Transit Signal Priority for Express Buses:
A Study of the Granville Corridor in Vancouver

by

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Abstract

Public transport facilities, especially in large metropolitan areas have gained significant popularity in recent years. In order to make these facilities more competitive with low occupancy private automobiles, transit authorities are adopting strategies that work in favour of transit vehicles. An emerging strategy that has attracted many cities is Transit Signal Priority (TSP).

Successful TSP strategies advocate lower transit travel times with minimal impacts to other users. These strategies have the potential to reduce transit travel times along high-density arterials by offering transit users reduced delays at signalized intersections. The success of TSP, however, depends on not one but many factors such as traffic volumes, transit headways, and transit loading zones, among others.

This research analyzed the effectiveness of TSP strategies, and the impacts of different variables on these strategies. The Granville corridor in Vancouver was used as a case study to conduct TSP analysis. A simulation model was developed for the Granville corridor. This model was analyzed for peak hour traffic using coordinated signals with variable active priority strategies. The study indicated significant priority usage at major signalized intersections. Owing to the high transit frequency along the Granville corridor, TSP benefited overall transit performance through reduced transit travel times. The benefits to transit were achieved with recoverable impacts on cross street vehicles. The study also analyzed the effects of active TSP strategies with uncoordinated signals.

Uncoordinated signals offered relatively lower improvements to transit buses without much improvement in the cross street delay.

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Chapter 1. Introduction

1.1. Background

During the past few decades, development in almost every major city in North America has been staggering. This can be attributed to the growing commercial environment and industrial growth, resulting in highly compact urban surroundings. The rapid-growing urban settlements have attracted people not only from the suburbs but also from other states, provinces, as well as countries. A rising concern during these changes has been the movement of people from various origins to respective destinations within the urban expanses (e.g.: Residence to work trips and vice-versa). The principal mode of transport for most of these trips has been the private automobile with added contribution from public transit vehicles.

Private automobiles have been the primary choice for transportation in almost all urban areas, mainly because they serve individual needs as compared to transit-based public needs. Higher usage of low occupancy private automobiles translates to additional infrastructure support. Since expansion of transportation infrastructures within major cities is limited, it has led to efforts in enhancing existing infrastructures by improving the efficiency of presently available facilities. At the same time, it has given rise to relative queries that have been analyzed frequently; for instance,

- Are there measures strong enough to encourage transit use and other efficient modes of transportation apart from private autos?
- Can the existing facilities encourage higher person throughput?

- Can the public transportation facilities be improved to attract more passengers onto the "Bus" or other highway transit modes?

Transit agencies have tried to keep up with the increasing transportation demand. But transit as a whole, has been limited in its functioning due to the following reasons,

1. A generally lower modal share for transit.
2. Longer travel times.
3. Deterioration in schedule adherence due to increased congestion on the urban roads and arterials (transit timeliness).

In order to overcome some of these difficulties, transit authorities have tried to improve service by giving priority to transit facilities; like LRT, Buses, and Streetcars. Potential priority strategies ensure improved travel times in addition to yielding better schedule adherence.

The City of Vancouver is a busy port and commercial centre situated on the western coastline of Canada. Being the third largest city in Canada, Vancouver depicts a well-connected and dense public transport system mainly operated by Translink and its subsidiaries. In order to facilitate better services, Translink has provided express buses along some of the major corridors in the city. Regardless of the shorter headways, the express buses face delays during peak hours. Thus, to ensure shorter and more consistent travel time for buses, the public transport system is investigating various improvement alternatives, transit signal priority being one of them.

TSP has seen much advancement in the recent past. Various TSP studies analyzing its benefits and impacts have been conducted in many major cities throughout North America. TSP strategies have ranged from simple adjustments in fixed signal timing plan to real time detector based active priority strategies. These studies have brought forth a number of variables or parameters that affect signal priority; signal control logic, transit service, bus stop locations to name a few.

This study evaluates the effectiveness of TSP strategies along Granville Street in Vancouver. This analysis would give an insight into transit as well as non-transit traffic behaviour with respect to TSP.

1.2. Research Objectives

The objectives of this research are,

- Investigate the benefits of various TSP strategies such as green extensions, and red truncations.
- Set up a simulation model to analyze the effectiveness of these TSP strategies and their relative impacts on various Measures of Effectiveness (MOE).
- Evaluate the effect of various signal, traffic, transit parameters on TSP
- Identify the best TSP strategy offering significant benefits to transit with minimal impacts on other traffic within the network.

Since this study uses a simulation based analysis, it will provide Translink with a useful tool to conduct feasibility analysis on different TSP scenarios.

1.3. Thesis Structure

The current chapter gives an introduction to the thesis scope and objectives. Chapter 2 provides a general literature review on previous TSP studies, the different TSP strategies used in these studies, and the parameters affecting the TSP strategies. Experimental set-up, simulation model parameters, signal priority control logic and measures of effectiveness (MOE) are discussed in Chapter 3. Chapter 4 analyzes the different TSP strategies and scenarios using the Granville corridor as a case study. Finally, Chapter 5 discusses the results of this study and the scope for future studies in TSP.

Chapter 2. Literature Review

2.1. Introduction

Past analyses of transit services have indicated that most transit delays occur either at transit stops or at traffic signals (Brilon et al, 1994). The delay at transit stops is partly dependant on the random presence of passengers, who wish to board the transit vehicle. Strategies to reduce these delays are generally limited. Traffic signals on the other hand, provide higher opportunities to reduce transit delays.

Delays at traffic signals usually contribute towards 10–20% of the total trip time for a bus and around 50% of the total delay incurred to it (Sunkari et al, 1995). At signalized intersections, transit vehicles can be given priority, which may reduce the average stopped delay of the transit vehicle, and thereby the overall passenger delay.

Different priority strategies benefiting buses have been explored in past studies. These strategies have developed over the years from fixed time passive strategies to more real-time active implementations. With the advent of Intelligent Transportation Systems priority strategies have been refined to be more effective and efficient with respect to transit travel time as well as service.

2.2. Priority Strategies

The concept of transit priority has been in the transportation industry since the 1960s. A priority experiment was conducted in Washington D.C. in 1962 (Sunkari et al, 1995), where the offsets of a signalized intersection were adjusted in order to coincide with the lower bus speeds, thus giving them priority. Based on past studies transit priority strategies have been classified into two categories, namely;

1. Passive Priority
2. Active Priority

Active and passive priority implementations are further broken down into sub-strategies depending on the traffic conditions, signal control logic, and transit service. The following sections discuss the different active and passive strategies used in past studies and their effectiveness.

2.2.1. Passive Priority

Passive priority strategies mainly consist of changes in signal timing plans to favour transit movements. These changes are based on time of the day for TSP implementation and historical bus arrival times. This strategy does not require the presence of transit in order to provide priority. Since the signal timings are predetermined and their logic is based on history the success rate using these strategies is lower. This is mainly due to varying traffic conditions. The variability in traffic conditions induces randomness into the bus arrival times at signalized intersections offering passive priority, thus reducing TSP effectiveness. However, passive priority strategies are attractive based on their cheaper and comparatively easier implementations. Passive priority strategies studied in the past are;

a. Cycle Length Adjustment:

In order to benefit transit vehicles, the cycle lengths of traffic signals are shortened by implementing this strategy (Figure 2.1). Shortening of signal cycle lengths enables early return of the transit phase, thus reducing stopped delays at the intersection. However, this priority treatment increases the frequency of intergreen phases causing additional lost times.

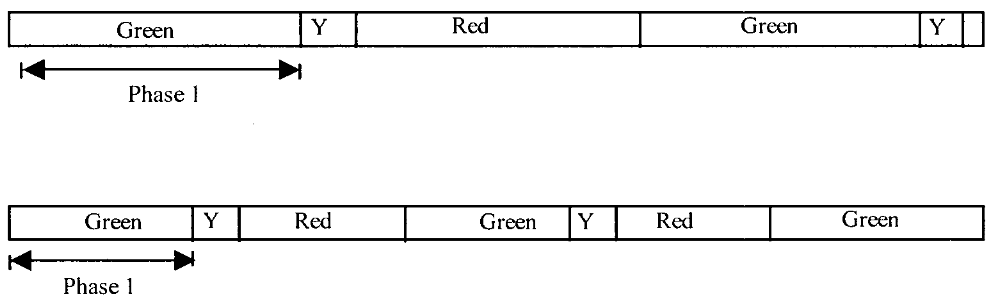

Figure 2.2. Cycle length adjustment.

Cycle length adjustment was used on an off-peak traffic simulation model in Austin, Texas (Garrow et al 1997). Analysis of the model showed an 11% decrease in transit travel time in the northbound direction and a 4% reduction in the southbound direction. The non-transit vehicles in the network also benefited from this strategy experiencing reduced delays.

b. Splitting of Phases:

In this strategy, the transit phase was split into smaller phases and introduced in between the non-transit phases (Figures 2.2 and 2.3). This strategy is used at signalized intersections having three or more phases.

Split phasing did show improvements in the Austin study with a 10% decrease in transit travel time in the northbound direction (Garrow et al, 1997). However, the southbound transit time increased by 2%. Therefore, this strategy did not exhibit as much effectiveness as the cycle length adjustment strategy.

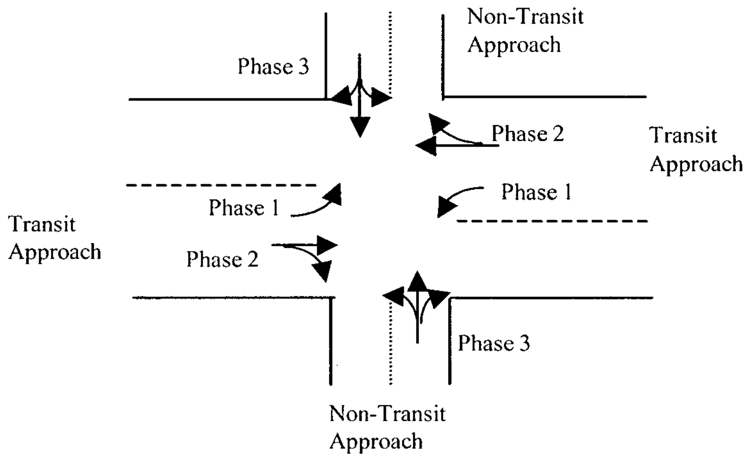

Figure 2.2. Three Phased Signalized Intersection with phase sequence.

Phase 1	Phase 2	Phase 3

Phase 1	Phase 2a	Phase 3	Phase 2b

Figure 2.3. Cycle Length Adjustment.

c. Phase Omission:

In this strategy, protected phases serving lower traffic volumes are omitted. This strategy is used when there is a protected left turn or right turn phase within a signal cycle.

A few of the signalized intersections along the simulated LRT corridor in Hillsboro provided protected left turn phases. These phases were removed during the priority control logic, thus giving more time to the LRT phase (Dale et al, 1999). As a result of this implementation a percentage of left turning traffic was diverted to another route, which reduced the opposing traffic for through street movements. This was done owing to the assumption that some of the left turning traffic would choose a different route following the deletion of the left turn phase. This strategy showed minor increase in average intersection delay (0-4 seconds/vehicle) with most intersections operating at an acceptable Level of Service of B or C. The average maximum queue lengths were below the capacity of most cross streets even after the priority implementation.

d. Areawide Timing Plan:

This treatment enables transit priority on an area/network wide basis. Transit is given priority based on signal progression, which is adjusted according to bus travel times, arrival rate and bus headways.

Dale et al (1999) used one-way progression along the LRT approach in their study. The strategy took into account the mean dwell time of LRT at stations along with the average acceleration and deceleration rates. Based on these values the strategy granted progression to the LRT approach. Since the areawide timing plan was implemented along with the phase omission strategy the results were the same as discussed in the earlier section.

e. Metering Vehicles

In this strategy, the buses enjoy the benefit of bypassing metered signals with the help of reserved bus lanes, special signal phases or by redirecting buses to non-metered lanes.

2.2.2. Active Signal Priority based on signal control logic

Active priority is granted only when the presence of a transit vehicle approaching an intersection is identified/detected. The transit vehicle can be identified by loop detectors, radio frequency transmitters or other AVLs (Automatic Vehicle Locating Systems).

a. Phase extension:

In this technique, the phase allowing transit vehicles to pass the intersection is extended. This strategy is usually effective when the transit vehicle is detected prior to the end of the transit phase. Based on average speed of the transit vehicle and distance of the detector location from the intersection the transit phase is extended up to a maximum assigned value to allow the transit vehicle to pass through.

b. Early Start:

This treatment is applied when the transit vehicle is expected to arrive during the non-transit phase. In order to avoid delay to transit vehicles, the non-transit phases are curtailed to a minimum assigned value (depending on safety of the cross street/pedestrian traffic), thus ensuring early start of the transit phase.

In most studies reviewed, TSP implementations that used green extensions also used red truncations. The effectiveness of these two strategies in past studies is thus discussed together.

In 1993, a study was conducted on a 2 mile section of Powell Boulevard in Portland, Oregon (Zaworski-Hunter et al, 1994). Two kinds of priority systems were used:

1. Tote systems by the Tote division of McCain Traffic Supply
2. LoopComm by Detector Systems.

Tote systems used radio frequency (RF) activated tags that were mounted on the buses. These tags were detected by RF readers installed on the side of the road. On the other hand, LoopComm used a special transmitter installed on the buses that were read by standard vehicle loop detectors embedded in the pavement. The traffic control logic used either green extension or red truncation as a priority strategy for the transit buses. The field results indicated that bus travel times in the peak direction reduced by 5% to 8%.

Following the Powell Boulevard study, another field test was carried out in Portland, Oregon using Opticom Signal Priority Systems (Zaworski-Hunter et al, 1995). The study was conducted on a 0.75mile section of NE Multnomah Street in Lloyd district. The signal strategy used, provided green extensions/ early green return without disrupting the normal signal coordination cycle. In case of near-side stops, Opticom emitters were provided with a facility of being de-energized whenever a halt at the near-side stop was required. The emitters would be energized again, once the bus left the stop. The field tests indicated a reduction in the bus travel times ranging from 4.7% to 7.1%.

Primavera, which is a Drive II project, was field tested in Leeds, UK using TIRIS (Texas Instruments Registration and Identification System) transponders (Fox et al, 1998). The project was implemented with the objective of integrating queue management, public transport priority and traffic calming strategies. The TIRIS detection system was integrated with SCOOT (Split Cycle Offset Optimization Technique) and SPOT (Signal Priority Optimization Technique) Urban Traffic Control (UTC) systems to meet its objectives.

The TIRIS transponders were fitted on the underside of buses. Detectors embedded in the road received signals from the transponders and the information was sent to TIRIS readers on the side of the road. The readers transmitted this information to the controller, which then processed the bus data and granted priority to the bus.

Simulation using field data was conducted in addition to real time field tests. The test results indicated that the SCOOT system along with the integrated strategy using TIRIS systems reduced bus travel times by around 8%.

Transit priority strategies, using green extensions and red truncations, were evaluated in a study conducted at Austin, Texas, (Garrow et al, 1997). In this study simulation analyses was carried out using a modelled corridor using TRAF-Netsim. The TRAF-Netsim model incorporated multiple time periods, which was adjudged useful in simulating signal priority. On every priority implementation the signal timing/cycle length was changed. Change in the signal timing/cycle length was achieved by substituting the normal signal cycle by pre-defined prority time periods. The time periods further comprised of time intervals. These time intervals were used by TRAF-Netsim to induce the priority stage. The study showed noticeable benefits for transit vehicles in the peak traffic direction with a priority success rate of up to 89% for far side bus stops in the peak traffic direction. Reduction in travel time per person ranged from 1.7% to 3.7% for the entire network.

