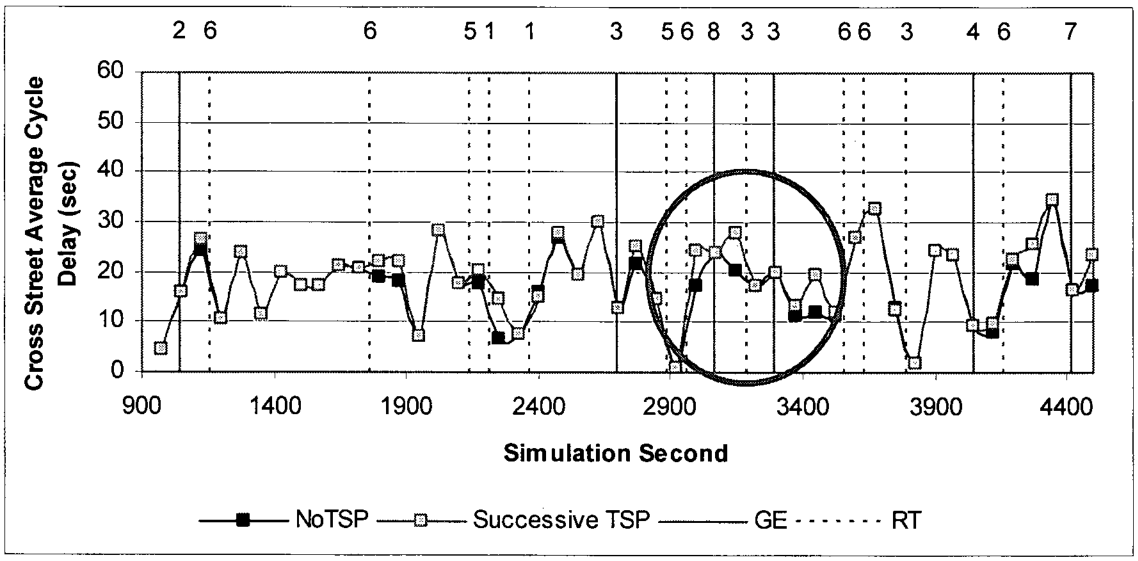

Figure 5-37 Successive TSP Impact on Cross Street Performance (v/c = 0.25)

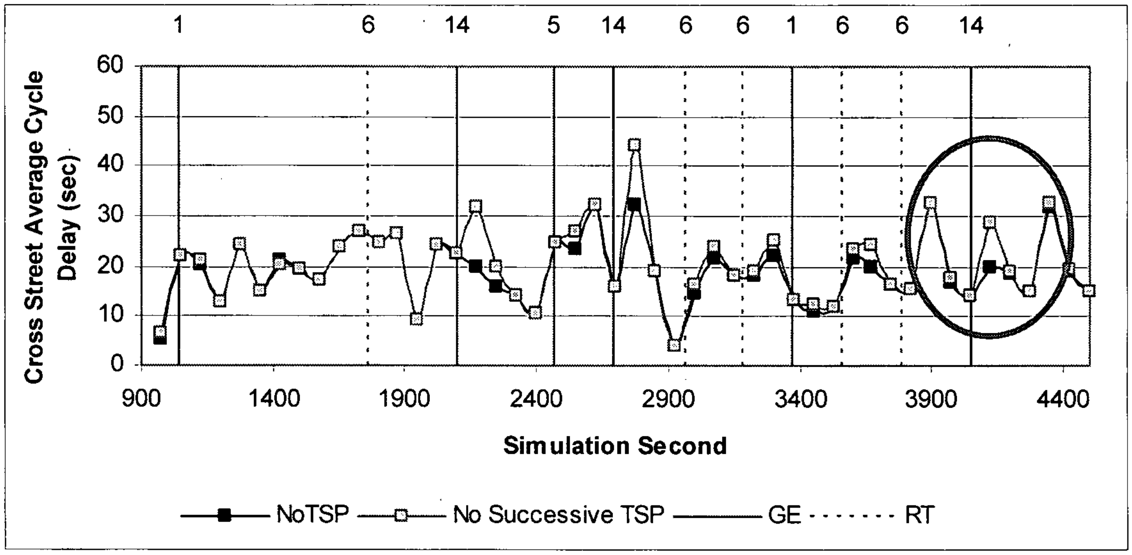

Figure 5-38 Non-Successive TSP Impact on Cross Street Performance (v/c = 0.50)

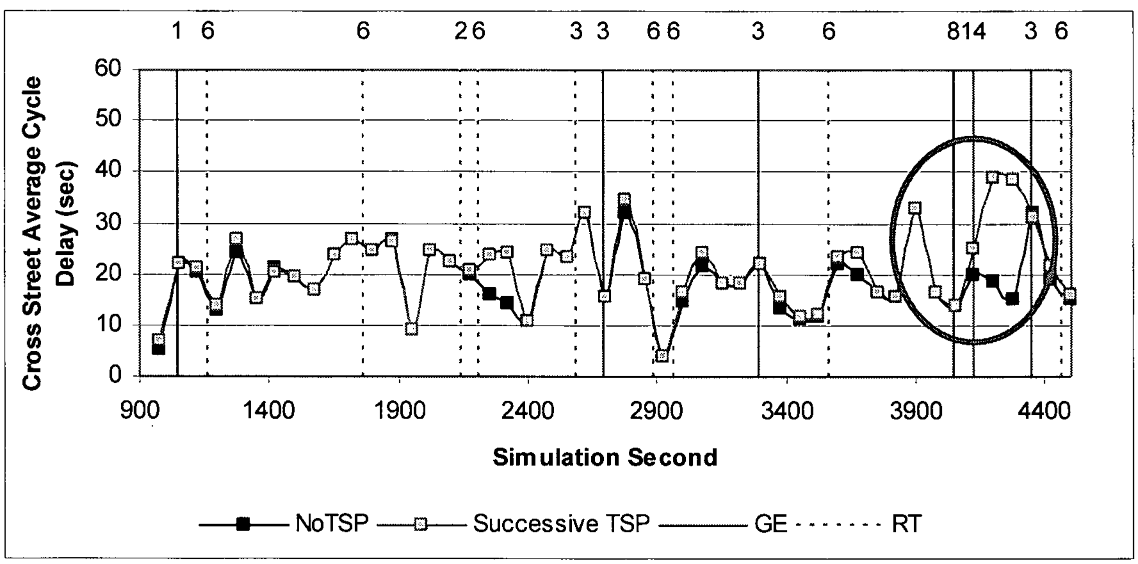

Figure 5-39 Successive TSP Impact on Cross Street Performance (v/c = 0.50)

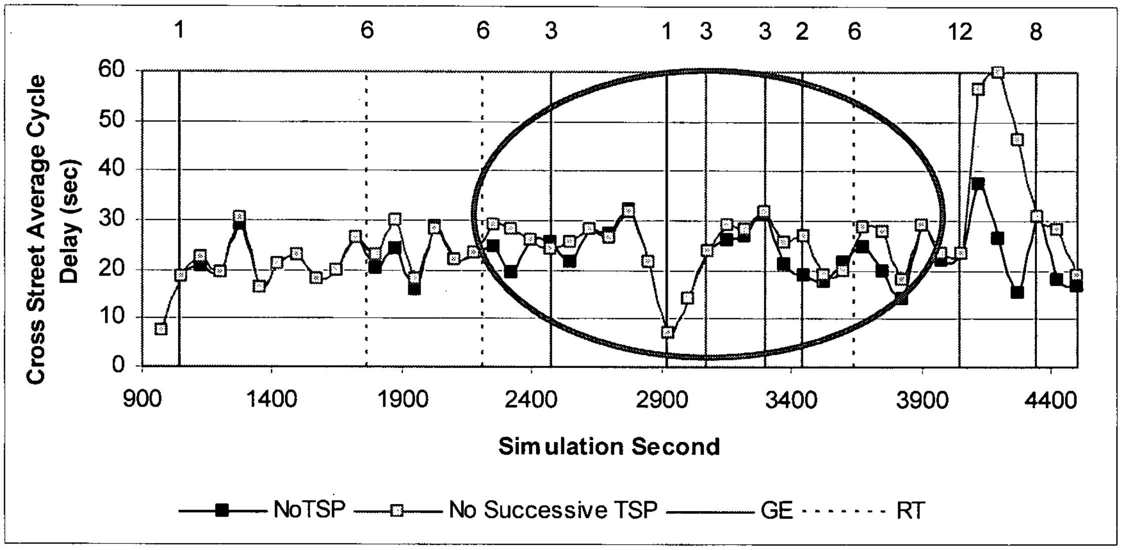

Figure 5-40 Non-Successive TSP Impact on Cross Street Performance (v/c = 0.80)

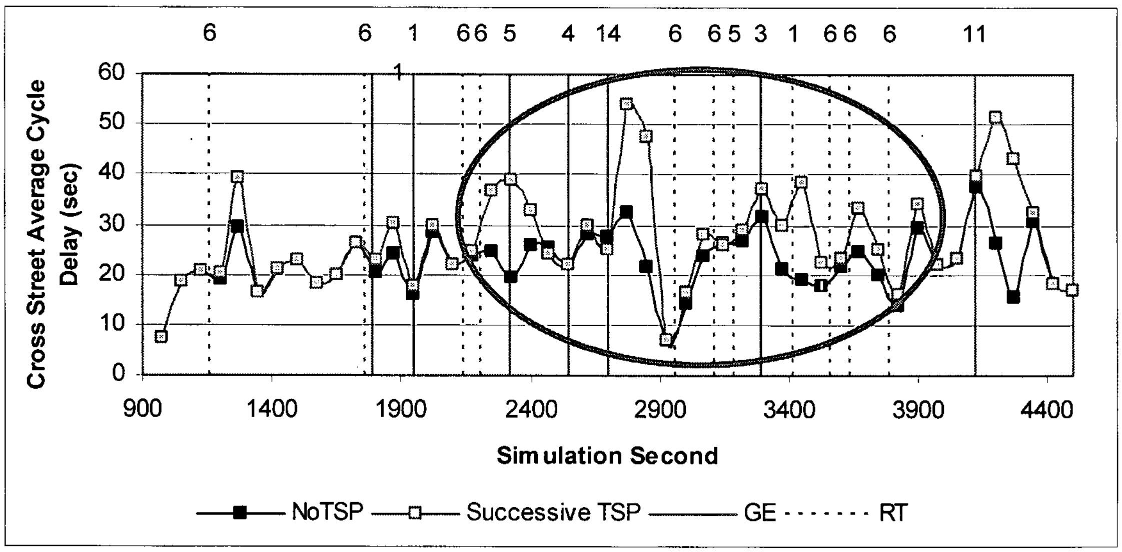

Figure 5-41 Successive TSP Impact on Cross Street Performance (v/c = 0.80)