Taylor et al (1998) conducted an evaluation of light rail transit signal priority strategies in Austin, Texas. They used the same network as used by the aforementioned bus priority strategy. In this study, a hypothetical LRT route was built running along the median of the arterial. This study analyzed the effect of active as well as passive transit signal priority on LRT as well as non-LRT vehicle operations. The study used green extensions as an active priority technique. Findings from the study indicated greater benefit to transit with passive priority strategies as compared to active strategies.

In Ann Arbor, Michigan, TRAF-NETSIM was used to simulate the traffic as well as to study bus pre-emption (Al-Sahili et al 1995). Green extensions and red truncations offered a maximum of 6% reduction in travel time to the transit bus. .

c. Special Phase Inclusion:

In this strategy, a special green phase benefiting the transit vehicle is included into the signal cycle, while as the other phases are blocked during this period.

VISSIM (micro simulation traffic model) was used to analyze the impact of Light Rail Transit (LRT) signal priority in downtown Hillsboro, Oregon (Dale et al, 1999). The Light Rail Vehicle (LRV) was detected by using VETAG loops, which were located at fixed points along the tracks. Owing to the close intersection spacing, each check-in loop detector was programmed to place a call to multiple controllers downstream of the detector. This procedure is also referred to as "Call Cascading". As soon as the VETAG detectors detected the LRT, all non-transit phases were suppressed and a special timer was used to include the transit phase. This timer allowed the LRT to pass through and then allowed a recovery phase to set in to allow the network to fall back to normal operation. The study supported the implementation of this strategy combined with phase omission and area timing plan strategies mentioned earlier.

d. Phase Suppression:

The phases experiencing low volumes are omitted ensuring early return of the transit phase in order to facilitate transit priority. The TSP study in Ann Arbor evaluated the effectiveness of this strategy (Al-Sahili et al 1995). The strategy did not show significant benefits to the bus in terms of travel time offering reduction in travel times of less than 3%.

e. Green Truncation for the Transit Phase:

A check-in detector is placed well before the signal as opposed to a normal detector location. The advance detector helps to inform the signal controller regarding the arrival of a transit vehicle. If the transit phase is on when the transit vehicle is detected, then the controller cuts down the green transit phase. This shortens the signal cycle length and allows early occurrence of the transit phase in the next cycle, providing the transit vehicle with better chances of meeting the green phase upon its arrival at the intersection.

2.2.3. Active Signal Priority based on Traffic Conditions

Depending on the traffic conditions, active signal priority strategies can fall under partial priority or full priority strategies.

i. Partial Priority:

Partial priority usually involves the implementation of either green extension or red truncation strategies in favour of the transit phase. The priority strategy can be implemented by using "window stretching". In window stretching green extensions or red truncations are provided in favour of the transit phase by taking green time from the non-transit phase. By doing this, coordination is maintained at the signalized intersection.

ii. Full Priority:

Full priority strategies involve the implementation of green extension and phase suppression, lift strategy, and HOV (High Occupancy Vehicle) weighted Policy for Adaptive Control (OPAC). The "lift" strategy can be used at intersections incorporating vehicle actuation/detection. The strategy ignores detection of vehicles on non-transit phases in order to recall the transit phase at the earliest. The HOV weighted OPAC technique uses person volume instead of vehicle volume in order to calculate the demand.

This system enables real time monitoring of the transit vehicles with the help of AVI (Automatic Vehicle Identification) systems.

Based on the traffic conditions, active priority can also be classified as unconditional or conditional priority.

iii. Unconditional Priority:

This type of priority strategy grants right of way to the transit vehicle when it is detected upstream of a signalized intersection. Transit is given priority irrespective of existing network conditions.

This strategy is usually effective for cross streets with low saturation levels, since the green extension or red truncation due to unconditional priority can have impacts on the cross street with high saturation levels. According to Garrow et al, for unbounded green extensions or red truncations, the simulation results indicated 18% and 20% decrease in the bus travel times in the northbound and southbound bus routes respectively.

iv. Conditional Priority:

This type of priority strategy allows right of way to transit vehicles based on the conditions at an intersection like; traffic volume on the transit approach, transit occupancy, transit schedule adherence, cross street queue-length, status of the signal when the bus/LRT is detected, time since last priority call, and constraints due to network's areawide timings.

SPPORT (Signal Priority Procedure for Optimization in Real Time), a priority model was generated and tested in Toronto, Canada (Yagar et al, 1991) for peak hour traffic. Real time traffic data were used in order to enhance the functioning of the intersection. The priority plan developed was used for the treatment of isolated intersections with large uncoordinated transit volumes. Traffic data was transmitted to SPPORT at regular intervals and based on the data, the model modified signal functioning in order to favour overall traffic. The model implemented the signal plan on the basis of certain events that were predefined; for instance, arrival of the streetcar on the conflicting approach, and cross street queue lengths. The results indicated a reduction in travel times complemented by a reduction of 20-25% in intersection delays at isolated intersections.

The Powell Boulevard study in Portland also used the Queue Jump technique in conjunction with the active priority strategies (Zaworski-Hunter et al 1994). The LoopComm system used in the study offered this technique at one of the intersections with a near-side stop. In the queue jump technique transit vehicles were allowed a predetermined advance green phase just ahead of the green phase for all vehicles in the transit direction. For successful implementation of this technique a designated transit lane was provided allowing the transit vehicle to have a head-start over the other non-transit vehicles. This technique worked well with the active priority strategies already being used along the study corridor offering transit a 4-7% reduction in travel times as compared to the base case.

2.2.3. Selective Plans:

Selective plans are designed with respect to each intersections within the transit network. They can be either a selection of active and passive priority strategies or a combination of both strategies.

Selective plans were implemented in An Arbor, Michigan (Al-Sahili et al, 1995). The study evaluated each intersection with four different TSP strategies. The strategy offering the best benefits to transit with minimal impacts to cross street vehicles was selected for respective intersections. This plan offered benefits up to 6% in the transit travel time with little or no effect on delays.

2.3. Measures of Effectiveness used in past studies

2.3.1. Travel Time

Transit travel time is the primary parameter used to evaluate TSP strategies. All the studies covered in this literature review used travel time as a primary MOE to analyze the benefits of providing active and passive priority strategies. Travel time in all studies was measured either as transit travel time, vehicle (transit and non-transit inclusive) travel time or person travel time. Garrow et al (1997) used person travel time to evaluate transit benefits for an individual intersection as well as for the entire network. The study assumed a predetermined value for person occupancy for vehicles and buses. Based on the assumption, the total person travel time was computed for vehicles on all approaches except the bus approach and for non-buses on the bus approach. The travel time was then compared with the person travel time for buses on the bus approach. The changes were not very significant since buses carried person trips roughly within 3% of the total person trips at the intersection. The effect of TSP strategies used in other studies reviewed in this chapter on transit travel time has already been discussed in the previous section.

2.3.2. Delay and Level of Service (LOS)

TSP strategies may benefit transit in term of improved travel times but at the same time may cause detrimental impacts on cross streets. An ideal TSP strategy would be the one that would offer maximum benefits to transit vehicles with minimum deterioration to cross street traffic.

Delays can be measured system wide (the transit approach and cross streets inclusive), for an isolated intersection or solely for the cross streets of an intersection. Cross street delay gives a good representation of the impact of TSP strategies on vehicles using the cross streets. System wide delays represent the network behaviour.

Almost all the studies reviewed in this chapter used some form of delay as a measure of effectiveness. Delays were measured either as vehicle delays or person delays. The Powell Boulevard study used cross street auto delays as well as cross street transit delays as one of its MOE (Zaworski-Hunter et al 1994). Analysis of the delays showed a minor impact on cross street autos (1%-2% increase). However there was a significant increase in cross street transit delay.

Combined vehicles and transit delays were measured in the study carried out in Toronto (Yagar et al, 1991). There was a 20-25% reduction in combined intersection delays at isolated intersections by using conditional priority. The LRT study in Hillsboro, Oregon also used intersection delay as one of the MOEs (Dale et al, 1999). The average intersection delay per vehicle was found to increase slightly with the phase inclusion kind of active priority. TSP operations increased the average intersection delay by 5 seconds. But LOS (Level of Service) for most of the intersections remained the same before and after the LRT priority implementation.

The simulation study conducted in Austin, Texas used passive as well as active priority strategies (Dale et al, 1999). For each strategy the study evaluated TSP impacts by using cross street delay as a primary MOE. Active strategies used during peak hour traffic had significant impacts on cross street delays. In some instances, priority strategies offering longer priority times caused unrecoverable delays to cross street traffic. Cross street delays experienced lower impacts when passive priority strategies were used during off-peak traffic conditions.

The LRT study in Austin used person delay as a dependant variable for evaluating the impact of active as well as passive TSP strategies. Analysis of person delay data revealed that passive priority strategies had lower impacts on cross street delays as compared to active strategies.

2.3.3. Vehicle Queue Lengths

Some studies used queue lengths as a MOE to evaluate priority strategies. Queue length measurements were used since they indirectly translated to delays. Queue lengths due to LRT priority did not experience noticeable change in the Hillsboro LRT study (Dale et al, 1999). A few intersections indicated an increase in queue lengths, with TSP usage. At one of the intersections the queue length exceeded the capacity and caused traffic fallbacks into upstream cross street intersections. The Powell Boulevard study (Zaworski-Hunter et al, 1995) used vehicle queue lengths along the transit approach to evaluate priority strategies. Upon using green extensions or red truncations queue lengths were found to increase along the cross street approach and the transit approach as well. This translated to an increase in overall intersection delay.

2.3.4. Vehicle Trips

The traffic model set up in Ann Arbor compiled vehicle trips as MOE data (Al-Sahili et al 1995). Transit vehicle trips improved with the implementation of active priority strategies. However non-transit vehicles were affected since they indicated reduced vehicle trips over the entire simulation run.

2.4. Parameters affecting TSP

2.4.1. Traffic Volumes or Saturation Levels

Effects of TSP strategies were found to vary with varying network traffic volumes (Garrow et al, 1997). The Austin model analyzed traffic and TSP behavior at different saturation levels. Unconditional priority strategies during low to moderate off-peak traffic periods showed recoverable disruptions to cross street traffic. As the cross street saturation levels increased, the intersection delay increased too. The increase in delay to cross street traffic was also proportional to the increase in extra green time offered to the transit phase. However, the intersections recovered to normal operation before the next expected priority call.

Disruptions caused to cross street traffic during high peak hour saturation levels were unrecoverable causing intersections failures. The Ann Arbor model conformed to the Austin study. The model showed better benefits to transit vehicles at lower volumes (Al-Sahili et al 1995). Low volumes also allowed the successful usage of a variety of priority strategies that could benefit transit.

2.4.2. Bus Stop Location and Dwell Times

The location of a bus stop with reference to a signalized intersection is important for successful priority usage. Bus stops can be located either upstream (near-side stops) or downstream (far-side stops) of an intersection. Near-side bus stops increase the variability in bus arrivals at subsequent downstream intersections owing to their random dwell times at the stops. Far-side stops offer more consistent bus arrivals thereby improving the frequency of successful priority calls.

Intersections having near side bus stops were treated differently by the Opticom Signal Priority Systems in the Portland study (Zaworski-Hunter et al, 1995). The Opticom emitters were provided with a facility of being de-energized whenever a halt at a near-side bus stop was required. Travel time reductions due to this implementation were in the range of 4.7% to 7.1% throughout the study corridor. However, due to improper use of the emitters, the reliability of the results in this study was questioned. The Austin transit model (Garrow et al, 1997) used near-side as well as far-side locations in the study network. Far-side stops offered better success for active TSP strategies as opposed to near-side stops.

2.4.3. Signal Control Logic

Most TSP strategies are based on the existing type of signal logic that is in operation within a study network. TSP strategies are implemented by changing these control logics in order to benefit transit vehicles. These changes affect the entire network being analyzed.

The majority of active priority strategies that were implemented took green time from cross streets and used it in favour of transit. While some strategies considered compensating the cross street phases in the phases following the transit phase, others continued normal signal operation after the transit phase without any compensation to the cross streets.

The Tote system in Portland used up to 10 seconds of green time from the cross street phase without compensation (Zaworski-Hunter et al, 1993). The cross street delays did not experience much deterioration by this strategy, however the buses on cross streets did experience delays.

Corridors operating in coordination usually fell out of synchronization when priority strategies were used (Williams et al, 1993). Although the priority strategies benefited transit on one hand they disrupted coordination and caused added delays to the non-transit vehicles using the network. The study carried out in Bremerton, Washington used Opticom Bus Priority System to conduct its analysis. In order to prevent substantial disruption to the cross streets the system was based on the following two conditions,

- The traffic signal offering priority fell back into coordination within 30 seconds of pre-emption.
- In case of consecutive priority calls, the second pre-emption would be executed only when all the other approaches at the intersections are catered to first.

The study was conducted for four routes in the Bremerton area. Bus travel times were computed by subtracting the time spent at stops from the total time that the bus was on the road during the trip.

Analysis of bus travel times indicated that the travel time of buses using pre-emption was around 10% lower than the travel time of buses without pre-emption. The route with the highest number of signalized intersections experienced the greatest decrease in the travel time and vice versa. The effect of the priority strategy on average delay was inconclusive since some of the cross streets experienced an increase in delays while the others experienced a decrease. This observation was due to the low frequency of buses that resulted in lower priority calls.

2.4.4. Transit Service and Headways

Priority usage depends on the transit service offered in terms of transit headways. The smaller the headway between transit vehicles, the higher will be the probability of priority usage and transit time reduction. Although shorter headways increase the success rate of priority strategies they also increase the impacts on non-transit vehicles.

The Austin study observed that priority success rate was dependant upon the bus headways and frequency of bus stops. Owing to the frequent bus stops in the study priority success rate was fairly low at a few intersections (Garrow et al, 1997). The LRT study in Hillsboro, observed that successful priority calls for back-to-back train arrivals within consecutive signal cycles at an intersection caused the most delays and traffic spillbacks (Dale et al, 1999).

2.5. Summary

The literature review gathered information regarding various aspects of Transit Signal Priority through past research and discussed them. From the review, TSP was found to be dependant on the following,

1. Time of the Day (peak or off-peak)
2. Transit service (LRT or Bus, headways).

3. Traffic along the transit corridor.

4. Traffic along cross streets, especially major cross streets

5. Priority strategy (Active/Passive) used.

6. Check-in Detector location

Based on the time of day, priority strategies were varied to offer efficient results. Effectiveness of various priority strategies, especially during peak hours depended on the capacity of the transit corridor and subsequently its degree of saturation. LRT service, owing to better predictability in arrival times, offered higher margin for improvement as compared to the less predictable bus arrivals. Bus arrivals were found to be dependant on the traffic along the bus corridor along with the distances between bus stops. Higher traffic volumes reduced the chances of transit buses benefiting from priority calls. On the other hand, fewer bus stop locations improved the bus arrival times at intersections. However, frequent priority usage induced greater disruption to traffic along the cross streets, especially major cross streets with denser traffic volumes.

The review also indicated that TSP studies conducted through a simulated environment offer greater in-depth analysis revealing the effects of key parameters such as traffic volumes, transit service, signal logic. At the same time such models offer a greater range of MOEs that can be evaluated and observed. Field studies on the other hand are closer to real time situations and offer results conforming to real time traffic conditions. However, field tests involve greater financial commitments.

TSP studies covered in this chapter have shown the potential to benefit transit vehicles without any significant impacts on other traffic. TSP strategies, if developed after accounting for the key parameters involved generally offer benefits on a network level.

Traffic networks that support a larger population of transit users tend to benefit more from the implementation of efficient TSP strategies. However, highly saturated networks skewed in favour of private automobiles undermine TSP benefits. Passive priority strategies work better in off-peak periods while active strategies work well with peak or close to peak traffic flows.

The literature review helped in setting up the scope for the current study. As mentioned earlier, the Granville corridor is used as a case study for analyzing different priority strategies. The set up and analysis framework for the corridor will be discussed in the following chapter.

Chapter 3. Experimental Design

3.1. Introduction

In the current study, the main benefactor from the TSP implementations will be the 98 B-Line Express that runs from Richmond, along No 3 Road to downtown Vancouver, along the Granville corridor. The study section of the Granville corridor will be set up to analyze TSP strategies for peak hour traffic using active priority strategies. The active strategies used are,

1. Green Extensions
2. Red truncations.

Priority will be granted to express buses based on an as and when required basis. For green extensions, the priority time lengths will be assigned a maximum value. But the logic itself will have the flexibility to cut short the priority phase as soon as the bus clears the intersection. The curtailment of green extensions will be achieved by using checkout detectors. Owing to this control logic attribute, successive green extension priority times at the same intersection would more than likely differ from each other depending on the variable bus arrival times at the check-in and checkout detectors. Also, variable red truncations times would be assigned based on the time the express bus was detected during the non-transit phase. However, the red truncations will be somewhat limited by the pedestrian phases that will be in operation along with the cross street phase. Depending on the time of detection of the express bus during the cross street phase the priority logic will be overridden by the safety logic favouring the cross street pedestrian traffic.

Since providing compensation to the phases following the transit phase did not create additional network benefits in the past studies signals along the Granville corridor will be designed to ignore the compensation to cross street phases (Williams et al, 1993). Also, to normalize the traffic up to manageable levels and avoid abnormal impacts to cross street traffic at least one normal signal cycle will function in between successive priority calls.

From the literature review, various traffic simulation models were identified (INTEGRATION, TRAF-Netsim, VISSIM to name a few). After reviewing the models and their attributes, it was decided to adopt VISSIM as the simulation model to carry out signal priority study.

VISSIM incorporated the signal priority strategies relatively well. In comparison to some other models, it gave flexibility in evaluating a wider group of Measures of Effectiveness (MOE) in conjunction with the various priority strategies. The following sections give an overview about VISSIM 3.5, the Granville study corridor and the required data/input parameters collected to conduct the model simulation. The data required to set up the entire network including the bus routes were obtained from the City of Vancouver and Translink.

3.2. VISSIM 3.5 – Microscopic Traffic Simulation Model

VISSIM is a time step and behaviour based microscopic simulation model. In other words, the model traces individual vehicles in the network and analyzes their behaviour with respect to time and traffic conditions. The simulation logic within VISSIM is capable of modeling urban traffic, rural traffic, freeways as well as public transit operations.

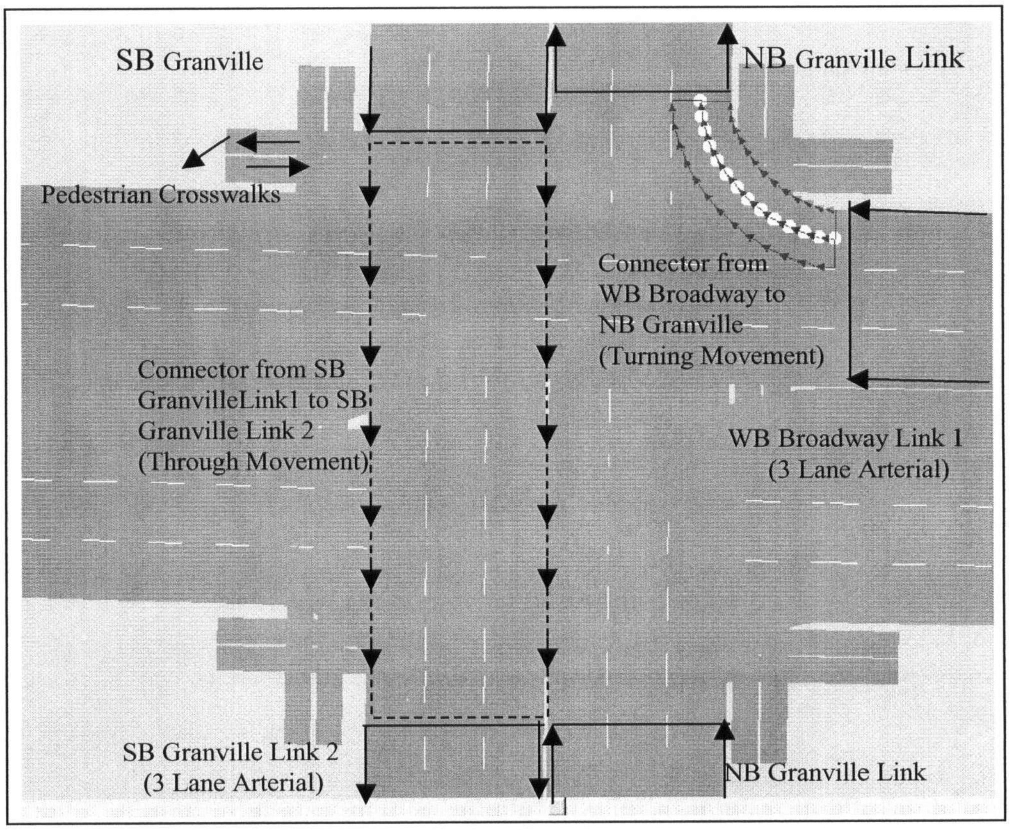

Figure 3.1. Network Intersection in VISSIM built using Links and Connectors

VISSIM generates street/highway networks in terms of links and connectors. Links are directional street/highway segments, which comprise of one or more lanes. They can be plotted to run between two successive intersections or can extend over several intersections depending upon the level of detail required. Links are connected to each other with the help of connectors. Connectors facilitate the movement of vehicles between links, enabling vehicles to travel through (through movement) as well as to turn left or right onto cross streets (turning movement).

VISSIM also allows the specification of pedestrian crosswalks, which can be plotted as independent links running across the streets. Figure 3.1 shows a sample network intersection in VISSIM, built using the link-connector method.

3.2.1. Network Plotting

Image files can be used to plot transportation networks in VISSIM. The files are into the model and converted to the desired scale to represent the real time network. After the scale conversion, the image file is used as a reference to plot the necessary links and connectors. The study network can thus be scaled and plotted in accordance with the real time network.

Maps of Granville corridor were downloaded from the GIS system used by Translink and the required link lengths between intersections were obtained from the City of Vancouver. The downloaded maps were combined into a single image file, which was uploaded into VISSIM and converted to the required scale. Figure 3.2 shows the 7.3 km (North-South) x 1.9 km (East-West) network section plotted in order to conduct the TSP study.

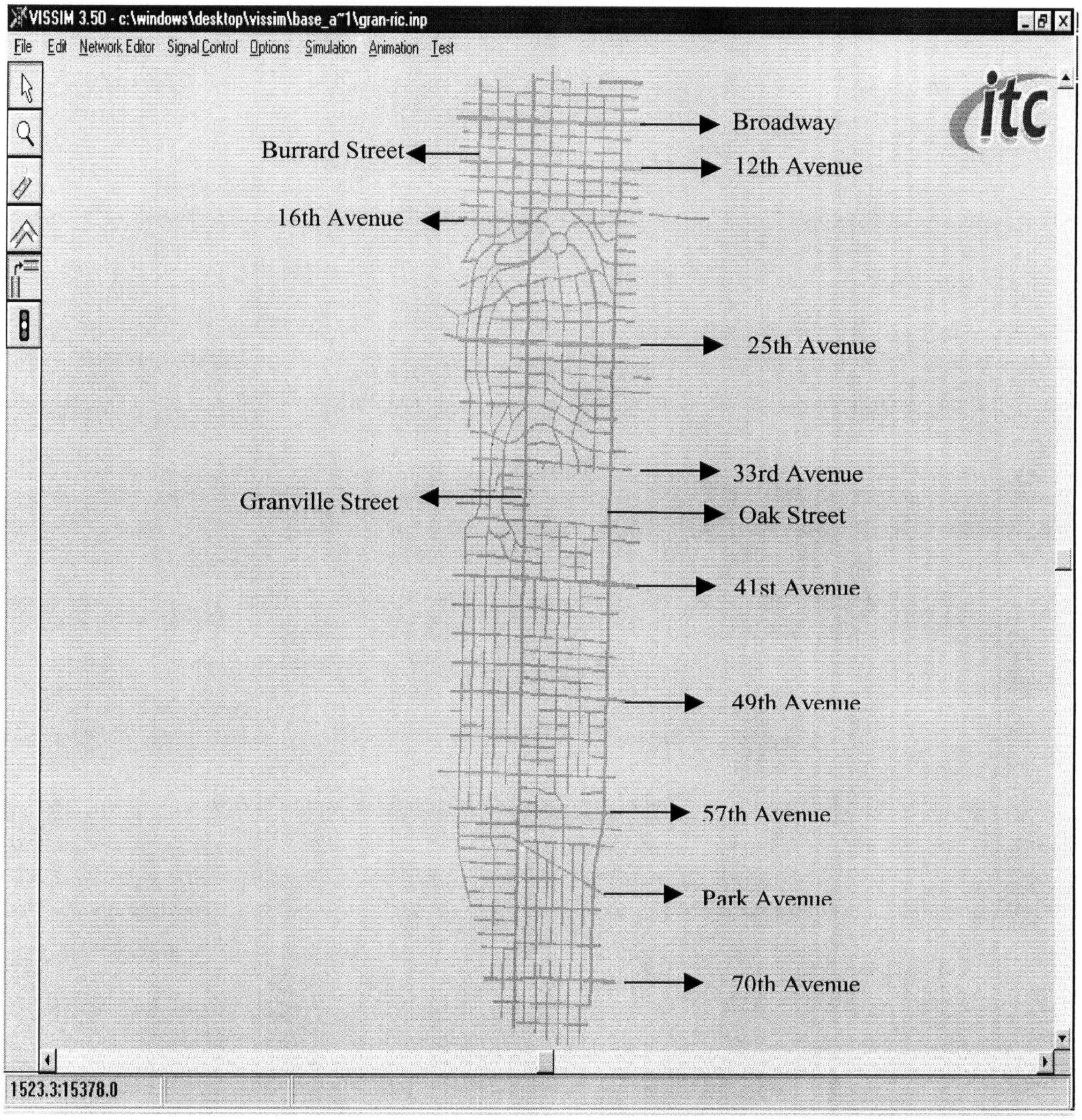

Figure 3.2. Map of the Granville Study Section.

The network comprised of three major streets running north-south with a number of cross streets/avenues running east-west. The section extended from 6th Avenue to 70th Avenue in the North-South direction, and from Burrard Street to Oak Street in the east-west direction. Amongst the major streets running north-south in the study section, Burrard street terminated at 16th Avenue, while Granville Street and Oak Street ran for the entire length of the study section, from 6th Avenue to 70th Avenue.

3.2.2. Traffic Volumes

Traffic volume data for the study network were acquired from City of Vancouver. The acquired data were in terms of directional intersection volumes, i.e. right turning, left turning and through traffic volumes for each approach into the intersection. The sum of the directional traffic volumes (vehicles/hour) into the intersection gave the total volume entering the intersection from the respective approach.

To generate traffic volumes in accordance with real time volumes, traffic feeders were set up at the entry point of each major approach (link) in the model. The total approach volume was fed into respective traffic feeders. The feeders generated random vehicle arrivals (in vehicles/hour) into the network based on assigned traffic volumes. Similarly, pedestrian volumes (persons/hour) were specified to pedestrian feeders at each entry pedestrian link running across signalized intersections.

In addition to traffic feeders, dummy signals were set up at entry links. These dummy signals followed the same timing plan as that of signals operating just upstream of the entry links of major approaches. This facilitated the traffic to be fed in periodic intervals and follow the same pattern as real time traffic.

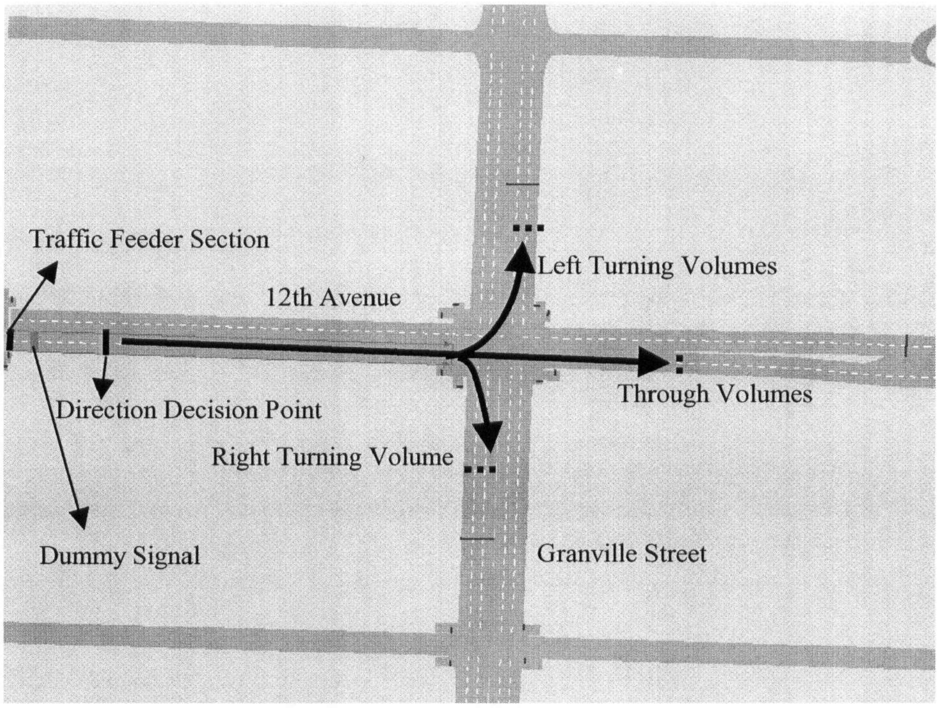

Figure 3.3. Directional Traffic Volume and Traffic Feeder Set-up.

Figure 3.3 shows the intersection of Granville Street and 12th Avenue. Traffic feeders were positioned on either ends of 12th Avenue for the eastbound and westbound approaches. The feeder on the west end of 12th Avenue was assigned a volume equal to the sum of westbound directional (left turning, right turning and through) traffic volumes into the intersection of Granville Street and 12th Avenue. In addition, a direction decision section was specified just downstream of the feeder section. This section randomly assigned directions (left turn, right turn or through movement) to each vehicle passing over it in proportion to the directional traffic volume distributions. The traffic would follow the direction assigned to them until they reached the next direction decision section within the network. Also, dummy signals were specified at the two entry links (east and west) of 12th Avenue. The signal had the same timing plan and logic as the one upstream to the entry links.

VISSIM also allows the specification of traffic compositions in order to attain realistic traffic flows. The traffic composition for Cars, Pedestrians and Heavy Vehicles along the major corridors in the network was based on data collected from the City of Vancouver.

3.2.3. Transit routes and headways:

In addition to the 98 B-Line express buses there were additional transit routes using the study network. Information on these routes was obtained from Translink.

Each bus route was input as a transit line in VISSIM. This transit line assigned an origin/entry link and destination/exit link within the network. As all the buses originated outside the study network, the time of their entry into the study section was computed based on the bus' arrival time to the first designated stop on its route within the study network. The scheduled bus arrival time to the first stop for each bus route within the study network was obtained from the Translink bus schedules.

The transit route and headway assignment for the Number 8 transit line within VISSIM is shown in figure 3.4 above. The Number 8 northbound bus entered the study network through Granville Street and traveled along the Granville corridor for the entire 7.3 km study section. It followed the same route as the 98 B-Line.