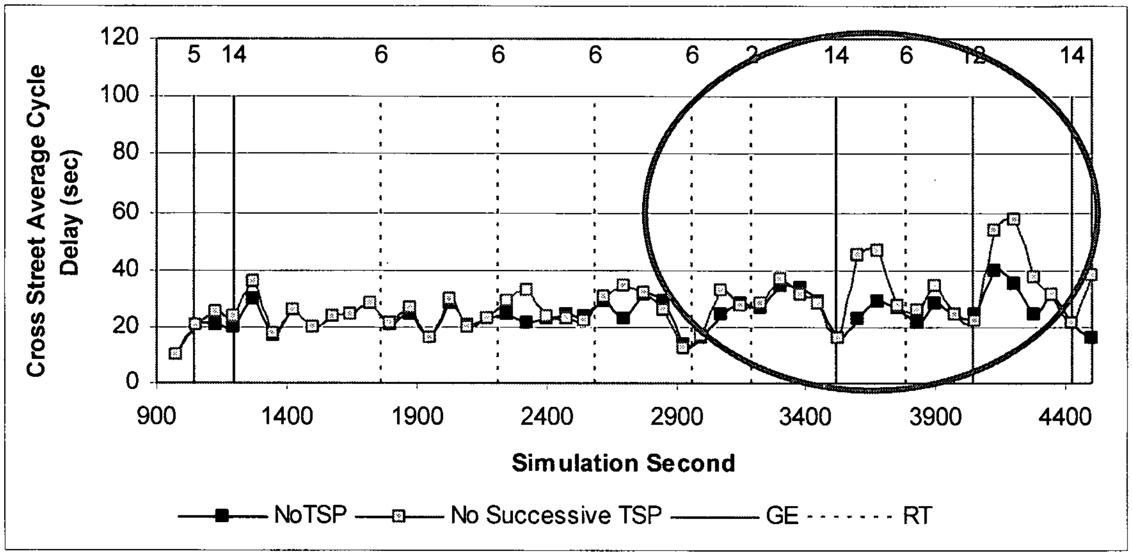

Figure 5-42 Non-Successive TSP Impact on Cross Street Performance (v/c = 0.90)

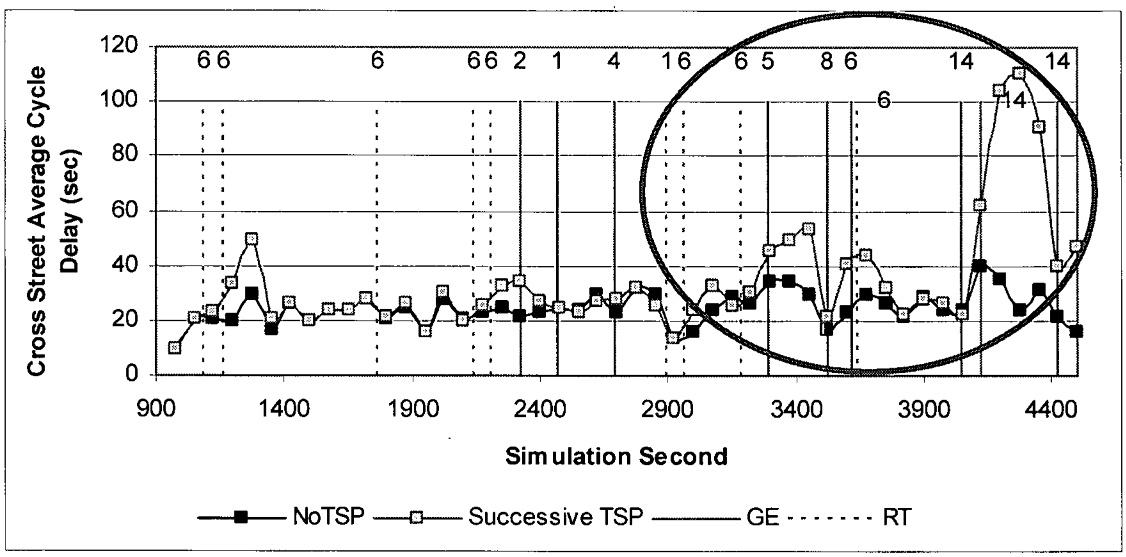

Figure 5-43 Successive TSP Impact on Cross Street Performance (v/c = 0.90)

Figure 5-36 to Figure 5-43 illustrate the following findings:

- At cross street v/c ratios at or below 0.80, allowing TSP calls in successive cycles only have minimal impact on the cross street performance. At this range of v/c ratios, the cross street would only need 2 to 3 cycles to recover and the increase in cross street delay would be minimal, even when successive TSP calls are allowed.

- At cross street v/c ratios above 0.80, allowing TSP calls in successive cycles could have a very significant impact on the cross street performance, such that the number of recovery cycles and the cross street delay would increase significantly. This suggests that the allowance of successive TSP calls would not be appropriate if the cross streets carry high traffic volume because of its significant impact on the cross street, yet minimal benefits to the B-Line buses as shown in Section 5.8.1.

- Additionally, the allowance of successive TSP calls would have significant impact on the cross street performance when the B-Line buses are operating at a small headway, at which a higher number of TSP calls would be requested in successive cycles.

Table 5-6 summarizes the number of recovery cycles with and without the allowance of successive TSP calls, under various cross street v/c ratio scenarios.

Table 5-6 Recovery Cycles (No Successive TSP vs. With Successive TSP)

# Recovery Cycles	v/c = 0.25	v/c = 0.50	v/c = 0.80	v/c = 0.90
Non-Successive TSP	2-3	2-3	2-4	3-4
Successive TSP	2-3	2-4	2-9	3-9

The above results illustrate some fluctuations in the number of recovery cycles for each scenario, which is attributed to the difference in the number and length of TSP calls each scenario obtained from the simulation.

The results shown in Figure 5-36 to Figure 5-43 are compared to that obtained by Garrow & Machemehl (1998). Table 5-7 shows a comparison of these results.

Table 5-7 Comparison of TSP Impact on Cross Street Performance (Garrow & Machemehl, 1998 vs. No successive TSP vs. Successive TSP)

Reported by	Garrow & Machemehl (1998)		98 B-Line Experiment (2002)	
Cross Street v/c Ratio	**GE = 10 sec**	**GE = 20 sec**	**GE = 14 sec No Successive TSP**	**GE = 14 sec Successive TSP**
0.25	N/A	N/A	Minimal	Minimal
0.50	N/A	N/A	Minimal	Moderate
0.80	Minimal	Moderate	Moderate	Significant
0.90	Moderate	Significant	Significant	Significant
1.00	Significant	Significant	Significant	Significant

Note: "N/A" represents results that were not reported. "GE" represents Green Extension and "RT" represents red truncation. The 98 B-Line experiment uses 2-minute B-Line bus headway for the analyses.

Both experiments show that TSP would have a more significant impact on the cross street performance at higher cross street v/c ratios. When no successive TSP is allowed, the result matches those obtained by Garrow & Machemehl (1998) for which TSP would have moderate impact on cross street performance at cross street v/c ratio of 0.80, and it would have a very significant impact on the cross street performance at or above cross street v/c ratios of 0.90. However, the allowance of successive TSP calls is observed to have more profound impact on the cross street performance because it would allow a higher number of TSP calls be granted, thereby triggering more frequent reduction in the cross street green time.

5.8.3 RECOVERY STRATEGY IMPACT ON TOTAL CORRIDOR DELAY

It is observed in Section 5.8.1 and Section 5.8.2 that the allowance of successive TSP calls could improve the B-Line bus performance (i.e., reduce the B-Line bus travel time) but deteriorate the cross street traffic performance (i.e., increase the cross street delay). In this section, the total corridor delay is analyzed to examine a balance of the impacts. This experiment considers B-Line bus headway of 4 minutes and cross street v/c ratios of 0.25, 0.5, 0.8, and 0.9. The use of a 4-minute B-Line bus headway aims to trigger higher number of TSP calls, thereby producing more obvious impact of TSP for the experiment.

Figure 5-44 shows the percentage change in total corridor delay on Granville Street, measured in vehicle delay, with and without the allowance of successive TSP calls, for different cross street v/c ratios.

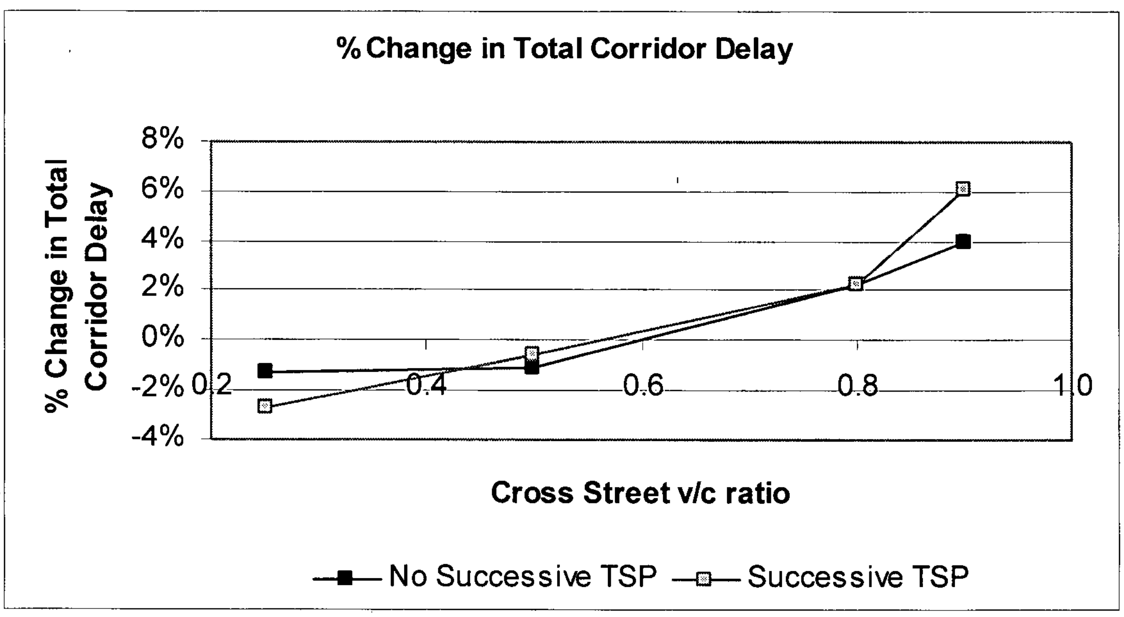

Figure 5-44 Recovery Strategy Impact on Total Corridor Delay

The above table illustrates the following impacts on total corridor delay when different recovery strategies and cross street v/c ratios are considered:

- At a low cross street v/c ratio, both non-successive TSP and successive TSP recovery strategies improve the total corridor delay. This is because both recovery strategies improve the B-Line bus and major traffic performance, while incur only minimal deterioration to the cross street performance.