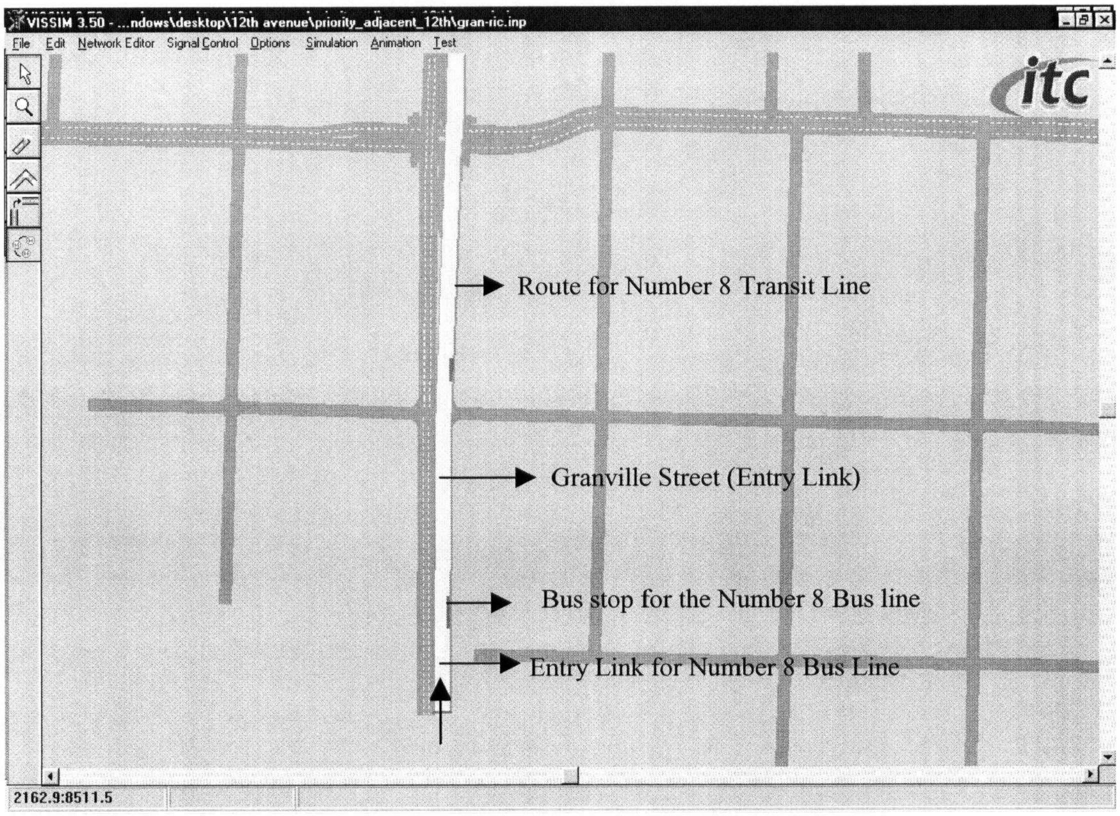

Figure 3.4. Transit Route Assignment.

The time required for the bus to travel from the entry link to the first designated bus stop was determined by running the simulation. The travel time measured was deducted from the scheduled arrival time to the first bus stop (bus stop arrival times obtained from Translink) in the study network. The resultant time was used to input as the entry time for the Number 8 bus into the network. Once the entry time of the first Number 8 bus was assigned, the headways for subsequent number 8 buses were input using the bus schedule.

The 98 B-Line bus route was assigned 10 minute headways in accordance with the real time bus schedule. All transit stops for 98 B-Line were located downstream (far-side) of the signalized intersections and their locations were defined as per the actual locations in the network. This removed the variability in dwell times and bus arrival times offered by near-side stops, thereby increasing the probability of successful priority calls. Transit stops within the express route were assigned uniform dwell times in order to facilitate better comparison between the base and priority scenarios.

3.2.4. Signal Timing Plans and Operating Logic:

The study area comprised of fixed, pedestrian-actuated, semi-actuated and fully actuated type signals. The logic and phase timings for each signal-controlled intersection within the study location were obtained from the City of Vancouver. VISSIM gave the flexibility to assign signals to intersections based on their logic (For e.g.; fixed, fully-actuated).

Timings for fixed signals were fed into VISSIM through the fixed signal-timing feature. This feature enabled the specification of timing plans for each directional phase as well as pedestrian phases at a signalized intersection. Most of the signalized intersections within the study area were coordinated having 75-second cycles. Offsets were defined for each signalized intersection in order to maintain coordination.

Semi-actuated and fully-actuated signals were designed within VISSIM using the Vehicle Actuated Programming (VAP) feature. The logic for each signal was programmed into a text file, which was compiled by VAP during each simulation run. In other words VAP enabled real-time functioning of signals, allowing the use of active priority strategies.

The logic and scenarios used for active priority will be discussed in more detail in sections 3.3 and 3.4.

3.2.5. Detectors:

Detectors within VISSIM can be used based on the needs and requirements of the analysis to be carried out. There were mainly three types of detectors used in this study. Detectors sensing vehicles for actuated signals, pedestrians for pedestrian actuated signals, and buses for transit priority.

Transit detectors were calibrated to identify B-line express buses on Granville Street. There were two kinds of transit detectors used:

1. Check-In Detectors
2. Checkout Detectors.

The check-in detectors were placed 100-150m upstream of the intersection while the checkout detectors were placed at the intersection. The checkout detectors were placed in order to improve the efficiency of the priority logic by allowing curtailment of green extensions once theexpress bus had cleared the intersection..

Figure 3.5 shows the check-in and checkout detectors used for the intersection of Granville Street Northbound and 70th Avenue. The logic/functioning for each detector was included in the VAP programs for respective signals.

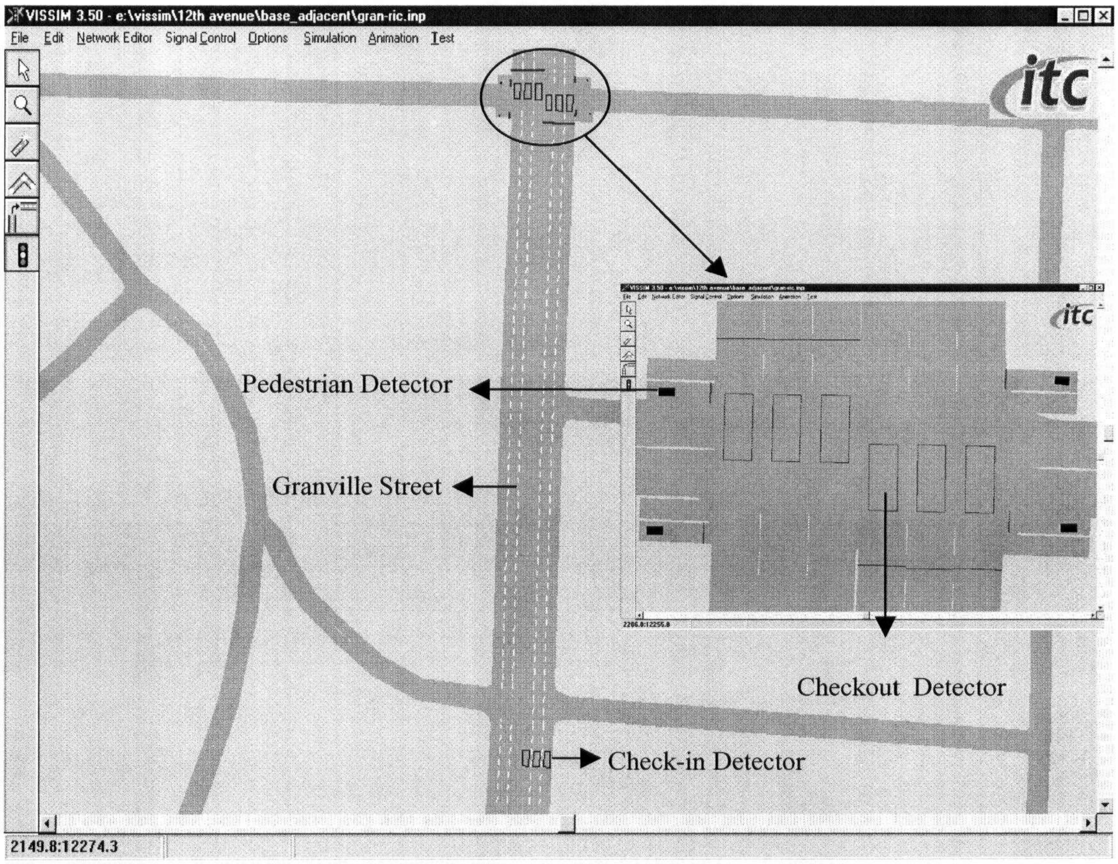

Figure 3.5. Check-in and Checkout detectors.

3.2.6. Measures of Effectiveness (MOE):

As the study section was relatively large (7.3km x 1.9km), a buffer time of 15 minutes was given prior to collecting MOE data for each simulation run. This buffer time would allow vehicles to fully occupy the network before the start of the data compilation programs.

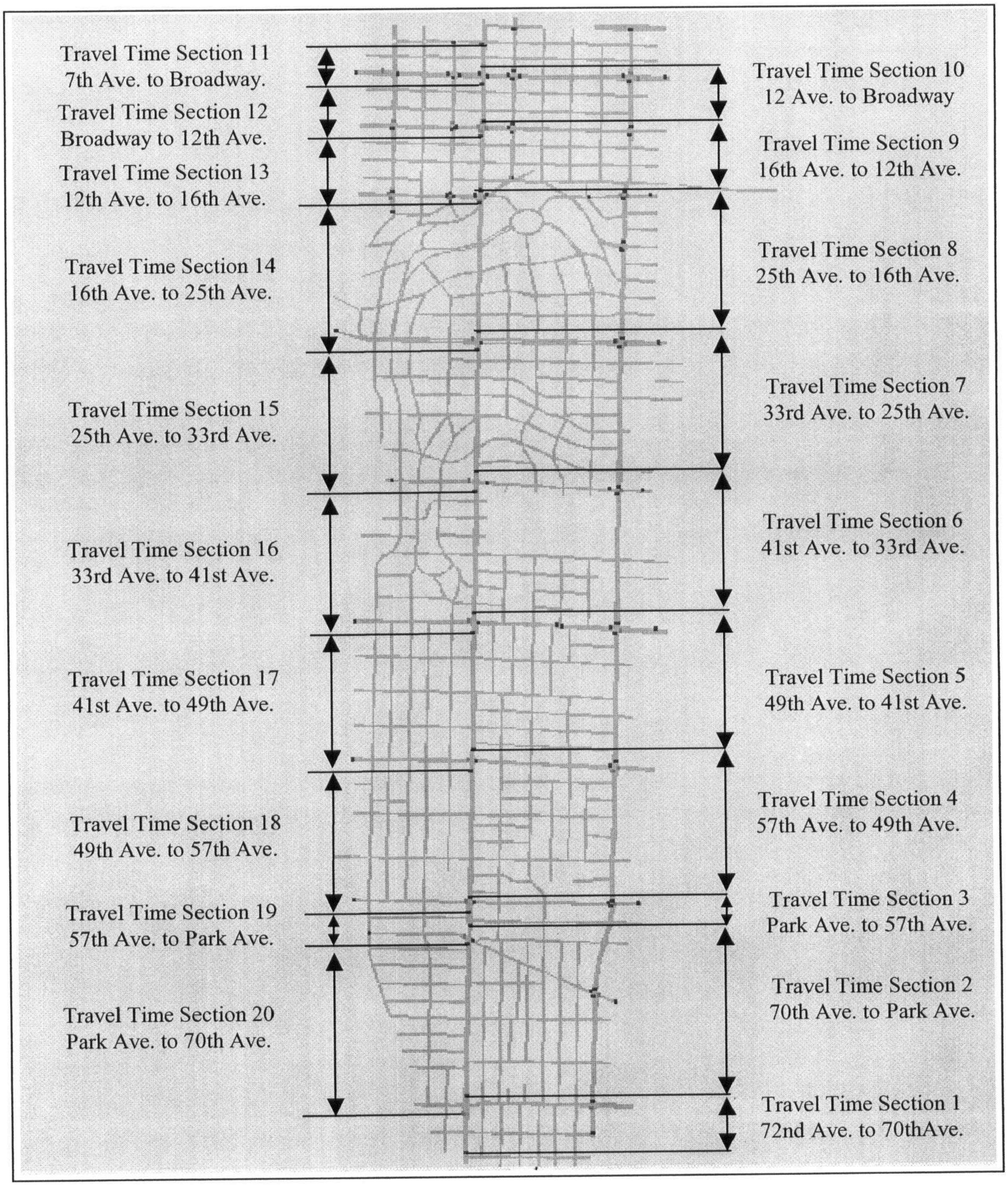

Figure 3.6. Transit Travel time measurement sections (peak direction) for Granville Street

Each simulation run lasted for 4500 seconds with the initial 900 seconds (15 minutes) as buffer time. Cross street delay, transit travel time, signal phase lengths and detector actuations were used as measures of effectiveness while conducting the simulation analysis.

To measure transit time, travel time sections were set-up between major intersections on Granville Street. Each travel time section had an entry and exit section. As soon as an express bus reached the entry point of the travel time section, VISSIM triggered the travel time module to record the transit time within the respective travel time section. Setting up the sections between major intersections would give an indication of the effectiveness of the TSP strategies at each major intersection. Since the initial 900 seconds were used as buffer time, travel time sections recorded average transit time for 3600 seconds. As seen in Fig 3.6, Granville Street was divided into 10 travel time sections in the South-North (peak hour) and North-South (off-peak hour) directions. Each of the 10 travel time sections measured transit time between two major intersections along the Granville corridor.

Travel time segments in VISSIM could be configured to measure vehicle delays as well. Delay (travel time) segments were set up for major cross streets in the study network. They measured delay at the end of specified time cycles. The time cycles in VISSIM can range from either an individual time step, to a signal cycle, or to an entire simulation cycle. For in-depth analysis, delays for cross streets across Granville Street were measured at the end of each signal cycle. Since majority of the signals along Granville

Street had a 75 second cycle, the delay segments were calibrated to record data at the end of 75-second cycles. Analysis of the compiled delay data also gave insight into the LOS for the cross street approaches to the respective intersection.

Effect of checkout detectors was determined by analyzing the signal phase length files as well as the detector actuations for respective signalized intersections.

The analysis framework for measuring and evaluating the MOEs are further discussed in section 3.6.

3.2.7. Calibration of VISSIM model:

Calibration is important to ensure that the simulated traffic network is operating similar to the real time network. In order to calibrate the model, actual transit times on two bus routes were measured during peak hours and were compared with the simulated travel times.

Mean Express Bus Travel Time (Average of three runs)		Difference between Actual and Simulated
Actual (seconds)	Simulation (seconds)	
887	864	2.6%

Table 3.1. Comparison of Simulation and Real time Travel Time for 98 B-line Express

The two bus routes chosen were:

1. The 98 B-Line Express route.
2. The Number 8 Bus route

Both routes ran along Granville Street for the entire study section. The Number 8 bus had more frequent stops as compared to the 98 B-Line express.

The field travel times were measured during morning peak hour traffic on three different mid-weekdays. Table 3.1 shows average travel time for the express bus along the Granville corridor. The difference between the simulated express bus transit times and the field measurements was 2.6%.

Mean No. 8 Bus Travel Time (Average of three runs)		Difference between Actual and Simulated
Actual (seconds)	Simulation (seconds)	
1064	1044	1.9%

Table 3.2. Comparison or Simulation and Real time Travel Time for Number 8 Bus

Average travel times for the Number 8 bus route are shown in Table 3.2. Since the number 8 was a non-express transit line, travel time was higher for the same length of the network as compared to the 98 B-Line express. The difference between the field and simulated average bus travel times was within 2%.

Since the transit times measured by the simulated environment were close to the actual observations the model set up was adjudged to give a good comparison between the present base scenario and the scenarios based on the various priority strategies used.

3.3. Priority Scenarios

Signal priority logic in VISSIM was set up to evaluate MOE (measures of effectiveness) for 10 second and 15 second variable green extension/red truncation strategies. Variable green extensions allowed the signals to cancel the transit phase as soon as the express bus cleared the intersection. Cancelling of the transit phase was achieved by using checkout detectors. Variable red truncations gave flexibility to cross street phases in offering surplus green time to the transit phase. This priority control logic is better explained in section 3.4

	10 Second Green Extension/Red Truncation	15 Second Green Extension/Red Truncation
5 seconds of minimum Pedestrian Walk time.	Priority Scenario 1	Priority Scenario 3
2 seconds of minimum Pedestrian Walk Time	Priority Scenario 2	Priority Scenario 4

Table 3.3. Active Priority Scenarios.