- At a high cross street v/c of ratio, the application of TSP would bring about deterioration in the total corridor delay. This is because the adverse effects TSP brings to the cross street traffic over-rides the benefit it brings to the B-Line buses.

- The total corridor delay is observed to be more sensitive to a successive TSP recovery strategy than to a non-successive TSP recovery strategy. This is shown by a higher improvement in total corridor delay at low cross street v/c ratios and a higher total corridor delay worsening at high cross street v/c ratios, when successive TSP recovery strategy is deployed.

- Based on interpolation of the plots, worsening of the total corridor delay would begin at v/c ratios above 0.6 when non-successive TSP or successive TSP recovery strategies is employed.

- Based on interpolation of the plots, a successive TSP strategy would not be ideal at cross street v/c ratios above 0.45, beyond which the TSP successiveness would worsen the total corridor delay improvement.

5.8.4 RECOVERY STRATEGY IMPACT ON GREEN EXTENSION EFFECTIVENESS

Comparative analyses are performed to investigate the impact of successive and non-successive TSP strategies on the green extension success rate and the checkout detector effectiveness, shown in Figure 5-45 and Figure 5-46 respectively.

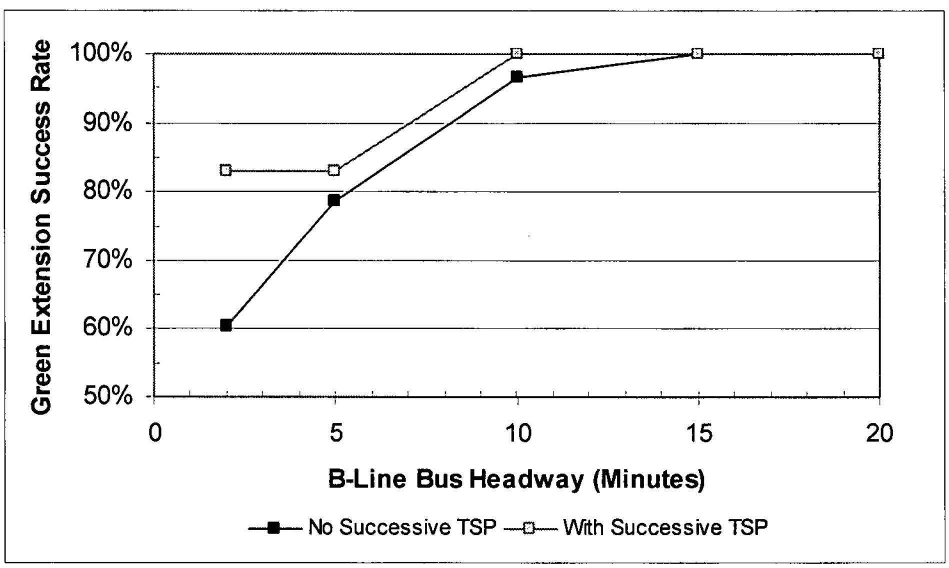

Figure 5-45 Recovery Strategy Impact on Green Extension Success Rate

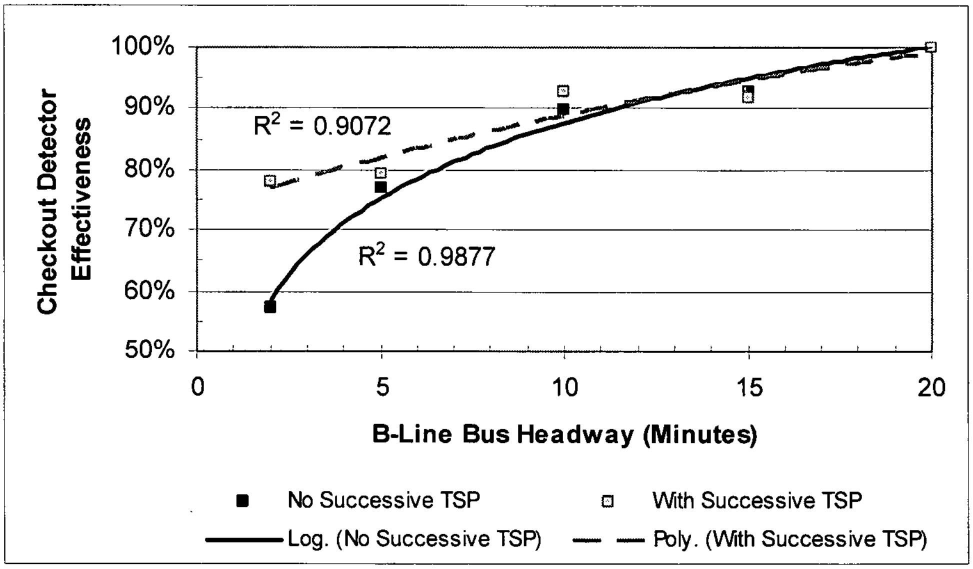

Figure 5-46 Recovery Strategy Impact on Checkout Detector Effectiveness

The above figures illustrate that:

- The allowance of successive TSP calls would not impact the green extension success rate and the checkout detector effectiveness at B-Line bus headways greater than 10 minutes. This is because a long B-Line bus headway, or a low B-Line bus arrival frequency, rarely causes two buses arriving in successive cycles.
- The allowance of successive TSP calls would impact the B-Line bus travel time improvement more significantly at B-Line bus headways below 10 minutes. This is because a smaller headway would trigger a higher number of B-Line buses to arrive in successive cycles.
- The 10-minute B-Line bus headway could be the threshold B-Line bus headway below which the allowance of successive TSP calls could further improve in the green extension effectiveness.

5.9 SIGNAL COORDINATION

The impact of signal coordination on TSP effectiveness is assessed. Two signal coordination scenarios are considered: (i) with signal coordination and (ii) no signal coordination. This experiment is performed on a corridor-basis and the details of the signal coordination scenarios are described in Section 4.2.9.

In this experiment, the "with coordination" scenario is used as a benchmark condition for the comparison. In other words, the change in the corridor, major traffic, cross street traffic and B-Line bus delays are compared to this benchmark scenario, i.e., when signal coordination is applied with the TSP implementation.

5.9.1 SIGNAL COORDINATION IMPACT ON TRAFFIC PERFORMANCE (ENTIRE CORRIDOR)

Table 5-8 shows the vehicular traffic delay results and the impact of signal coordination on TSP effectiveness. The TSP effectiveness is expressed as the change in traffic delay after removing coordination from the Granville Street corridor. The assessments are performed for the entire corridor (i.e., combination of the major and cross streets traffic), the Granville Street traffic and the cross street traffic. The performances of the B-Line buses and the general traffic, evaluated by Granville Street approach, are described in the next section (Section 5.9.2).

Table 5-8 Signal Coordination Impact on TSP Effectiveness (Entire Corridor)

Total Delay (seconds)	Delay with coordination *	Delay with No Coordination *	Removing Coordination	
			Delay Change **	Delay Change (%) **
Entire Corridor	8458.2	8607.0	148.9	2%
Granville Street traffic (vehicle)	6216.3	6341.0	124.7	2%
Cross Street traffic	2260.6	2250.1	-10.4	0%

* TSP is implemented for the evaluation.

** The change or percentage change in delay is with respect to the "with signal coordination" scenario, which reflects the actual condition on the Granville Street corridor.

Results from Table 5-8 show that removing the signal coordination from the Granville Street corridor would increase the entire corridor delay and the Granville Street traffic delay. On the other hand, removing coordination from the corridor would result in minimal improvement in the cross street delay because the green time for the cross street is allowed to be maintained (i.e., not shortened) after a TSP call. These results suggest that, for the highest TSP improvement in the total corridor delay, TSP should be applied on a coordinated corridor.

This result agrees with Daniel (1997)'s proposal that providing priority for transit vehicles in a non-coordinated network would increase the overall vehicle delay in the network.

5.9.2 SIGNAL COORDINATION IMPACT ON TRAFFIC PERFORMANCE (BY GRANVILLE STREET APPROACH)

Using the same definition of TSP effectiveness mentioned in Section 5.9.1, this section examines the impact of signal coordination on TSP effectiveness for the two Granville Street approaches, i.e., the northbound and the southbound approaches. Removing the Granville Street signal coordination could affect these two approaches differently because the original coordination parameters heavily favor the northbound traffic, which is the commuter traffic during the AM peak period (i.e., the studied period of this experiment). Table 5-9 illustrates the total delay and the change in TSP effectiveness after removing signal coordination on the Granville Street corridor, by Granville Street approach.

Table 5-9 Signal Coordination Impact on TSP Effectiveness (By Approach)

Delay (seconds)	Delay with coordination *	Delay with No Coordination *	Removing Coordination	
			Delay Change **	Delay Change (%) **
Impact on Northbound Traffic Performance				
B-Line Buses	209.7	223.3	13.6	6%
Major traffic (vehicle)	3820.3	4460.0	639.7	17%
Impact on Southbound Traffic Performance				
B-Line Buses	299.1	299.0	-0.1	0%
Major traffic (vehicle)	2396.0	1899.2	-496.8	-21%

* **The delay values are of scenarios with the implementation of TSP.**

** **The change or percentage change in delay is with respect to the "with coordination" scenario, which is the actual scenario on the Granville Street corridor.**

Table 5-9 shows that removing signal coordination from the Granville Street corridor would worsen the total delay of the northbound traffic and the northbound B-Line buses, which the original coordination heavily favors. Removing coordination from the northbound approach would make the arrival of vehicles at a signal uncontrollable, i.e., a vehicle or a platoon of vehicles could arrive anytime in a cycle. As more vehicles would arrive during red when coordination is removed, the waiting time and the delay of the northbound traffic and the northbound B-Line buses would increase.