One of the safety regulations followed by City of Vancouver is to have a minimum of 5 seconds of 'Walk' time for pedestrians at any signalized intersection before the signal changed to 'Flash Don't Walk' (FDW). Based on this requirement, if the express bus was detected during the cross street phase then the priority logic would first have to allow 5 seconds of 'Walk' time followed by the required FDW time. After fulfilling the above, the logic would transfer the remainder of the cross street green time or the surplus green time to the transit phase.

The surplus green time offered to the transit phase by red truncations could range from 1 second up to the maximum allowable limit set for the strategy (10 seconds or 15 seconds). Some intersections with short cross street phases along the corridor would be unable to offer surplus green times up to the maximum limit after sufficing the "Walk" and FDW times. Since the FDW could not be altered, the other option to maximize surplus green times at such short cross street phases was to further reduce the Walk time. Hence signals functioning with 2 seconds of pedestrian "walk" times were included as one of the strategies. By implementing priority strategies allowing 2 seconds of 'Walk' time, cross streets would be in a position to give higher surplus green times to the transit phase.

Based on the above discussion, there were four priority scenarios developed as shown in Table 33. The functioning of the variable priority logic developed in this study is explained through examples in the following section.

3.4. Priority Control Logic

Majority of the signals along Granville Street are coordinated having 75 second cycles. To prevent deterioration to signal coordination, TSP logic was designed to rearrange green times within a signal cycle and provide priorities to express buses through green extensions or red truncations.

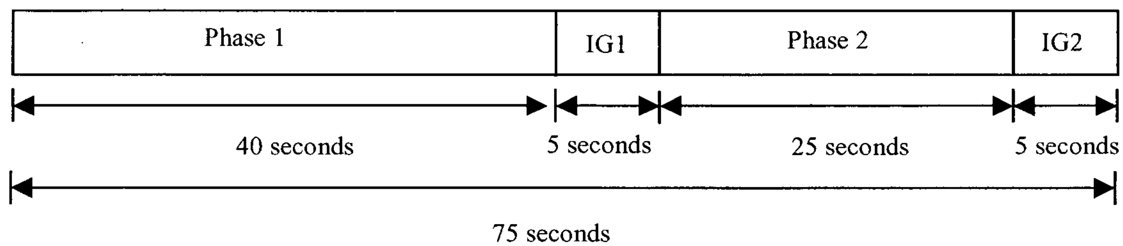

Figure 3.7. Two Phased 75 second Signal cycle.

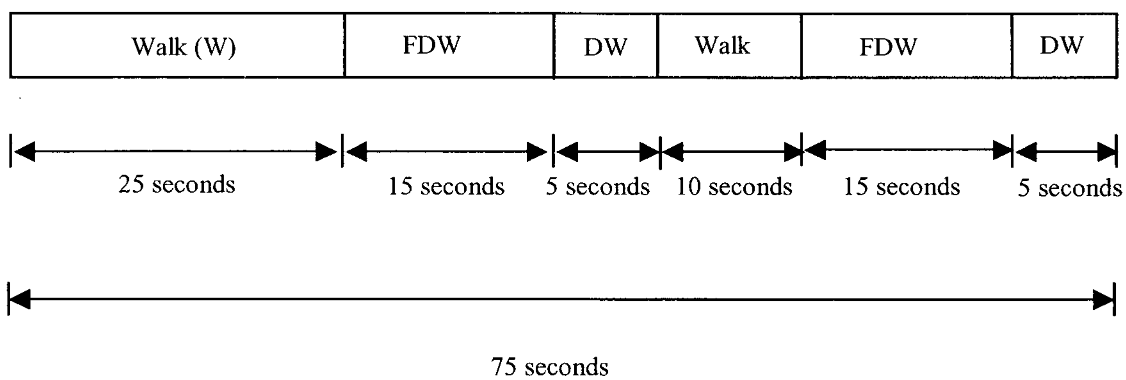

Figure 3.8. Normal Pedestrian Phase for two phased 75 second Signal cycle.

Figure 3.7 shows a complete 75-second signal cycle of one of the intersections on Granville Street. The north-south phase is represented by Phase 1 while Phase 2 denotes the east-west phase. The green time during phase 1 favours express buses in the peak as well as the off-peak direction. The north-south phase is also referred to as the transit phase. The east-west phase is the one favouring the cross street traffic. Figure 3.8 shows the distribution of pedestrian 'Walk', 'Flash Don't Walk' and 'Don't Walk' times for Phase 1 and Phase 2 of the same intersection.

The following cases explain the functioning of priority logic along the Granville corridor based on various traffic and signal conditions, and bus arrival times. The intersection indicated in Figure 3.7 is used as an illustration. The cases listed use Priority scenario 1, which allows 10 seconds of green extension/red truncation along with the contingency of minimum 5 seconds of cross street pedestrian walk time during red truncations.

Case 1:

An express bus is detected by the check-in detector 38 seconds into Phase 1. On detecting the bus, normal signal logic is replaced by the priority logic. The priority logic allows a further 10 second extension for phase 1, from 40 seconds to 50 seconds. At the 45th second, the checkout detector detects the express bus and cancels the priority phase.

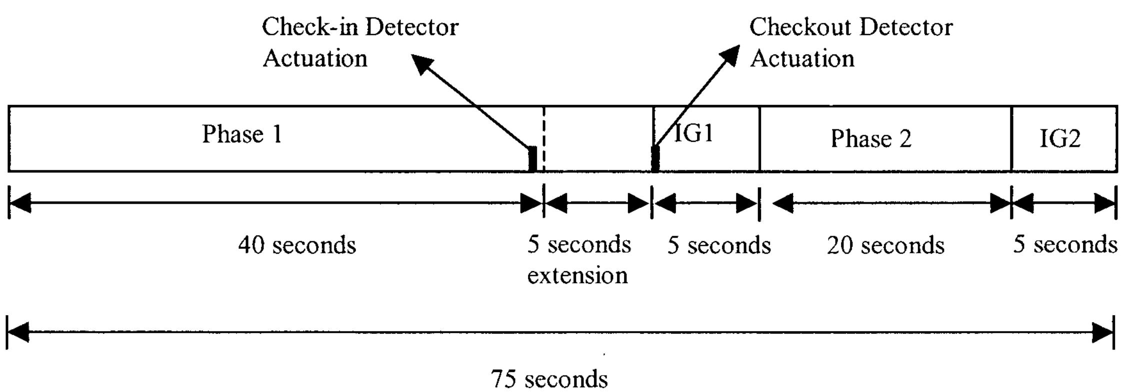

Figure 3.9. Signal Priority Logic when Express Bus is detected during Phase 1

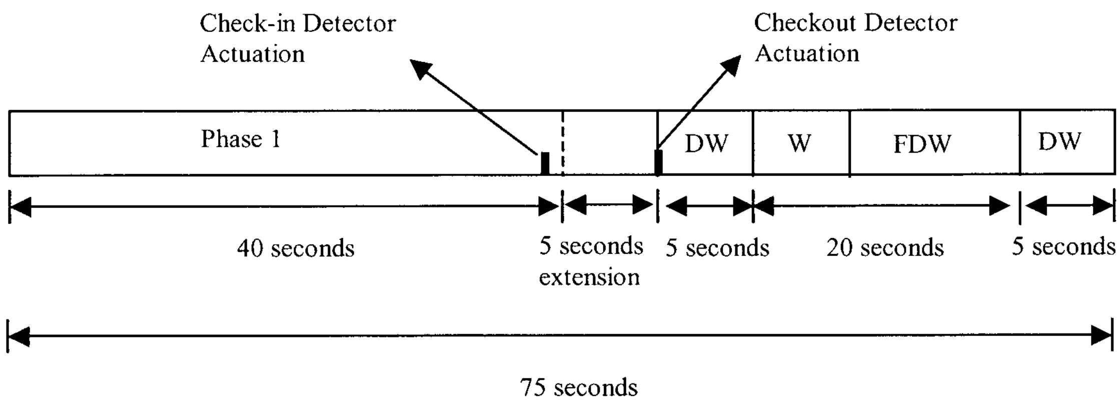

Figure 3.10. Pedestrian Signal Priority Logic when Bus is detected during Phase1

The 5 seconds of additional green time used for Phase 1, is taken from Phase 2 (Figure 3.9). Phase 2, following the priority phase, will now be 20 seconds long with 5 seconds of pedestrian 'Walk' time followed by 15 seconds of 'Flash Don't Walk' time (Figure 3.10).

Case 2:

Similar to Case 1, the transit bus is detected 38 seconds into Phase 1, but the checkout detector detects the bus 46 seconds into Phase 1.

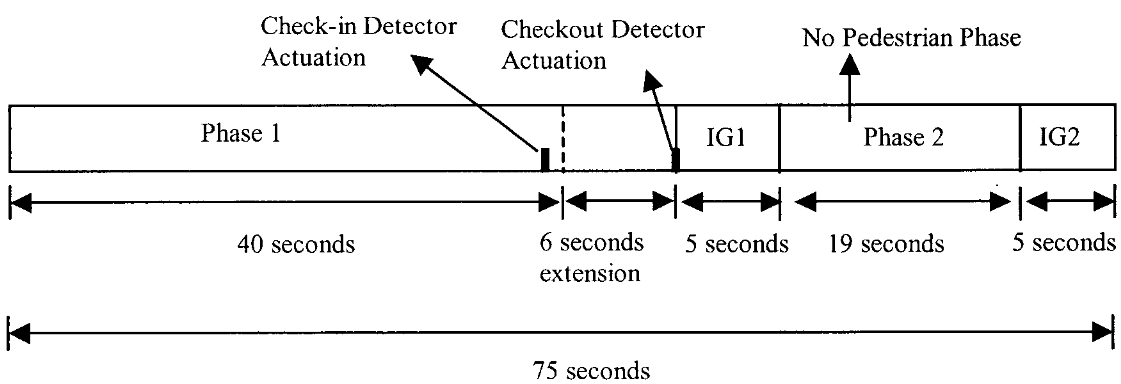

Figure 3.11. Signal Priority when Express Bus is detected during Phase 1, pedestrian phase for Phase 2 is not activated.

Since the following Phase 2 cannot accommodate a pedestrian "Walk" time of 5 seconds or more, the walk phase is cancelled until the next signal cycle. The logic is further explained in Figure 3.11.

Case 3:

The express bus is detected during the intergreen phase between phase 1 and phase 2. After detecting the express bus, phase 2 is shortened by 10 seconds. As the pedestrian phase could not be accommodated within the shortened cross street phase, it is not activated along with phase 2 (Figure 3.12). The surplus 10 seconds of green time from phase 2 is used by the following phase 1 or transit phase.

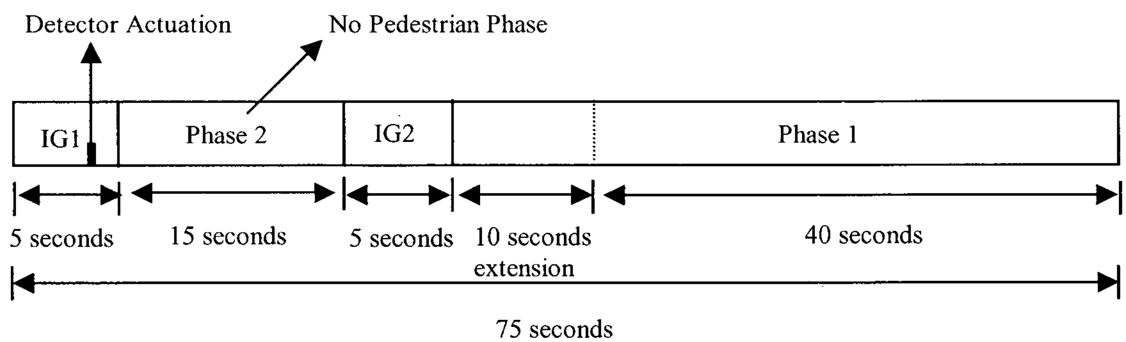

Figure 3.12. Signal Priority Logic when Express is detected during Intergreen Phase between Phase 1 and Phase 2, Pedestrian Phase for Phase 2 not activated.

Case 4:

The check-in detector is activated by an express bus during phase 2. In other words, the express bus is detected during the cross street pedestrian phase. In this case priority logic evaluates 2 conditions before granting priority,

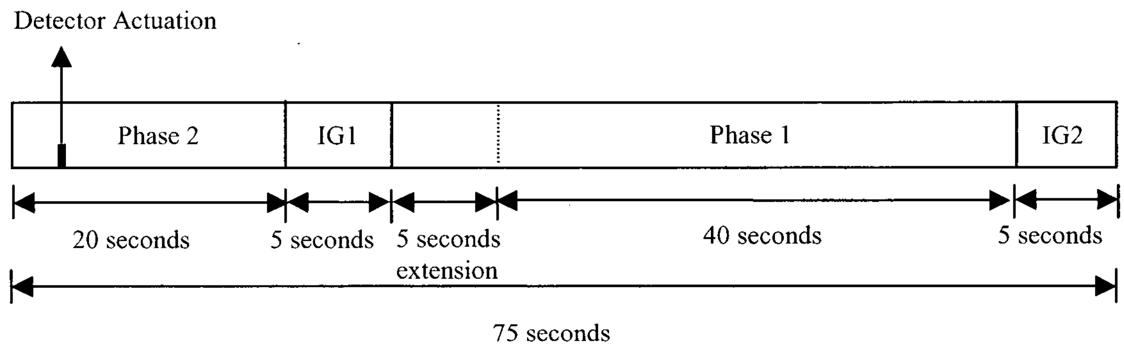

Figure 3.13. Signal Priority Logic when Express bus is detected during Phase 2

- Minimum 5 seconds of pedestrian 'Walk' time is available to the cross steet
- FDW time is available to cross street pedestrian traffic.

After the above two conditions are met, the priority logic cuts short cross street green phase and the green time available within Phase 2 is redistributed in favour of Phase 1 in the next signal cycle (Figure 3.13).

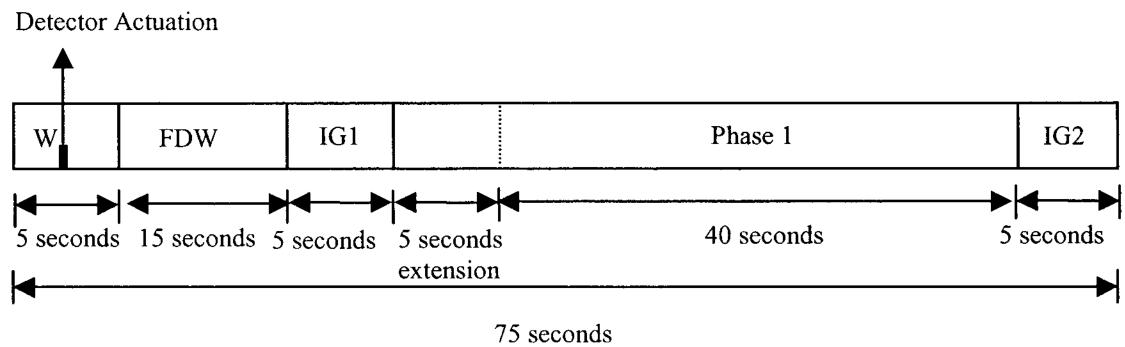

Figure 3.14. Pedestrian Logic when Express bus is detected during Phase 2.

According to Figure 3.8, Phase 2 allows 10 seconds of 'Walk' time and 15 seconds of FDW time. If the express bus is detected during Phase 2 then the maximum allowable green time truncation for the phase is 5 seconds (considering the condition for minimum 'Walk' time and FDW time). As shown in Figure 3.14 if the bus is detected during the first 5 seconds of Phase 2, the priority logic truncates the phase to 20 seconds from 25 seconds. In other words, the logic allows 5 seconds of 'Walk' time followed by FDW, before the start of the next phase. The following Phase 1 (priority phase for express bus) gets additional 5 seconds as part of the priority logic. If the bus were to be detected at the 6th second of Phase 2, then the priority logic would truncate the phase by 4 seconds. On the other hand, if the bus were to be detected after the 10th second of Phase 2, then no priority would be possible.

3.5. Simulation Framework

As mentioned earlier, owing to the large size of the study network, each simulation scenario was run for 4500 seconds with the initial 900 seconds being used as buffer time. Providing buffer time allowed the model to fill up the network and have it operating closer to real time conditions before recording data for MOEs. As a result, actual data collection was done for the final 3600 seconds of each simulation run.

VISSIM being a behaviour-based traffic simulation model is sensitive to changes in its parameters, including signal functioning logic. To attain comparative results between the base scenario and priority scenarios, the simulation model was run with 25 different random seeds each. Average values of MOEs obtained from these 25 runs were used to conduct TSP analysis.

From each simulation run, delay data files were compiled for four major cross streets along Granville Street: 12th Avenue, 16th Avenue, 25th Avenue and 49th Avenue (Figure 3.2). 12th Avenue and 16th avenue were chosen for the delay analysis in order to identify effects of priority on 2 major cross streets in close proximity of each other. 25th Avenue had a significant number of left turning vehicles while 49th Avenue consisted of mainly through traffic.

Cross street delay sections for the four intersections were configured to compile data at the end of each signal cycle. As intersections on Granville Street had 75-second cycles, delay sections were configured to record data at the end of each 75-second cycle. In addition, the sections accounted for the buffer time and respective offsets at each intersection. For instance, if an intersection had an offset of 21 seconds, then the delay sections at that intersection were configured to begin recording data after 921 seconds at every 75-second interval up to 4500 seconds.

Detector actuation, transit travel time, and signal phase data files were compiled in a similar manner along with the cross street delay data files for each study intersection.

3.6. Analysis Framework for MOEs

3.6.1. Travel Time

The test section of Granville Street was divided into 10 travel time segments (Figure 3.6) in either direction. Travel time segments allowed a closer analysis of major intersections along the corridor, especially the 4 study intersections. Average transit travel time for each segment was computed from the 25 travel time files generated from the 25 random seeds for each priority scenario. The data computed provided travel time for express and non-express buses running on Granville Street.

3.6.2. Average Priority Usage and Checkout Detector Actuations

The priority logic used along the Granville corridor was variable. As a result, priority times varied from 1 second to 10 or 15 seconds depending on the priority strategy being used (refer Table 3.1 for priority strategies). The average priority usage indicated effectiveness of the different TSP strategies being used (green extensions/red truncations) and length of priority time offered by these strategies to express buses in order to clear the downstream intersection.

Priority usage tables were set up in order to know the priority usage times at each intersection under study. These tables gave the average priority usage per simulation run. The tables classified priority usage times under three 5-second intervals i.e. 0-5 seconds, 5-10 seconds, and 10-15 seconds. For example, a green extension of 4 seconds for priority scenario 1 at 12th avenue was classified under 0-5 second priority interval. The count of successful green extensions between this 0-5 second interval was tabulated and expressed as percentage of the total number of successful priority calls for the intersection and respective priority strategy (based on the 25 runs).

This priority usage table gave a good indication of efficient priority times (in 5 second intervals) required for express buses to successfully clear the intersection. Further, this also enabled in the determination of the best strategy to be adopted based on green extension/red truncation times being used at each intersection.

Data for the priority usage table were obtained from the signal/detector record files generated by VISSIM for each simulation run. The files recorded the detector actuation and green time distribution for each phase of a signalized intersection. The data was compiled at every simulation time step. Priority signal stages within the record files were identified by the changed green time distributions as well as the checkout detector actuations.

Checkout detectors came into play during green extensions. The checkout detector table was set-up to give average checkout detector usage for each priority scenario based on checkout detector actuation counts. The table displayed the usability of checkout detectors at the study intersections. Detector usage at each study intersection was expressed as a percentage of the total successful green extensions for respective priority scenarios.

3.6.3. Delay

Average delay was used for the analysis based on data files compiled from 25 runs for each scenario at each intersection. The average delay for individual priority scenarios was calculated at the end of each signal cycle and then represented graphically for comparison.

3.6.4. Level of Service

From the average delay data level of service for the four cross streets under study were listed in the Level of Service Table.

3.7. Summary:

VISSIM was chosen as the traffic simulation program to analyze the Granville corridor and conduct the TSP study, since it allowed analysis of a wider range of MOEs. In addition to this, VISSIM provides flexibility in programming different priority strategies for signals by using its VAP feature.

The Granville model was set up using parameters obtained from the City of Vancouver and Translink. Signal priority logic were input into the simulation model with green extensions and red truncations being the two active TSP strategies imparting priority to the 98 B-Line express buses. The TSP control logic developed accounted for cross street pedestrian traffic while granting priority to express buses.

To justify the benefits offered by the TSP strategies; travel time, cross street delay, priority usage, level of service and checkout detector usage were set up as MOEs. Once the Granville model was set up, the base scenario was calibrated by comparing the field and simulated average transit times along Granville corridor. Following the network set up, simulation runs were conducted and data files were compiled. Analysis and results from these data files are discussed in the next chapter.

Chapter 4. Real Time Active Priority Analysis for 98 B-Line

4.1. Introduction

The main focus of this TSP (Transit Signal Priority) study was to obtain an efficient active priority methodology during peak hours. Such a methodology would not only increase the effectiveness of priority logic in terms of better transit travel time, but would also have minimal detrimental effects on cross street delays. The impacts of various active signal priority logics and their effectiveness during peak hour form the main focus of the feasibility analysis discussed and analyzed in this chapter.

4.2. Travel Time Analysis

Average transit travel times for each scenario are indicated in Table 4.1. Figures 4.1, 4.2, 4.3 and 4.4 show the change in travel time under each scenario for express and non-express buses in the peak and off-peak direction. Data used for plotting the graphs are indicated in Tables A-1 to A-4 in the appendix. Travel time improved for the B-Line express under all priority scenarios in the peak (North-South) traffic flow direction (Figure 4.1).

In the peak direction, priority scenario 1 showed a 6.2% improvement over the base scenario for express buses while scenario 3 offered the highest improvement of 7.5% (Table 4.1). Priority scenarios 2 and 4 offered improvements of 6% and 7.1% respectively. Amongst the 4 scenarios there was just a percentage difference in travel times with Scenario 3 offering the best results. In the off-peak direction, transit time improvements to express buses were quite similar for all priority scenarios (Figure 4.2).

Simulation Scenario	Direction of Traffic Flow	Total Length of Section (m)	Average B-Line Express Travel Time (sec)	Variance (sec^2)	Average Non-Express Bus Travel Time (sec)	Variance (sec^2)
Base Scenario	South-North	7099	857	448	899	210
Priority Scenario 1		7099	803	285	853	123
Priority Scenario 2		7099	806	281	874	250
Priority Scenario 3		7099	793	283	846	115
Priority Scenario 4		7099	796	305	876	278
Base Scenario	North-South	7644	842	907	832	3677
Priority Scenario 1		7644	800	373	797	552
Priority Scenario 2		7644	805	402	801	932
Priority Scenario 3		7644	792	380	804	551
Priority Scenario 4		7644	797	366	803	1005

Table 4.1. Table of Average Total Travel Time – All scenarios

Source: Tables A-1 to A-4 in Appendix.

From Fig 4.1 and 4.2, it can be seen that average express bus travel time was lower for the base scenario in the off-peak direction (North-South) as compared to the base scenario in the peak traffic flow direction (South-North). This was mainly due to lower traffic volumes, and smaller delays in the off-peak direction. As a result, improvements offered by the four TSP scenarios were comparatively lower for express buses running along the North-South Granville corridor. Another reason for lower improvements in the off-peak direction was owing to the low frequency of buses in that direction.

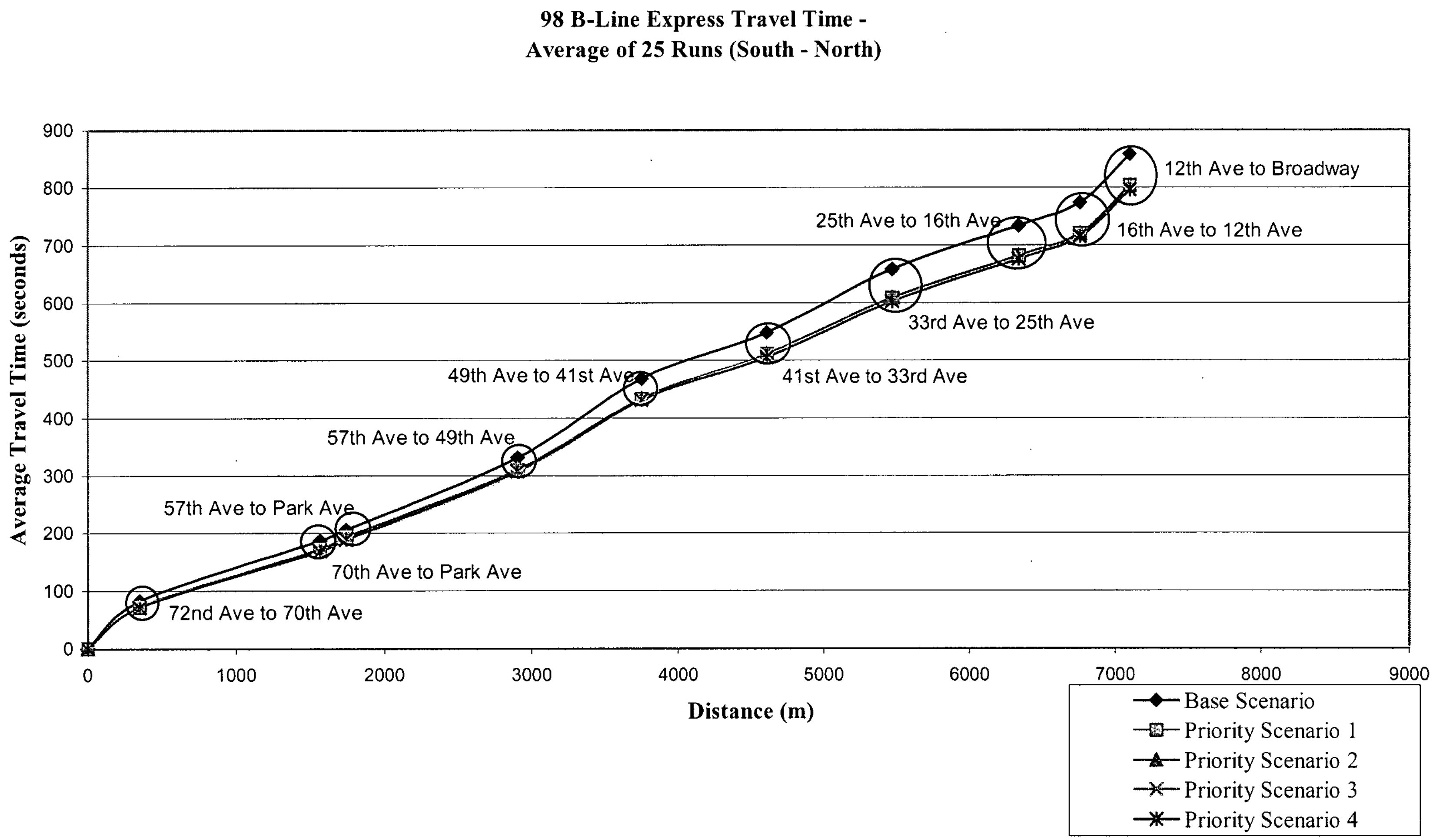

Figure 4.1. Travel Time comparison between Base and Priority Scenarios for 98 B-Line Express in the peak direction.

Source: Table A-1 in Appendix.

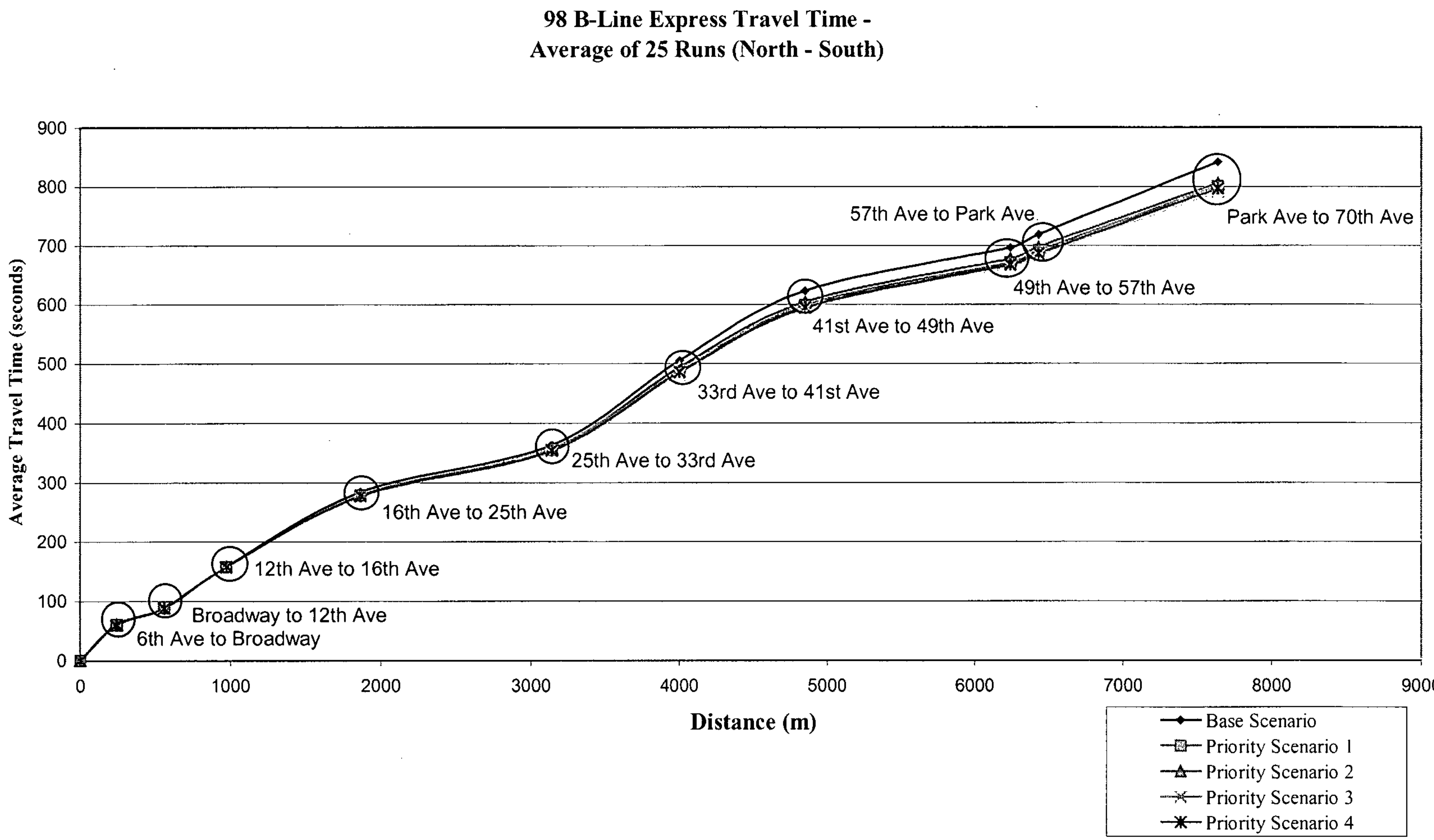

Figure 4.2. Travel Time comparison between Base and Priority Scenarios for 98 B-Line in the non-peak direction.