On the other hand, removing coordination from the Granville Street corridor brings about slight improvement to the southbound B-Line buses and significant improvement to the southbound traffic, which the original coordination does not favor. This could be attributed to the fact that the adverse impact from the original signal coordination on the southbound traffic is removed.

However, during the studied period (i.e., the AM peak period), the number of northbound vehicles almost doubles that of the southbound traffic. Consequently, it would not be appropriate to sacrifice the majority of the traffic (i.e., the northbound traffic) for the benefit of the minority of the traffic (i.e., the southbound traffic). As a result, coordination should be maintained with TSP application for the benefit of the majority road users on the corridor.

5.10 CHAPTER SUMMARY

This chapter presents the results and analyses from nine sets of experiments, which study the influences of twelve selected traffic parameters on the impacts and effectiveness of TSP. Major findings from these experiments are given in Table 5-10.

Table 5-10 Summary of Major Findings from the Experiments

Traffic Parameters	Major Findings
Granville Street (or major traffic) Volume	• The improvement in B-Line bus travel time with TSP is most significant under moderate-to-heavy traffic condition (i.e., between v/c ratio of 0.6 to 0.9). • The improvement in B-Line bus performance with TSP is minimal when the Granville Street traffic is approaching capacity because TSP does not provide additional capacity to the traffic. • The improvement in B-Line bus performance with TSP is minimal at very light traffic condition because the B-Line buses would perform well at light traffic regardless if TSP is implemented. • The effectiveness of green extension (i.e., green extension success rate and checkout detector effectiveness) would decrease as Granville Street volume increases because traffic delay would impact the capability of a B-Line bus to check out successfully during the green extension phase.
B-Line Bus Headway	• Based on the analyses on TSP's improvement on B-Line bus travel time, 10 minutes is observed to be the optimal headway at which TSP would bring the highest improvement in B-Line bus travel time under the default traffic condition on Granville Street (i.e., v/c ratio of 0.74 or 2000 Veh/hr). • At B-Line bus headway greater than the optimal B-Line bus headway, TSP only causes minimal improvement in the B-Line bus performance because fewer number of TSP calls would be requested. • At B-Line bus headway smaller than the optimal B-Line bus headway, TSP has limited impact on the B-Line bus performance because a higher B-Line bus volume would increase the B-Line bus delay in the network. • Smaller B-Line bus headway would cause more significant impact on cross street delay. Significant increase in cross street delay is observed at B-Line bus headway at or below 5 minutes.

B-Line Bus Headway (Cont'd)	• The green extension success rate and checkout detector effectiveness would be decreased as the B-Line bus headway gets smaller. This is because, for the experiment, TSP calls are not allowed in two successive cycles.
Cross Street v/c Ratio	• When TSP calls are restricted in two successive cycles, TSP would have a significant impact on the cross streets at v/c ratios at or above 0.9. Within this range of cross street v/c ratios, TSP would cause significant increases in the cross street delay and the number of cross street recovery cycles.
Left-turn & Opposing-through Volume	• TSP effectiveness would decrease at an intersection with heavy left-turn volume and opposing-through volume that controls the dissipation of the left-turn traffic. • Provision of a protected left-turn phase could improve the TSP effectiveness and the B-Line bus performance at signalized intersections with moderate left-turn and opposing-through volumes. • Provisions of a protected left-turn phase and an exclusive left-turn lane could maintain the TSP effectiveness at signalized intersections with heavy left-turn and opposing-through volumes.
Right-turn & Pedestrian Volume	• The effectiveness of TSP would decrease at intersections with heavy right-turn traffic because heavy right turn traffic would hinder the movement of the B-Line buses. • High pedestrian volume would hinder the dissipation of right turn traffic at an intersection, thereby increasing the delay of B-Line buses and reducing the effectiveness of TSP. • Provision of an exclusive right-turn lane would be necessary to maintain the effectiveness of TSP at signalized intersections with heavy right-turn traffic. • The green extension success rate and checkout detector effectiveness of the B-Line buses would decrease as the right-turn and pedestrian volumes at an intersection increase.
Bus Stop and Detector Locations	• A nearside bus stop would bring about a higher delay to B-Line buses than a farside bus stop would. This is because a significant portion of the green extension would be wasted while loading and unloading passengers at a nearside bus stop.

Bus Stop and Detector Locations (Cont'd)	• The impact of bus stop location on the B-Line bus performance would be reduced as the bus approach saturation level increases. This is because, at high B-Line bus approach saturation level, the B-Line bus performance would be more influenced by the traffic delay from congestion than by the bus stop location. • A higher number of green extensions would be called when a nearside bus stop is used. This is because the passenger dwelling at a nearside bus stop would waste a significant portion of the B-Line bus travel time between the check-in detectors and the intersection, thereby increasing the number of green extensions needed by the B-Line buses to clear the intersection. • A farside bus stop would give higher green extension success rate and checkout detector effectiveness (GE success rate: 70% to 100%) than a nearside bus stop would (GE success rate: 40% to 60%). This is again because a significant portion of the green extension would be wasted while loading and unloading passengers at a nearside bus stop. • The sensitivity of the B-Line bus delay to the check-in detector location would be minimal when a nearside bus stop is placed. This is because the performance of the B-Line buses would be more influenced by the dwell time at the bus stop than by the location at which the bus is detected. • The B-Line bus delay would be more sensitive to the check-in detector location when a farside bus stop is used. This is because there would be less influence from the bus dwelling on the B-Line bus delay at a farside bus stop. • For a red truncation call, locating the check-in detectors further from an intersection to a certain limit would improve the B-Line bus delay. This is because the red truncation call could be requested more in advance, thereby allowing the vehicle queue at the intersection to dissipate more in advance before the bus arrives. • For a green extension call, locating the check-in detectors further from an intersection, to a certain limit (i.e., the clearance distance of the B-Line buses), would improve the B-Line bus delay. This is because the green extension could be requested more in advance, thereby increasing the chance a green extension be called.

Bus Stop and Detector Locations (Cont'd)	• The green extension success rate and checkout detector effectiveness would drop beyond a certain check-in detector distance (i.e., the clearance distance of the B-Line buses) from an intersection stop bar. This is because a significant portion of the green extension would be wasted when the B-Line buses have to travel longer distances to the intersection after checking in.
TSP Strategy	• Deployment of a TSP strategy with higher maximum green extension could improve the B-Line bus performance. This is because a longer maximum green extension would provide a longer green time window for the B-Line buses to clear the intersection. • The impacts of TSP levels off at a maximum green extension of above 10 seconds. This is because, in the experiment, the B-Line buses seldom call a green extension over 10 seconds. • The green extension success rate and the checkout detector effectiveness would improve with an increase in the length of the maximum green extension deployed. This is because a longer maximum green extension time for the B-Line buses would create a longer green time window for the buses to clear the intersection after checking in, thereby increasing the chance that a bus could check out successfully.
Recovery Strategy	• The allowance of TSP calls in two successive cycles would begin to have some impacts on the B-Line bus performance at B-Line bus headways at or below 10 minutes. This is because a higher number of successive TSP calls would be requested at a smaller B-Line bus headway. • When TSP calls are allowed in successive cycles, TSP would have a significant impact on the cross streets at v/c ratios at or above 0.8. And a successive TSP strategy would have a higher impact on the cross streets than a non-successive TSP strategy because a higher number of TSP calls would be granted, thereby increasing the shortening of the cross street green time. • The allowance of successive TSP calls would increase the green extension success rate and the checkout detector effectiveness at B-Line bus headways smaller than 10 minutes. This is because a higher number of TSP calls would be requested in successive cycles with smaller bus headways.

Recovery Strategy (Cont'd)	• The total corridor delay is observed to be more sensitive to a successive TSP recovery strategy than to a non-successive TSP recovery strategy. This is attributed to the higher B-Line bus benefits but also to the higher adverse effects on the cross streets when TSP calls are allowed in successive cycles. • Based on the interpolation of the plots, worsening of the total corridor delay would begin at v/c ratios above 0.6 and 0.58 when non-successive TSP and successive TSP recovery strategies are deployed, respectively. • Based on the analyses on TSP's improvement on the total corridor delay, a successive TSP strategy would not be ideal at cross street v/c ratios at or above 0.45 when a successive TSP strategy brings about less total corridor delay improvement than a non-successive TSP strategy does.
Signal Coordination	• Application of TSP on a coordinated corridor would bring about lower corridor delay and major traffic delay than a non-coordinated corridor would. This is because a coordinated corridor would provide a green wave for the peak direction traffic, thereby reducing the stopping of the major traffic at signals and their influence on the B-Line bus delays. • Removing coordination from the Granville Street corridor, with TSP implemented, would bring slight improvement in the cross street delay because the green time for the cross street could be maintained after a TSP call is granted. • Removing coordination from the Granville Street corridor would worsen the performance of the northbound general traffic and the northbound B-Line bus, which the original coordination heavily favors during the AM peak period. • On the other hand, removing coordination from Granville Street could improve the performance of southbound traffic, which the original coordination does not favor during the AM peak period.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the findings, conclusions and recommendations of this research.

6.1 CONCLUSIONS

In this research, nine sets of experiments are performed using a VISSIM micro-simulation model to evaluate the individual influence of twelve traffic parameters on the impacts and effectiveness of TSP. The traffic parameters studied include Granville Street (or bus approach traffic) volume, B-Line bus headway, cross street volume/capacity ratio, left-turn and opposing-through volume, right-turn and pedestrian volume, bus stop and bus check-in detector location, TSP strategy (green extension and red truncation), recovery strategy (successive TSP and non-successive TSP strategy) and signal coordination.

These traffic parameters are tested for their individual influences on the impacts of TSP, the effectiveness of TSP and the effectiveness of green extension. Based on these results, generic guidelines and decision rules are developed for the implementation of TSP.

Key findings of this research, along with the recommended generic guidelines of TSP applications, from the nine experiments are summarized below.