Source: Table A-2 from Appendix.

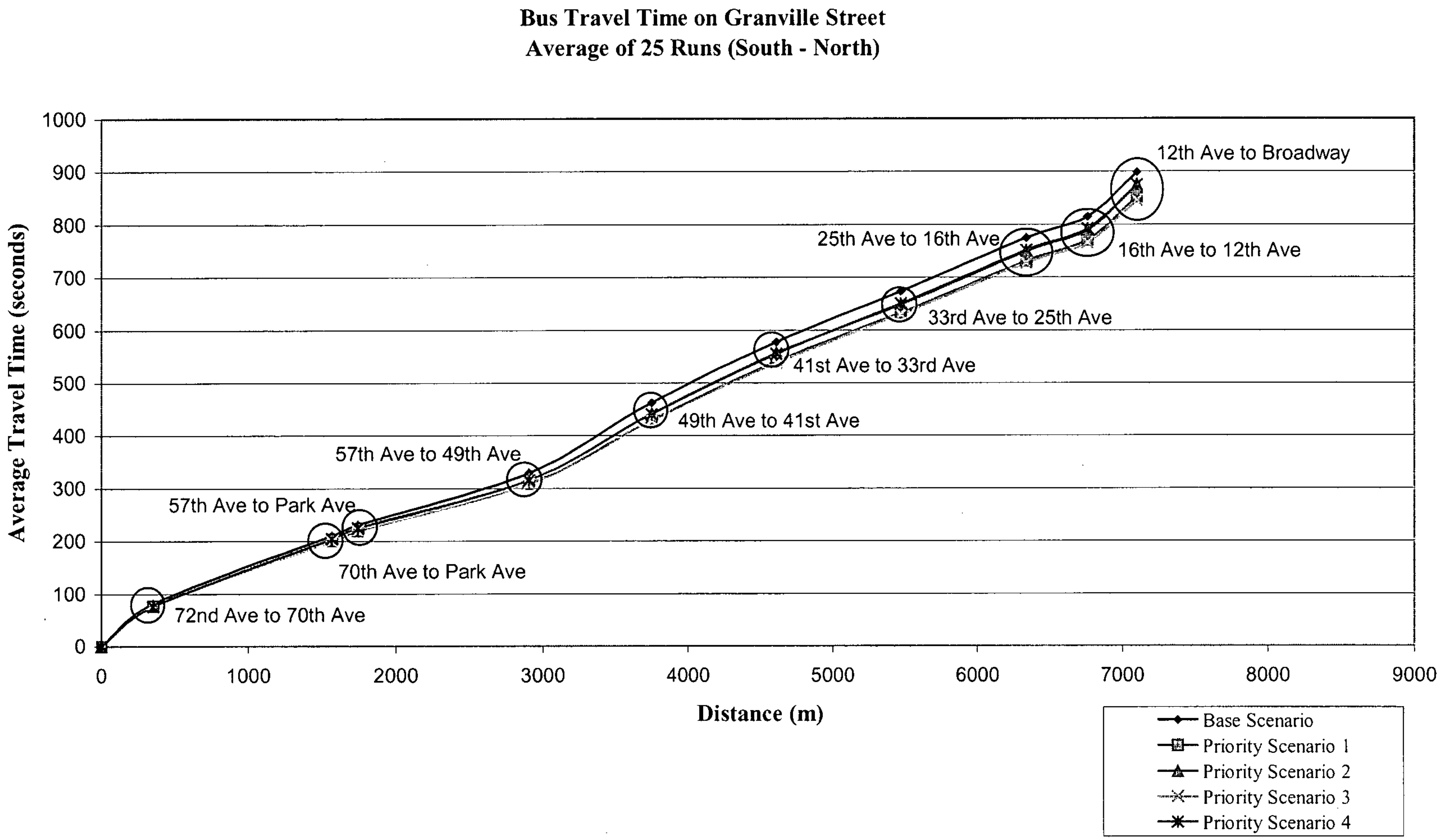

Figure 4.3. Travel Time comparison between Base and Priority Scenarios for non-express buses in the peak direction.

Source: Table A-3 in Appendix

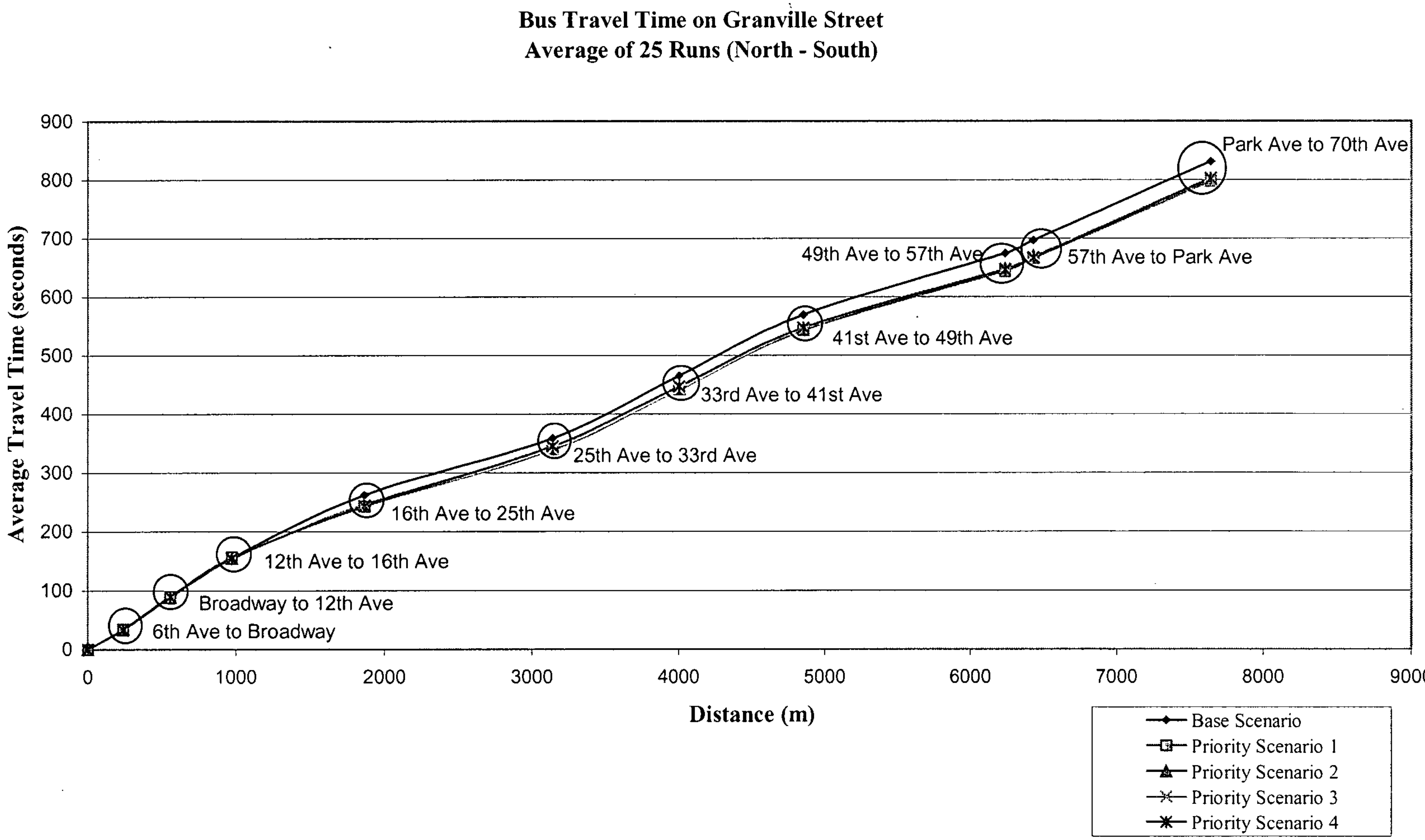

Figure 4.4. Travel Time comparison between Base and Priority Scenarios for non-express buses in the non-peak direction.

Source: Table A-4 in Appendix

According to Table 4.1, priority scenario 1 offered a 5% improvement in the express travel time while priority scenario 3 offered the highest improvement of 6%. A 4.4% improvement was observed by implementation of priority scenario 2, while there was a 5.3% improvement in travel time over the base scenario by implementing priority scenario 4.

Average non-express bus travel time showed best performance under priority scenario 3 in the peak direction. Scenario 3 offered a 5.9% improvement over the base scenario transit time with most improvements between 57th avenue and 33rd Avenue. This was a significant benefit for transit users, mainly because of the high frequency of non-express buses (around 31 – 34 buses per hour). Transit buses benefited between 57th and 16th Avenue since the intersections were spaced at sufficient distances, offering improved running time for buses. Improvement in travel time was slightly lower at 5.1% for priority scenario 1. Priority scenarios 2 and 4 showed minor improvements in travel time of 2.4% and 2.6% respectively.

In addition, the variance in average travel times of express as well as non-express buses for scenario 3 was lower as compared to the other scenarios. This meant that buses under scenario 3 had more consistent travel times in both the peak and off-peak traffic directions (Table 4.1). Amongst the different priority scenarios, scenario 2 and 4 showed greater variation in the average travel times. In order to get a deeper insight into the longer travel times and higher variance offered by scenarios 2 and 4, individual simulation runs were observed. A few of the runs offered better travel time improvements for scenarios 2 and 4 as compared to scenarios 1 and 3. However, some runs showed longer travel times for transit. In most of these cases, red truncations were found to be one of the causes for the longer travel times and higher variance. Since both scenarios 2 and 4 offered longer red truncations (with the 2 second 'Walk' time), the buses experienced comparatively greater delays at the downstream intersections due to the signals falling out of coordination.

Summary

Priority scenario 3 offered lowest transit times and improved consistency amongst the 4 priority strategies analyzed. It allowed up to 15 seconds of priority time while maintaining a minimum of 5 seconds of Walk time for cross street pedestrian traffic. Most improvements offered by scenario 3 were between 57th avenue and 33rd avenue. In other words, this strategy worked effectively when the signalized intersections were well spaced out allowing ample running time for the express buses. Improvements offered by scenario 1 though lower than scenario 3 were quite comparable.

Scenario 1 and 3 indicated an advantage over scenarios 2 and 4. Priority offered by scenarios 2 and 4 showed higher variance and lower improvements. This was mainly due to the usage of red truncations, which allowed the express bus to successfully clear the intersection offering priority, but caused greater disruptions in coordination at the downstream intersections as compared to scenarios 1 and 3. Analysis of the MOEs would give better understanding of the key parameters governing these improvements.

Individual travel time segments encompassing the 4 major intersections under study will be further analyzed in the following sections.

4.3. Intersection Analysis

Four intersections along the Granville corridor with respective cross streets were individually analyzed in this study: 12th Avenue, 16th Avenue, 25th Avenue, and 49th Avenue. 12th and 16th Avenues were in close proximity of each other and were chosen for the analysis to know the effects of the TSP strategies on closely spaced major intersections.

12th avenue and 16th avenue are major intersections in close proximity of each other and would exhibit the impacts of TSP strategies on closely spaced signalized intersections. 25th Avenue was selected since it had a significant number of left turning vehicles without a left-turn protected phase. Analysis of the intersection would give an insight into TSP impacts on cross streets with significant left turning volumes. 49th avenue had mainly through traffic along the cross street approach with well-spaced signalized intersections in either direction (33rd avenue in the north and 49th avenue in the south). This would allow the analysis to study TSP effects on well-spaced major intersections.

Each intersection was analyzed with respect to transit travel time improvements (North-South direction) and priority usage along the Granville corridor, and delays experienced by cross streets as a result of these priority calls. The intersections were analyzed for the four TSP scenarios using 25 random seeds for each scenario.

4.3.1. 12th Avenue and Granville Street:

Table 4.2 shows the average priority usage per simulation run and priority usage times based on 25 runs for the intersection of 12th avenue and Granville Street. The usage of priority was fairly low for the intersection of 12th Avenue. Among successful priority calls, green extensions were more frequent than red truncations. This was mainly due to the green time distribution at the intersection. The intersection offered a comparatively longer green phase (40 seconds) in the north-south transit direction as compared to the east-west green phase (26 seconds) during a normal 75-second signal cycle.

A major portion of this short cross street phase consisted of the FDW time. Owing to pedestrian crossing needs, the probability of successful priority calls during the cross street phase was thus reduced. In other words, once the cross street phase was active there was not enough surplus green time that could be offered to the transit phase. This is also justified by the red truncation priority usage at 12th avenue (Table 4.3). Within successful red truncations majority of the calls, offered surplus green time in the 6-10 second range, which could be offered only if the express buses were detected during the cross street intergreen phase.

Closer investigation of individual simulation runs indicated a few runs where priority was not used at all for all scenarios. The low priority usage can also be attributed to the close proximity of 12th avenue to major intersections along Granville Street, mainly Broadway in the north and 16th avenue to the south. 16th avenue boasted a comparatively higher priority usage with majority of them being green extensions (Table 4.4). If priority was offered as green extension at 16th avenue or Broadway then the bus would more than likely have to wait at 12th avenue. For instance, consider an express bus that uses green extensions to clear the intersection of 12th avenue. As the signals are coordinated, the cross street phase would be active at 12th avenue when the bus is detected by the upstream check-in detector. The east-west cross street phase being short and based on the priority logic being used (discussed in Case 3 and 4 of section 4.3), the probability of red truncation type of strategy being successfully used would be small (Table 4.2). This limitation resulted in the express bus having to wait at the 12th avenue intersection.

	Average Successful Priority Usage per Simulation run	Priority Usage Time					
		Successful Green Extension (%)			Successful Red Truncation (%)		
		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Priority Scenario 1	1.32	36%	36%	---------	3%	24%	---------
Priority Scenario 2	1.32	36%	36%	---------	3%	24%	---------
Priority Scenario 3	1.28	25%	44%	0%	3%	9%	19%
Priority Scenario 4	1.28	25%	47%	0%	3%	0%	25%

Table 4.2. Average priority usage 12th Avenue based on 25 simulation runs

Source: Tables A-7 to A-10 in Appendix.

TSP scenarios 3 and 4 used longer green extension times (between 6-10 seconds) as compared to scenarios 1 and 2. In case of red truncation scenarios 3 and 4 indicated higher usage of truncation times between 11-15 seconds.

Table 4.2 shows that during successful green extensions, the express buses cleared the intersection within 10 seconds of surplus green times. A closer analysis of each simulation run for individual priority scenarios indicated that on most occasions the green extension time provided was 7 seconds or less. Therefore, during green extensions the express buses generally cleared the intersection within 7 seconds.

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 2 (seconds)	Priority Scenario 3 (seconds)	Priority Scenario 4 (seconds)
B-Line Express						
16th Ave to 12th Ave (South - North)	423	40	39	39	37	40
Variance		17	17	17	12	17
Broadway to 12th Ave (North - South)	319	28	29	29	29	29
Variance		1	1	1	1	1
Non-express Bus						
16th Ave to 12th Ave (South - North)	423	40	40	40	39	41
Variance		6	6	7	6	7
Broadway to 12th Ave (North - South)	319	54	56	54	55	55
Variance		3	3	3	3	3

Table 4.3. Average travel time for express and non-express 12th Avenue (peak and non-peak direction)

Source: Tables A-1 to A-4 in Appendix.

Transit times for express as well as non-express buses in the peak and non-peak direction along with the variance (based on 25 runs) are shown in Table 4.3. Each travel time section used for transit time measurements extended from a major intersection downstream of 12th avenue to a point just upstream of 12th avenue in either direction (Figure 3.6). Table 4.3 showed minor improvements in travel times for express buses. The highest improvement to express bus travel time in the peak direction was that of 3 seconds (7.5%) offered by priority scenario 3.