Granville Street Volume:

1. The improvement in B-Line bus travel time with TSP is most significant under moderate-to-heavy traffic condition (i.e., between v/c ratio of 0.6 to 0.9).

2. The improvement in B-Line bus performance with TSP is minimal when the Granville Street traffic is approaching capacity because TSP does not provide additional capacity to the traffic.

3. The improvement in B-Line bus performance with TSP is minimal at very light traffic condition because the B-Line buses would perform well at light traffic regardless if TSP is implemented.

4. The effectiveness of green extension (i.e., green extension success rate and checkout detector effectiveness) would be decreased as the Granville Street volume increases because traffic delay would impact the capability of a B-Line bus to check out successfully during the green extension phase.

TSP Guideline #1:	**TSP application would be most effective under moderate-to-heavy bus approach traffic condition.**

B-Line Bus Headway:

5. Based on the analyses on TSP's improvement on B-Line bus travel time, 10 minutes is observed to be the optimal headway at which TSP would bring the highest improvement in B-Line bus travel time under the default traffic condition on Granville Street (i.e., v/c ratio of 0.74 or 2000 Veh/hr).

6. At B-Line bus headway greater than the optimal B-Line bus headway, TSP only causes minimal improvement in the B-Line bus performance because fewer number of TSP calls would be requested.

7. At B-Line bus headway smaller than the optimal B-Line bus headway, TSP has limited impact on the B-Line bus performance because a higher B-Line bus volume would increase the B-Line bus delay in the network.

8. Smaller B-Line bus headway would cause more significant impact on cross street delay. Significant increase in cross street delay is observed at B-Line bus headway at or below 5 minutes.

9. The green extension success rate and checkout detector effectiveness would be decreased as the B-Line bus headway gets smaller. This is because, for the experiment, TSP calls are not allowed in two successive cycles.

TSP Guideline #2:	**There would be an optimal headway for TSP application which would bring the highest effectiveness of TSP.**
TSP Guideline #3:	**TSP could bring significant adverse impact on the cross street traffic at small bus headways.**

Cross Street v/c Ratio:

10. When TSP calls are restricted in two successive cycles, TSP would have a significant impact on the cross streets at v/c ratios at or above 0.9. Within this range of cross street v/c ratios, TSP would cause significant increases in the cross street delay and the number of cross street recovery cycles.

TSP Guideline #4:	**TSP should be avoided under conditions that would generate significant adverse impacts to the cross streets.**

Left-turn & Opposing-through Volume:

11. TSP effectiveness would decrease at an intersection with heavy left-turn volume and opposing-through volume that controls the dissipation of the left-turn traffic.

12. Provision of a protected left-turn phase could improve the TSP effectiveness and the B-Line bus performance at signalized intersections with moderate left-turn and opposing-through volumes.

13. Provisions of a protected left-turn phase and an exclusive left-turn lane could maintain the TSP effectiveness at signalized intersections with heavy left-turn and opposing-through volumes.

TSP Guideline #5:	**Left-turn volume and its associated queue could impact the effectiveness of TSP.**
TSP Guideline #6:	**For the highest effectiveness of TSP, exclusive left-turn lane and/or protected left-turn phase should be considered when applying TSP at signalized intersections with heavy left-turn and opposing-through volumes.**

Right-turn & Pedestrian Volume:

14. The effectiveness of TSP would decrease at intersections with heavy right-turn traffic because heavy right turn traffic would hinder the movement of the B-Line buses.

15. High pedestrian volume would hinder the dissipation of right turn traffic at an intersection, thereby increasing the delay of B-Line buses and reducing the effectiveness of TSP.

16. Provision of an exclusive right-turn lane would be necessary to maintain the effectiveness of TSP at signalized intersections with heavy right-turn traffic.

17. The green extension success rate and checkout detector effectiveness of the B-Line buses would decrease as the right-turn and pedestrian volumes at an intersection increase.

TSP Guideline #7:	**Right-turn volume and its associated queue could impact the effectiveness of TSP.**
TSP Guideline #8:	**For the highest effectiveness of TSP, exclusive right-turn lane should be considered when applying TSP at signalized intersection with heavy right-turn and pedestrian volumes.**

Bus Stop and Detector Locations:

18. A nearside bus stop would bring about a higher delay to B-Line buses than a farside bus stop would. This is because a significant portion of the green extension would be wasted while loading and unloading passengers at a nearside bus stop.

19. The impact of bus stop location on the B-Line bus performance would be reduced as the bus approach saturation level increases. This is because, at high B-Line bus

approach saturation level, the B-Line bus performance would be more influenced by the traffic delay from congestion than by the bus stop location.

20. A higher number of green extensions would be called when a nearside bus stop is used. This is because the passenger dwelling at a nearside bus stop would waste a significant portion of the B-Line bus travel time between the check-in detectors and the intersection, thereby increasing the number of green extensions needed by the B-Line buses to clear the intersection.

21. A farside bus stop would give higher green extension success rate and checkout detector effectiveness (GE success rate: 70% to 100%) than a nearside bus stop would (GE success rate: 40% to 60%). This is again because a significant portion of the green extension would be wasted while loading and unloading passengers at a nearside bus stop.

22. The sensitivity of the B-Line bus delay to the check-in detector location would be minimal when a nearside bus stop is placed. This is because the performance of the B-Line buses would be more influenced by the dwell time at the bus stop than by the location at which the bus is detected.

23. The B-Line bus delay would be more sensitive to the check-in detector location when a farside bus stop is used. This is because there would be less influence from the bus dwelling on the B-Line bus delay at a farside bus stop.

24. For a red truncation call, locating the check-in detectors further from an intersection to a certain limit would improve the B-Line bus delay. This is because the red truncation call could be requested more in advance, thereby allowing the vehicle queue at the intersection to dissipate more in advance before the bus arrives.

25. For a green extension call, locating the check-in detectors further from an intersection, to a certain limit (i.e., the clearance distance of the B-Line buses), would improve the B-Line bus delay. This is because the green extension could be requested more in advance, thereby increasing the chance a green extension be called.

26. The green extension success rate and checkout detector effectiveness would drop beyond a certain check-in detector distance (i.e., the clearance distance of the B-Line buses) from an intersection stop bar. This is because a significant portion of the green extension would be wasted when the B-Line buses have to travel longer distances to the intersection after checking in.

TSP Guideline #9: For high effectiveness of TSP and high effectiveness of green extension, a farside bus stop should be placed.

TSP Guideline #10: The location of a check-in detector should be carefully considered when a farside bus stop is placed because the TSP effectiveness and the bus performance are sensitive to the detector location when a farside bus stop is placed.

TSP Guideline #11: If the approach distance allowed, placing the bus check-in detector further from the intersection to a certain limit (i.e., within the clearance distance for the maximum green extension interval) could improve the B-Line bus performance and maintain the effectiveness of green extension.

TSP Strategy:

27. Deployment of a TSP strategy with higher maximum green extension could improve the B-Line bus performance. This is because a longer maximum green extension would provide a longer green time window for the B-Line buses to clear the intersection.

28. The impacts of TSP levels off at a maximum green extension of above 10 seconds. This is because, in the experiment, the B-Line buses seldom call a green extension over 10 seconds.

29. The green extension success rate and the checkout detector effectiveness would improve with an increase in the length of the maximum green extension deployed. This is because a longer maximum green extension time for the B-Line buses would create a longer green time window for the buses to clear the intersection after checking in, thereby increasing the chance that a bus could check out successfully.

TSP Guideline #12: Deployment of a higher maximum green extension could improve the bus performance and effectiveness of green extension.

Recovery Strategy:

30. The allowance of TSP calls in successive cycles would begin to have some impacts on the B-Line bus performance at B-Line bus headways at or below 10 minutes. This is because a higher number of successive TSP calls would be requested at a smaller B-Line bus headway.

31. When TSP calls are allowed in successive cycles, TSP would have a significant impact on the cross streets at v/c ratios at or above 0.8. And a successive TSP strategy would have a higher impact on the cross streets than a non-successive TSP strategy because a higher number of TSP calls would be granted, thereby increasing the shortening of the cross street green time.

32. The allowance of successive TSP calls would increase the green extension success rate and the checkout detector effectiveness at B-Line bus headways smaller than 10 minutes. This is because a higher number of TSP calls would be requested in successive cycles with smaller bus headways.

33. The total corridor delay is observed to be more sensitive to a successive TSP recovery strategy than to a non-successive TSP recovery strategy. This is

attributed to the higher B-Line bus benefits but also to the higher adverse effects on the cross streets when TSP calls are allowed in successive cycles.

34. Based on the interpolation of the plots, worsening of the total corridor delay would begin at v/c ratios above 0.6 and 0.58 when non-successive TSP and successive TSP recovery strategies are deployed, respectively.

35. Based on the analyses on TSP's improvement on the total corridor delay, a successive TSP strategy would not be ideal at cross street v/c ratios at or above 0.45 when a successive TSP strategy brings about less total corridor delay improvement than a non-successive TSP strategy does.

TSP Guideline #13: The allowance of successive TSP calls should be carefully considered at cross streets with high v/c ratio and when the bus headway is small.

Signal Coordination:

36. Application of TSP on a coordinated corridor would bring about lower corridor delay and major traffic delay than a non-coordinated corridor would. This is because a coordinated corridor would provide a green wave for the peak direction traffic, thereby reducing the stopping of the major traffic at signals and their influence on the B-Line bus delays.

37. Removing coordination from the Granville Street corridor, with TSP implemented, would bring slight improvement in the cross street delay because the green time for the cross street could be maintained after a TSP call is granted.

38. Removing coordination from the Granville Street corridor would worsen the performance of the northbound general traffic and the northbound B-Line bus, which the original coordination heavily favors during the AM peak period.

39. On the other hand, removing coordination from Granville Street could improve the performance of southbound traffic, which the original coordination does not favor during the AM peak period.

TSP Guideline #14: For the best performance of the entire corridor, signal coordination should be maintained when implementing TSP.

6.2 RECOMMENDATIONS

The impacts and effectiveness of any TSP implementations are site-specific, i.e., the influences of a traffic parameter on TSP impacts and effectiveness might vary from one traffic location to another. As a result, generic guidelines are recommended for TSP applications. The generic guidelines for TSP application recommended are:

TSP Guideline #1: TSP application would be most effective under moderate-to-heavy bus approach traffic condition.

TSP Guideline #2: There would be an optimal headway for TSP application which would bring the highest effectiveness of TSP.

TSP Guideline #3: TSP could bring significant adverse impact on the cross street traffic at small bus headways.

TSP Guideline #4: TSP should be avoided under conditions that would generate significant adverse impact to the cross streets.

TSP Guideline #5: Left-turn volume and its associated queue could impact the effectiveness of TSP.

TSP Guideline #6: For the highest effectiveness of TSP, an exclusive left-turn lane and/or a protected left-turn phase should be considered when applying TSP signalized intersections with heavy left-turn and opposing-through volumes.

TSP Guideline #7: Right-turn volume and its associated queue could impact the effectiveness of TSP.

TSP Guideline #8: For the highest effectiveness of TSP, an exclusive right-turn lane should be considered when applying TSP at signalized intersections with heavy right-turn and pedestrian volumes.

TSP Guideline #9: For high effectiveness of TSP and high effectiveness of green extension, a farside bus stop should be placed.

TSP Guideline #10: The location of a check-in detector should be carefully considered when a farside bus stop is placed because the TSP effectiveness and the bus performance are sensitive to the detector location when a farside bus stop is placed.

TSP Guideline #11: If the approach distance allowed, placing the bus check-in detector further from the intersection to a certain limit (i.e., within the clearance distance for the maximum green extension interval) could improve the B-Line bus performance and maintain the effectiveness of green extension.

TSP Guideline #12: Deployment of a higher maximum green extension could improve the bus performance and maintain the effectiveness of green extension.

TSP Guideline #13: The allowance of successive TSP calls should be carefully considered at cross streets with high v/c ratio and when the bus headway is small.

TSP Guideline #14: For the best performance of the entire corridor, signal coordination should be maintained when implementing TSP.

Decision rules for TSP applications are also recommended in this research specifically for the case study of the 98 B-Line bus route on Granville Street. The decision rules of the TSP application are:

Decision Rule#1: TSP application would be most effective at Granville Street v/c ratios between 0.6 and 0.9.

Decision Rule#2: 10-minute B-Line bus headway is the optimal B-Line bus headway that brings the highest effectiveness of TSP in the B-Line bus travel time improvement.

Decision Rule#3: TSP brings about significant adverse impact on cross street at B-Line bus headways at or smaller than 5 minutes.

Decision Rule #4: When successive TSP is allowed, TSP could have significant adverse impact on cross streets at v/c ratios at or above0.9. Whereas when successive TSP is allowed, TSP would have significant adverse impact on cross streets at v/c ratios at or above 0.80.

Decision Rule #5: Successive TSP could be allowed at intersection with cross street v/c ratios of less than 0.50.

Decision Rule #6: Successive TSP begins to have some impact on cross street performance at B-Line bus headways smaller than 10 minutes, for a bus approach v/c ratio of 0.75.

Decision Rule #7: The worsening of the total corridor delay would begin at v/c ratios above 0.6 and 0.58 when non-successive TSP and successive TSP recovery strategies are deployed, respectively.

Decision Rule #8: A successive TSP strategy would not be ideal at cross street v/c ratios at or above 0.45 when a successive TSP strategy brings about less total corridor delay improvement than a non-successive TSP strategy does.

Decision Rule #9: If the approach distance allowed, placing the bus check-in detector further from the intersection to a certain limit (i.e., within 200 meters) could improve the B-Line bus performance and maintain the effectiveness of green extension.

Decision Rule #10: Signal coordination along Granville Street should be maintained for a higher effectiveness of the TSP application and a better performance of the entire corridor.

6.3 FUTURE RESEARCHES

This research attempts to provide a comprehensive analysis of TSP application in association with its surrounding traffic environment. This research investigates the influences of twelve traffic parameters on the impacts and effectiveness of TSP applications. Additional parameters suggested for future researches include pedestrian clearance time (or flash don't walk time), signal phasing scheme (e.g., the number of phases), conditional TSP strategy (e.g., based on bus schedule adherence or bus passenger occupancy), other transit priority measures such as an exclusive bus lane, and development of an operation that would optimize the TSP impacts as well as the coordination in a network.

Additionally, this research only focuses on the traffic parameters' influences on the effectiveness of TSP, effectiveness of green extension, and the impacts of TSP on B-Line bus and cross street performance. Further researches should evaluate the TSP performance by comparing the person-delay or the total corridor delay, which would be more appropriate measures to assess the balance between the transit performance improvement and the impacts on other general traffic.

Moreover, as proposed by Agrawal et al (2002), the shift in routing decision of drivers at the immediate vicinity of a TSP corridor should also be considered when analyzing TSP. This could reflect the traffic reality in which some vehicles might take advantage of the improved travel time on the TSP corridor, while some might attempt to avoid the impacted intersections.

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APPENDICES

APPENDIX A AVAILABLE DATA

Appendix A-1: Actual 98 B-Line Bus Check-in Detector Locations.

Appendix A-2: Actual 98 B-Line Bus Stop Locations.

Appendix A-3: Normalized Weekday Granville Street Traffic Counts.

Appendix A-4: Actual Peak Hour Intersection Counts at Major Granville Street Intersections.

Appendix A-5: Left-turn Restrictions on Granville Street.

Appendix A-6: Parking Restrictions on Granville Street.

Appendix A-7: Signal Timing Plans on Granville Street.

APPENDIX B MODEL CALIBRATIONS

Appendix B-1: Calibrated Granville Street Volume.

Appendix B-2: Calibrated Left-turn Volume (1-Hour Simulation).

Appendix B-3: Calibrated Right Turn Volume (1-Hour Simulation).

APPENDIX C V/C RATIO CALCULATIONS

Appendix C-1: V/C Ratio Calculations for Granville Street.

Appendix C-2: V/C Ratio Calculations for 70th Avenue (Eastbound).

APPENDIX A AVAILABLE DATA

Appendix A-1: Actual 98 B-Line Bus Check-in Detector Locations
(Sources: IBI Group)

North-South Road	East-West Road	Signal Type	Approach Distance Upstream from Intersection (meters)	
			Northbound	Southbound
Granville St	71st Ave	Ped-Actuated	N/A	N/A
Granville St	70th Ave	Pre-timed	54.5	103
Granville St	68th Ave	Ped-Actuated	122.7	120
Granville St	64th Ave	Ped-Actuated	125	96
Granville St	63rd Ave	Ped-Actuated	N/A	N/A
Granville St	59th Ave /Park	Semi-Actuated	106.5	116
Granville St	57th Ave	Semi-Actuated	105.6	110.4
Granville St	49th Ave	Pre-timed	123	102.2
Granville St	45th Ave	Ped-Actuated	N/A	N/A
Granville St	41st Ave	Pre-timed	103.2	113
Granville St	37th Ave	Ped-Actuated	N/A	N/A
Granville St	33rd Ave	Pre-timed	105.3	108.7
Granville St	Nanton Ave	Ped-Actuated	N/A	N/A
Granville St	25th Ave / King Edward	Pre-timed	109.7	96.9
Granville St	16th Ave	Pre-timed	126.2	102.7
Granville St	14th Ave	Ped-Actuated	103.4	103.3
Granville St	13th Ave	Ped-Actuated	103.3	110
Granville St	12th Ave	Pre-timed	103.2	103.7
Granville St	10th Ave	Ped-Actuated	104	52
Granville St	9th Ave / Broadway	Pre-timed	N/A	N/A
Granville St	7th Ave	Semi-Actuated	119.3	117

Note: "N/A" represents where the check-in detectors are not applied at the intersection.

Appendix A-2: Actual 98 B-Line Bus Stop Locations

North-South Road	East-West Road	Northbound		Southbound	
		Location*	Distance ** (m)	Location	Distance (m)
Granville St	71st Ave	Farside	31	N/A	N/A
Granville St	70th Ave	N/A	N/A	Farside	30
Granville St	49th Ave	Farside	41	Farside	54
Granville St	41st Ave	Farside	48	Farside	41
Granville St	25th Ave	Farside	56	Farside	43
Granville St	9th Ave / Broadway	Nearside	39.6	Farside	56

Note: "N/A" represents bus stop is not located on the intersection approach.
* Location with respect to the intersection: "Farside" represent location downstream of the intersection, and "Nearside" represents location upstream of the intersection.
** Approach distance from the intersection, expressed in meters.

Appendix A-3: Normalized Weekday Granville Street Traffic Counts

(Sources: City of Vancouver, British Columbia, Canada)

Street	Location	Direction	Year	7-9 AM	4-6 PM	7AM-6 PM	24 Hour
Granville	29th Ave	Southbound	2001	3,371	5,847	21,288	31,952
		Northbound	2001	4,651	4,026	19,853	28,715
	43rd Ave	Southbound	2001	2,817	4,349	16,631	25,467
		Northbound	2001	4,104	3,162	16,594	24,309
	56th Ave	Southbound	2001	3,251	5,439	21,681	31,364
		Northbound	2001	5,285	3,673	20,150	28,984
	63rd Ave	Southbound	1996	3,469	3,421	15,732	23,316
		Northbound	1996	2,402	2,368	15,499	23,948

Appendix A-4: Actual Peak Hour Intersection Counts at Major Granville Street Intersections

(Sources: City of Vancouver, British Columbia, Canada)

Intersection	Northbound			Southbound			Westbound			Eastbound		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Granville & 9th Ave	0	1415	38	26	731	25	76	875	32	23	774	33
Granville & 12th Ave	38	1504	23	0	853	13	62	230	5	3	499	637
Granville & 16th Ave	487	1510	232	54	1462	33	89	1066	162	120	1090	156
Granville & 25th Ave	3	1993	71	16	1471	16	19	196	26	73	298	56
Granville & 33rd Ave	2	2128	32	174	1369	36	59	835	95	83	704	29
Granville & 41st Ave	73	1925	38	38	1322	19	65	429	81	61	508	72
Granville & 49th Ave	18	2033	26	13	1447	24	173	125	30	95	154	78
Granville & 57th Ave	44	1955	35	357	1158	4	14	51	287	5	21	7
Granville & 59th Ave	0	1234	8	215	1211	48	69	382	130	52	496	201
Granville & 70th Ave	345	1642	22	50	914	31	96	758	67	121	776	71

Appendix A-5: Left-turn Restrictions on Granville Street
(As of January 2002)

Intersection	NORTHBOUND (Monday - Friday)	SOUTHBOUND (Monday - Friday)
Granville & 6th Ave	***No LT Restriction***	15:00 - 18:00
Granville & 7th Ave	9:30 - 15:00 (Except bicycle)	9:30 - 18:00 (Except bicycle)
Granville & 8th Ave	9:30 - 15:00	9:30 - 18:00
Granville & 9th Ave	7:00 - 18:00	Anytime
Granville & 10th Ave	9:30 - 15:00	9:30 - 18:00
Granville & 11th Ave	9:30 - 15:00	9:30 - 18:00
Granville & 12th Ave	7:00 - 18:00	7:00 - 18:00
Granville & 13th Ave	9:30 - 15:00	9:30 - 18:00
Granville & 14th Ave	9:30 - 15:00	9:30 - 18:00
Granville & 15th Ave	9:30 - 15:00	9:30 - 18:00
Granville & 16th Ave	Anytime	7:00 - 9:30 & 15:00 - 18:00
Granville & 25th Ave	***No LT Restriction***	7:00 - 9:30 & 15:00 - 18:00
Granville & 33rd Ave	7:00 - 9:30 & 15:00 - 18:00	7:00 - 9:30 & 15:00 - 18:00
Granville & 37th Ave	***No LT Restriction***	All time (except bicycle)
Granville & 49th Ave	7:00 - 9:30 & 15:00 - 18:00	7:00 - 9:30 & 15:00 - 18:00
Granville & 57th Ave	7:00 - 9:30 & 15:00 - 18:00	7:00 - 9:30 & 15:00 - 18:00
Granville & 70th Ave	15:00 - 18:00	***No LT Restriction***
Granville & 71st Ave	***No LT Restriction***	7:00 - 9:30 & 15:00 - 18:00

Note: The time period shown are period when left-turn is not allowed.

Appendix A-6: Parking Restrictions on Granville Street
(As of January 2002)

Granville Section		NORTHBOUND	Granville Section		SOUTHBOUND
From	**To**	**(Monday - Friday)**	**From**	**To**	**(Monday - Friday)**
Marine	71 Ave	6:30 - 18:30	**6** Ave	7 Ave	15:00 - 18:00
71 Ave	70 Ave	6:30 - 18:30	**7** Ave	8 Ave	15:00 - 18:00
70 Ave	68 Ave	7:00 - 9:30	**8** Ave	9 Ave	15:00 - 18:00
68 Ave	67 Ave	7:00 - 9:30	**9** Ave	10 Ave	Anytime
67 Ave	63 Ave	7:00 - 9:30	**10** Ave	11 Ave	15:00 - 18:00
63 Ave	62 Ave	7:00 - 9:30	**11** Ave	12 Ave	15:00 - 18:00
62 Ave	59 Ave	7:00 - 9:30	**12** Ave	13 Ave	15:00 - 18:00
59 Ave	57 Ave	7:00 - 9:30	**13** Ave	14 Ave	15:00 - 18:00
57 Ave	54 Ave	7:00 - 9:30	**14** Ave	15 Ave	15:00 - 18:00
54 Ave	53 Ave	7:00 - 9:30	**15** Ave	16 Ave	15:00 - 18:00
53 Ave	49 Ave	7:00 - 9:30	**16** Ave	**Balfour**	15:00 - 18:00
49 Ave	45 Ave	7:00 - 9:30	**Balfour**	25 Ave	15:00 - 18:00
45 Ave	41 Ave	7:00 - 9:30	**25** Ave	26 Ave	7:00 - 9:30, 15:00 - 18:00
41 Ave	40 Ave	All time	**26** Ave	27 Ave	15:00 - 18:00
40 Ave	37 Ave	7:00 - 9:30	**27** Ave	28 Ave	15:00 - 18:00
37 Ave	33 Ave	7:00 - 9:30	**28** Ave	29 Ave	15:00 - 18:00
33 Ave	27 Ave	7:00 - 9:30	**29** Ave	32 Ave	15:00 - 18:00
27 Ave	25 Ave	7:00 - 9:30	**32** Ave	33 Ave	15:00 - 18:00
25 Ave	**Balfour**	7:00 - 9:30	**33** Ave	34 Ave	15:00 - 18:00
Balfour	Matthew	7:00 - 9:30, 15:00 - 18:00	**34** Ave	35 Ave	15:00 - 18:00
Matthew	16 Ave	7:00 - 9:30, 15:00 - 18:00	**35** Ave	36 Ave	15:00 - 18:00
16 Ave	15 Ave	All time	**36** Ave	37 Ave	15:00 - 18:00
15 Ave	14 Ave	7:00 - 9:30	**37** Ave	38 Ave	15:00 - 18:00
14 Ave	13 Ave	7:00 - 9:30	**38** Ave	Connaught	15:00 - 18:00
13 Ave	12 Ave	7:00 - 9:30	Connaught	41 Ave	No stopping anytime
12 Ave	11 Ave	7:00 - 9:30	**41** Ave	43 Ave	9:30 - 18:00
11 Ave	10 Ave	7:00 - 9:30	**43** Ave	45 Ave	15:00 - 18:00
10 Ave	9 Ave	7:00 - 18:00	**45** Ave	47 Ave	15:00 - 18:00
9 Ave	8 Ave	All time	**47** Ave	49 Ave	15:00 - 18:00
8 Ave	7 Ave	7:00 - 9:30	**49** Ave	52 Ave	15:00 - 18:00
7 Ave	6 Ave	7:00 - 9:30	**52** Ave	54 Ave	15:00 - 18:00
6 Ave	5 Ave	7:00 - 9:30	**54** Ave	57 Ave	15:00 - 18:00
			57 Ave	58 Ave	15:00 - 18:00
			58 Ave	59 Ave	15:00 - 18:00
			59 Ave	63 Ave	15:00 - 18:00
			63 Ave	64 Ave	15:00 - 18:00
			64 Ave	68 Ave	15:00 - 18:00
			68 Ave	70 Ave	15:00 - 18:00
			70 Ave	71 Ave	15:00 - 18:00

Note: The time period shown are period when on-street parking is <u>not</u> allowed.

Appendix A-7: Signal Timing Plans on Granville Street
(Sources: City of Vancouver, British Columbia, Canada)

Cross Street	Signal Type	Offset	NS Phase			EW-LT Phase		EW Phase				NS-LT Phase	
			GMax	FDW	Y+AR	GMax	Y+AR	GMax	GMin	FDW	Y+AR	GMax	Y+AR
9 Ave *	Fixed Time	42	37	15	5	6	4	18	16	11	5	--	--
10 Ave	Pedestrian	33	47	*N/A*	6	--	--	17	17	11	5	--	--
11 Ave (New)	Pedestrian	27	48	*N/A*	6	--	--	16	16	10	5	--	--
12 Ave *	Fixed Time	29	40	12	5	--	--	26	21	14	4	--	--
13 Ave	Pedestrian	21	48	*N/A*	6	--	--	16	16	10	5	--	--
14 Ave	Pedestrian	14	45	*N/A*	6	--	--	19	19	11	5	--	--
16 Ave *	Fixed Time	28	21	11	5	--	--	21	18	13	5	19	4
25 Ave *	Fixed Time	15	37	18	6	--	--	27	15	10	5	--	--
27 Ave	Pedestrian	0	49	*N/A*	6	--	--	15	15	9	5	--	--
33 Ave *	Fixed Time	31	41	6	5	--	--	24	16	10	5	--	--
37 Ave	Pedestrian	72	48	*N/A*	6	--	--	16	16	10	5	--	--
41 Ave *	NS-LT Actuated	65	28	16	5	--	--	25	20	15	5	8	4
45 Ave	Pedestrian	34	48	*N/A*	6	--	--	16	16	10	5	--	--
49 Ave *	Fixed Time	8	41	7	5	--	--	24	16	11	5	--	--
57 Ave *	Semi-Actuated	27	48	10	4	--	--	19	18	11	4	--	--
59 Ave *	Semi-Actuated	29	29	13	5	--	--	23	22	15	4	10	4
63 Ave	Pedestrian	74	47	*N/A*	6	--	--	17	17	11	5	--	--
64 Ave	Pedestrian	74	45	*N/A*	6	--	--	19	19	10	5	--	--
68 Ave	Pedestrian	56	45	*N/A*	6	--	--	19	19	10	5	--	--
70 Ave *	Fixed Time	44	25	13	5	--	--	25	21	16	5	11	4

Note: " * " represents signal plan of a major intersection. "GMax" represents maximum green time of the phase; "GMin" represents minimum green time of the phase; "Y+AR" represents the clearance time of the phase, i.e., yellow plus all-red; and "N/A" represents that the north-south pedestrian flash don't walk time is not applicable at the pedestrian signals.

APPENDIX B MODEL CALIBRATIONS

Appendix B-1: Calibrated Granville Street Volume

Approached Intersection	Real (or Inputted) Entering Volume (Veh/hr)				
	500 Veh/hr	1,000 Veh/hr	1,500 Veh/hr	2,000 Veh/hr	2,500 Veh/hr
Granville & 70th Ave	527	1,016	1,500	1,985	2,485
Granville & 59th Ave	526	1,013	1,497	1,980	2,479
Granville & 57th Ave	526	1,014	1,496	1,980	2,479
Granville & 49th Ave	523	1,009	1,495	1,987	2,479
Granville & 41st Ave	521	1,009	1,494	1,983	2,479
Granville & 33rd Ave	518	1,006	1,488	1,988	2,489
Granville & 25th Ave	500	980	1,467	1,990	2,473
Granville & 16th Ave	498	982	1,464	1,989	2,469
Granville & 12th Ave	495	973	1,463	1,988	2,458
Granville & 9th Ave	496	971	1,460	1,987	2,444

Note: The values shown are average of results from five simulation runs.

Appendix B-2: Calibrated Left-turn Volume (1-Hour Simulation)

Inputted LT Volume	Measured LT Volume (Veh/hr)
25	28
50	63
100	119
150	185
200	245

Note: The values shown are average of results from five simulation runs. Calibrated left-turn volume results of the exclusive left-turn phase, exclusive left-turn lane and opposing-through of 1,000 Veh/hr (or v/c = 0.37) is used. This is to reduce the difficulty in left-turn traffic dissipation.

Appendix B-3: Calibrated Right Turn Volume (1-Hour Simulation)

Inputted RT Volume	Measured RT Volume (Veh/hr)
50	63
150	178
250	302

Note: The values shown are average of results from five simulation runs. Calibrated Right Turn volume results of the exclusive right turn lane and pedestrian volume of 50 Ped/hr is used. This is to reduce the difficulty in right turn traffic dissipation.

APPENDIX C V/C RATIO CALCULATIONS

Appendix C-1: V/C Ratio Calculations for Granville Street

The v/c ratios for both Granville Street approaches are calculated based on the 1994 Highway Capacity Manual (HCM). These v/c ratios are used for the Granville Street volume experiments described in Section 4.2.1.

The capacity of a lane group is the theoretical capacity of the lane group if 100% green time were available [HCM, 1994]. For the Granville Street volume experiments, both the northbound and southbound Granville Street approaches belong to the same lane group because they have their green time starts and ends at the same time. The capacity of a lane group is calculated as:

$$c_i = s_i * \frac{g_i}{C}$$

where c_i = capacity of lane group i, vehicles/hr;
s_i = saturation flow rate of lane group i, pcphgpl, passenger cars/hr/lane group;
g_i = effective green time for lane group i, second; and
C = cycle length, second.

The saturation flow rate is suggested in the 1994 HCM Model using the following algorithm:

$$s = s_o * N * f_w * f_{HV} * f_g * f_p * f_{bb} * f_a * f_{RT} * f_{LT}$$

where s = total saturation flow rate for lane group, vehicles/hr/lane group;
s_o = ideal saturation flow rate per lane, usually taken at 1,900 pcphgpl;
N = number of lanes in the lane group;
f_w = adjustment factor for lane width;
f_{HV} = adjustment factor for heavy vehicle presence;
f_g = adjustment factor for grade;
f_p = adjustment factor for parking conditions;
f_{bb} = adjustment factor for local bus blockage;
f_a = adjustment factor for area type;
f_{RT} = adjustment factor for right-turning vehicles; and
f_{LT} = *adjustment factor for left-turning vehicles.*

And the effective green time (g_i) is defined as:

$$g_i = G_i + Y_i - t_L$$

where g_i = effective green time for phase i, seconds
G_i = actual green time for phase i, seconds;
Y_i = sum of yellow plus all red intervals for phase i, seconds; and
t_L = sum of start-up plus clearance lost times for phase I, seconds.

The calculations of saturation flow rate for the Granville Street approaches, the average effective green time, and the capacity are based on the following assumptions:

1. It is assumed that the capacity along Granville Street be estimated by the average of the Granville Street capacities at major signalized intersections along Granville Street (i.e., Granville and Broadway, Granville and 12th Avenue, Granville and 16th Avenue, Granville and 25th Avenue, Granville and 33rd Avenue, Granville and 41st Avenue, Granville and 49th Avenue, Granville and 70th Avenue).

2. It is assumed that the ideal saturation flow rate on Granville Street be 1,900 pcphgpl.

3. The "NoTAC model" assumes 3.5 meter wide lanes, 2% heavy vehicle, 0% grade, no on-street parking, no right-turn traffic, and no left-turn traffic on Granville Street, as explained in Section 4.1.1 and Section 4.1.2.

4. No start-up or clearance lost time is assumed.

5. It is assumed that the buses mainly impact the rightmost lane, where all regular buses and B-Line buses run.

6. It is assumed that the Granville Street corridor be not representing a central business district (i.e., CBD).

Based on the assumptions immediately above, the adjustment factors and the Granville Street saturation flow rate are:

$$f_w = 1.00 + \frac{w-12}{30} = 1.00 + \frac{10.5-12}{30} = 0.950$$

where w = lane width, feet.

$$f_{HV} = \frac{1}{1 + P_{HV} * (E_{HV} - 1)} = \frac{1}{1 + 0.02 * (2-1)} = 0.980$$

where PHV = proportion of heavy vehicles; and
EHV = passenger car equivalent for one heavy vehicle.

$$f_{bb} = \frac{N - (N_B / 250)}{N} = \frac{1 - (10/250)}{1} = 0.960$$

where N = number of lanes affected by bus; and
N_B = number of buses stopping per hour.

$f_g = 1.00$ (No gradient is assumed on Granville Street)

$f_p = 1.00$ (No parking is assumed on Granville Street)

$f_a = 1.00$ (Non-CDB is assumed for Granville Street)

$f_{RT} = 1.00$ (No right-turn traffic assumed on Granville Street)

$f_{LT} = 1.00$ (No left-turn traffic is assumed on Granville Street)

$$s = s \ * N * f_w * f_{HV} * f_g * f_p * f_{bb} * f_a * f_{RT} * f_{LT} = 1900 * 3 * 0.95 * 0.98 * 0.96 = 5096$$

Using the calculated saturation flow rate and the cycle length of 75 seconds for all signalized intersections along Granville Street, the capacities of each major intersection are summarized in Table C-1 below.

Table C-1 Granville Street Capacities at Major Intersections

Intersection	Effective Green (seconds)	Saturation Flow Rate (veh/hr/group)	Capacity (veh/hr)
Granville and Broadway	37	5,096	2,514
Granville and 12th Ave	40	5,096	2,718
Granville and 16th Ave	44	5,096	2,990
Granville and 25th Ave	37	5,096	2,514
Granville and 33rd Ave	41	5,096	2,786
Granville and 41st Ave	40	5,096	2,718
Granville and 49th Ave	41	5,096	2,786
Granville and 70th Ave	40	5,096	2,718
		Average Capacity	**2,718**

The v/c ratios for different Granville Street volume are shown in **Table C-2**.

Table C-2 v/c Ratios on Granville Street

Granville Volume (Veh/hr)	Capacity (veh/hr)	v/c Ratio
500	2,718	**0.18**
1,000	2,718	**0.37**
1,500	2,718	**0.55**
2,000	2,718	**0.74**
2,500	2,718	**0.92**
2,700	2,718	**0.99**

Appendix C-2: V/C Ratio Calculations for 70th Avenue (Eastbound)

The v/c ratios of the eastbound approach on 70th Avenue, for different cross street volumes, are calculated based on the 1994 Highway Capacity Manual (HCM) Model. These v/c ratios are used for the cross street volume and recovery strategy experiments described in Section 4.2.3 and Section 4.2.8 respectively.

The capacity of the eastbound lane group at the intersection Granville Street and 70th Avenue is calculated as:

$$c_i = s_i * \frac{g_i}{C}$$

where c_i = capacity of lane group i, vehicles/hr;
s_i = saturation flow rate of lane group i, pcphgpl, passenger cars/hr/lane group;
g_i = effective green time for lane group i, second; and
C = cycle length, second.

The saturation flow rate is suggested in the 1994 HCM Model using the following algorithm:

$$s = s_o * N * f_w * f_{HV} * f_g * f_p * f_{bb} * f_a * f_{RT} * f_{LT}$$

where s = total saturation flow rate for lane group, vehicles/hr/lane group;
s_o = ideal saturation flow rate per lane, usually taken at 1,900 pcphgpl;
N = number of lanes in the lane group;
f_w = adjustment factor for lane width;
f_{HV} = adjustment factor for heavy vehicle presence;
f_g = adjustment factor for grade;
f_p = adjustment factor for parking conditions;
f_{bb} = adjustment factor for local bus blockage;
f_a = adjustment factor for area type;
f_{RT} = adjustment factor for right-turning vehicles; and
f_{LT} = adjustment factor for left-turning vehicles.

And the effective green time (g_i) is defined as:

$$g_i = G_i + Y_i - t_L$$

where g_i = effective green time for phase i, seconds
G_i = actual green time for phase i, seconds;
Y_i = sum of yellow plus all red intervals for phase i, seconds; and
t_L = sum of start-up plus clearance lost times for phase I, seconds.

The calculations of saturation flow rate for the Granville Street approaches, the average effective green time, and the capacity are based on the following assumptions:

1. It is assumed that the ideal saturation flow rate on 70th Avenue be 1,900 pcphgpl.
2. The "NoTAC model" assumes 3.5 meter wide lanes, 2% heavy vehicle, 0% grade, no on-street parking, no right-turn traffic, and no left-turn traffic on Granville Street, as explained in Section 4.1.1 and Section 4.1.2.
3. No start-up or clearance lost time is assumed.
4. It is assumed that 70th Avenue be not representing a central business district (i.e., CBD).

Based on the assumptions immediately above, the adjustment factors and the Granville Street saturation flow rate are:

$$f_w = 1.00 + \frac{w-12}{30} = 1.00 + \frac{10.5-12}{30} = 0.950$$

where w = lane width, feet.

$$f_{HV} = \frac{1}{1+P_{HV}*(E_{HV}-1)} = \frac{1}{1+0.02*(2-1)} = 0.980$$

where PHV = proportion of heavy vehicles; and
EHV = passenger car equivalent for one heavy vehicle.

$f_{bb} = 1.00$ (There is no bus running on the eastbound approach on the 70th Avenue)

$f_g = 1.00$ (No gradient is assumed on Granville Street)

$f_p = 1.00$ (No parking is assumed on Granville Street)

$f_a = 1.00$ (Non-CDB is assumed for Granville Street)

$f_{RT} = 1.00$ (No right-turn traffic assumed on Granville Street)

$f_{LT} = 1.00$ (No left-turn traffic is assumed on Granville Street)

$$s = s\ *N*f_w*f_{HV}*f_g*f_p*f_{bb}*f_a*f_{RT}*f_{LT} = 1900*2*0.95*0.98 = 3539$$

Based on the calculated saturation flow rate and the cycle length of 75 seconds, the capacity of the eastbound approach at the intersection of Granville Street and 70th Avenue is:

$$Capacity = s * \frac{g}{C} = 3539 * \frac{25}{75} = 1180 \text{ Veh/hr}$$

The v/c ratios for different 70th Avenue volume are shown in Table C-3.

Table C-3 v/c Ratios on 70th Avenue (Eastbound)

70th Ave Volume (Veh/hr)	Capacity (veh/hr)	v/c Ratio
295	1,180	**0.25**
590	1,180	**0.50**
944	1,180	**0.80**
1,062	1,180	**0.90**
1,180	1,180	**1.00**