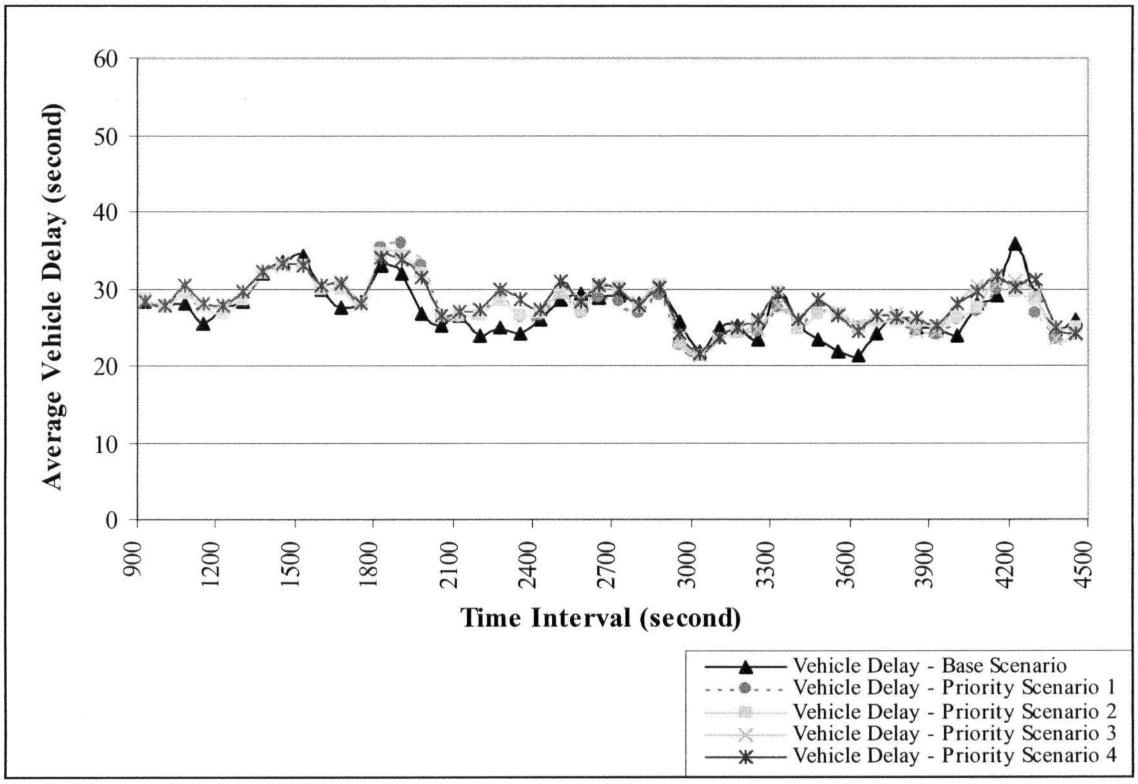

Figure 4.5. Vehicle delay Eastbound 12th Avenue - Average of 25 Random Seeds

Source: Table A-22 in Appendix

The variance in travel time remained the same for all scenarios in the peak as well as non-peak direction with the exception of express bus travel times for scenario 3 in the peak direction. Scenario 3 showed slightly lower variance in the express bus travel times.

The improvement for non-express buses was negligible in the peak direction for most scenarios. This can be attributed to the low priority usage in the peak as well as the non-peak direction.

As part of the 12th Avenue analysis, average delay data were compiled and plotted from 25 simulation runs for each scenario. Figure 4.5 shows the average delay at the end of each signal cycle for eastbound traffic at 12th avenue. Delay data used to plot the graphs are indicated in Table A-22 in the appendix. Average delay for cross street traffic rose for all priority scenarios in comparison to the base scenario. Among the 4 TSP scenarios delay did not vary significantly since in most instances the surplus green times provided by the scenarios were the same (Tables A-7 to A-10 in appendix). The graph shows that cross street delay increased whenever priority was offered to express buses.

Cross street delay deteriorated 1800, 2100, 3200 and 3900 seconds into the simulation (Figure 4.5). Successful priority calls generally occurred at one or a combination of these four time steps within individual random seeds under each priority scenario. On each of the four occasions, the intersection recovered to the base scenario delay within 4 signal cycles. The deterioration in vehicle delay was slightly higher for scenarios 3 and 4 as compared to scenarios 1 and 2. This was mainly due to higher priority time lengths used during scenarios 3 and 4 (Table 4.2).

Summary:

At the 12th Avenue intersection, simulations with priority scenarios 3 or 4 generally used longer green extension time, i.e. between 11-15 seconds. Longer usage of priority time was also observed for the red truncation strategy under the latter two scenarios. The deterioration to the cross street experienced during scenarios 3 and 4 although higher, allowed the intersection to recover within similar number of signal cycles as scenarios 1 and 2 (Figure 4.6). Thus offering priority at the intersection of 12th Avenue and Granville Street, did exhibit slight improvements in the express bus travel times without substantial deterioration to the cross street delay. Priority usage at 12th Avenue was affected by the close proximity of 16th avenue, which exhibited a comparatively higher priority usage (Table 4.4).

4.3.2. 16th Avenue and Granville Street

Priority usage despite being low showed relatively better usage at the 16th avenue intersection (Table 4.2 and 4.4) as compared to the 12th avenue intersection. Amongst successful priority calls, usage of green extensions was higher than red truncation. In other words, express buses had a higher arrival rate during the north-south express bus phase as compared to the east-west cross street phase. Table 4.4 indicates that, of the 4 priority scenarios used, scenario 4 exhibited highest priority usage.

The number of green extensions using more than 10 seconds of priority time was fairly low at the 16th avenue intersection. Within the 6-10 second interval, the length of priority time used for green extensions was mainly 8 seconds or less. In addition, there were a significant number of successful green extensions requiring a priority time of 5 seconds or less (Table 4.4). Red truncations for scenarios 3 and 4 showed prominent priority usage times that were between the 11-15 second interval. For scenarios 1 and 2, red truncations were primarily within the 6-10 seconds interval.

Average Successful Priority Usage per Simulation run	Priority Usage Time					
	Successful Green Extension (%)			Successful Red Truncation (%)		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
2.12	36%	26%	---------	13%	25%	---------
2.2	25%	29%	---------	11%	35%	---------
2.36	34%	27%	2%	15%	0%	22%
2.48	32%	23%	2%	6%	13%	24%

Table 4.4. Average priority usage at 16th Avenue based on 25 simulation runs

Source. Table A-11 to A-14 in Appendix.

Scenario 2 performed marginally better than the other scenarios in terms of express bus transit time improvements. However, with express and non-express buses inclusive, scenario 3 showed a better performance in terms of travel time with a lower variance. Express bus travel time improved by 4% for scenario 3. Improvements of 2.9% and 3.1% were offered to non-express buses by scenarios 1 & 3. Improvements to non-express buses offered by scenarios 2 and 4 were negligible (Table 4.5).

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 2 (seconds)	Priority Scenario 3 (seconds)	Priority Scenario 4 (seconds)
B-Line Express						
25th Ave to 16th Ave (South - North)	867	76	73	72	73	74
Variance		31	19	11	14	12
12th Ave to 16th Ave (North - South)	414	69	69	69	68	69
Variance		2	1	2	2	2
Non-express Bus						
25th Ave to 16th Ave (South - North)	867	101	98	101	97	101
Variance		8	9	9	8	9
12th Ave to 16th Ave (North - South)	414	66	66	66	66	66
Variance		3	4	3	3	4

Table 4.5. Average travel time for express and non-express buses at 16th Avenue (peak and non-peak direction)

Source. Tables A-1 to A-4 in Appendix.

Cross street delay behaviour profiles shown in Fig 4.6 were similar since the average priority usage was almost the same for all scenarios (Table 4.4). Priority offered at simulation second 2100 and 4300 showed higher deterioration for scenarios 3 and 4. However, in most cases, cross streets required similar number of signal cycles for all scenarios to recover to the base scenario cross street delay. Priority offered 2600 seconds into the simulation showed longer recovery times for scenario 3 and 4 as compared to scenarios 1 and 2. This is in accordance with Table 4.4, which indicates higher usage of red truncation between the 11 to 15 second interval (22% and 24% respectively) for the latter two scenarios. Thus for the 16th avenue intersection, although scenario 4 offered higher average priority usage and priority time lengths (Table 4.4), it was scenario 3 that most benefited the bus travel times upstream and downstream of the intersection (Table 4.5).

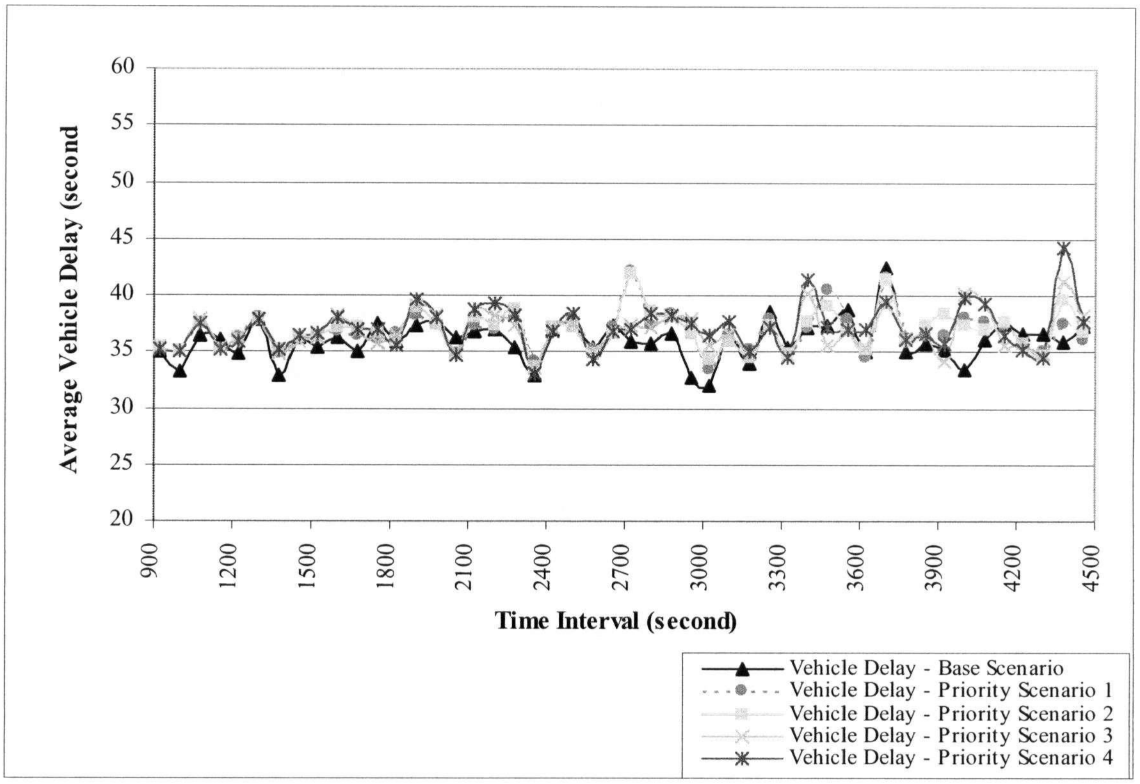

Figure 4.6. Vehicle delay at Westbound 16th Avenue - Average of 25 Random Seeds

Source: Table A-23 in Appendix.

Summary:

Within successful priority calls at the 16th avenue intersection, green extensions had a higher usage as compared to red truncations. Successful green extensions for all scenarios did not use the surplus green times up to the maximum limit (10 seconds for scenarios 1 and 2 and 15 seconds for scenarios 3 and 4). Majority of the red truncations were in the 6 to 10 second interval for scenarios 1 and 2 and the 11 to 15 second interval for scenarios 3 and 4. The low priority usage at the intersection did not impact cross street delay which showed recoverable delays on all priority calls (Figure 4.6) The time available between two successful priority calls provided ample opportunity for the cross streets delay to recover to the base scenario Similar to 12th avenue, base scenario green time distribution at 16th Avenue is skewed in favour of the North-South transit phase. This reduced the probability of successful priority calls during the cross street phase.

4.3.3. 25th Avenue and Granville Street

Unlike the prior intersections analyzed (12th avenue and 16th avenue), the 25th avenue intersection had almost equal distribution of green times between the transit and cross street phases. This increased the probability of successful red truncations during active cross street phases. Also, if the bus were to be detected during the early stages of the cross street phase, then the red truncation strategy would be in a position to accommodate the FDW time with the 5-second 'Walk' time and yet offer surplus green times to the transit phase up to the maximum limit (10 or 15 seconds). This was not possible at the earlier two intersections. Since 25th avenue could offer the maximum surplus green time of 10 and 15 seconds with the 5-second 'Walk' time, scenarios 2 and 4 were not used at 25th avenue.

The 25th avenue intersection showed a higher priority usage than 12th and 16th avenues (Tables 4.2, 4.4 and 4.6). For scenario 1, amongst successful priority calls, green extensions showed a slightly higher usage than red truncations. In most cases, the red truncations were offered within the 6-10 second interval. Within the interval, majority of the truncation lengths were close to 10 seconds. On the other hand, for green extensions, priority usage times were prominent within the 1 to 5 second as well as the 5 to 10 second interval (Table 4.6). Majority of the green extensions in the 6 to 10 second interval had usage times of 7 seconds or less.

Scenario 3, similar to scenario 1, showed a slightly higher usage of green extensions as compared to red truncations. A few of the successful green extensions (8%) indicated priority usage time between the 11 to 15 second interval (Table 4.6). Almost all of the successful red truncations were in the 11 to 15 second interval. The higher success rate for priority was mainly due to the distribution of green times to the different phases within each signal cycle. Since the cross street green time formed a good portion of the entire signal cycle the probability of detecting express buses during the cross street phase and successfully offering them priority was higher.

	Average Successful Priority Usage per Simulation run	Priority Usage Time					
		Successful Green Extension (%)			Successful Red Truncation (%)		
		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Priority Scenario 1	3.64	25%	35%	---------	0%	40%	---------
Priority Scenario 3	3.68	28%	21%	8%	1%	0%	42%

Table 4.6. Average priority usage at 25th Avenue based on 25 simulation runs

Source: Tables A-15 to A-18 in Appendix.

Travel times were in favour of express buses at 25th avenue showing noticeable improvements for all scenarios (Table 4.7). This observation was in close agreement with the average priority usage shown in table 4.6. Scenario 1 offered an 11% decrease in express bus travel times along the peak traffic direction as compared to the base scenario. In the off peak direction express buses experienced a 4.7% improvement under the same scenario. Scenario 3 offered express bus transit time reductions of 13.6% and 6.3% in the peak and off-peak direction respectively. Since signalized intersections were further apart upstream and downstream of 25th Avenue (850-900 m), there was a higher variance in bus travel times under the base scenario. This variance was significantly reduced when the priority scenarios were implemented thereby bringing more consistency to express and non-express bus travel times, both in the peak as well the non-peak direction.

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 3 (seconds)
B-Line Express				
33rd Ave to 25th Ave (South-North)	860	110	98	95
Variance		87	19	19
16th Ave to 25th Ave (North - South)	894	127	121	119
Variance		233	78	44
Non-express Bus				
33rd Avenue to 25th Avenue (South-North)	860	96	92	92
Variance		27	17	23
16th Ave to 25th Ave (North - South)	894	108	87	90
Variance		2667	125	125

Table 4.7. Average travel time for express and non-express buses at 25th Avenue (peak and non-peak direction)

Source: Tables A-1 to A-4 in Appendix

Non-express buses benefited from scenarios 1 and 3 as well. Both scenarios indicated an improvement of 4.2% in the peak traffic direction for non-express buses. In the off-peak direction the buses experienced significant improvements of 19.4% and 16.7% for scenarios 1 and 3 respectively. As indicated earlier, the average number of non-express buses in the peak direction during the length of the simulation was close to 36 in comparison to the 10 buses in the off-peak direction. Thus, the higher improvement in the off-peak direction was offered to a comparatively lower frequency of non-express buses.

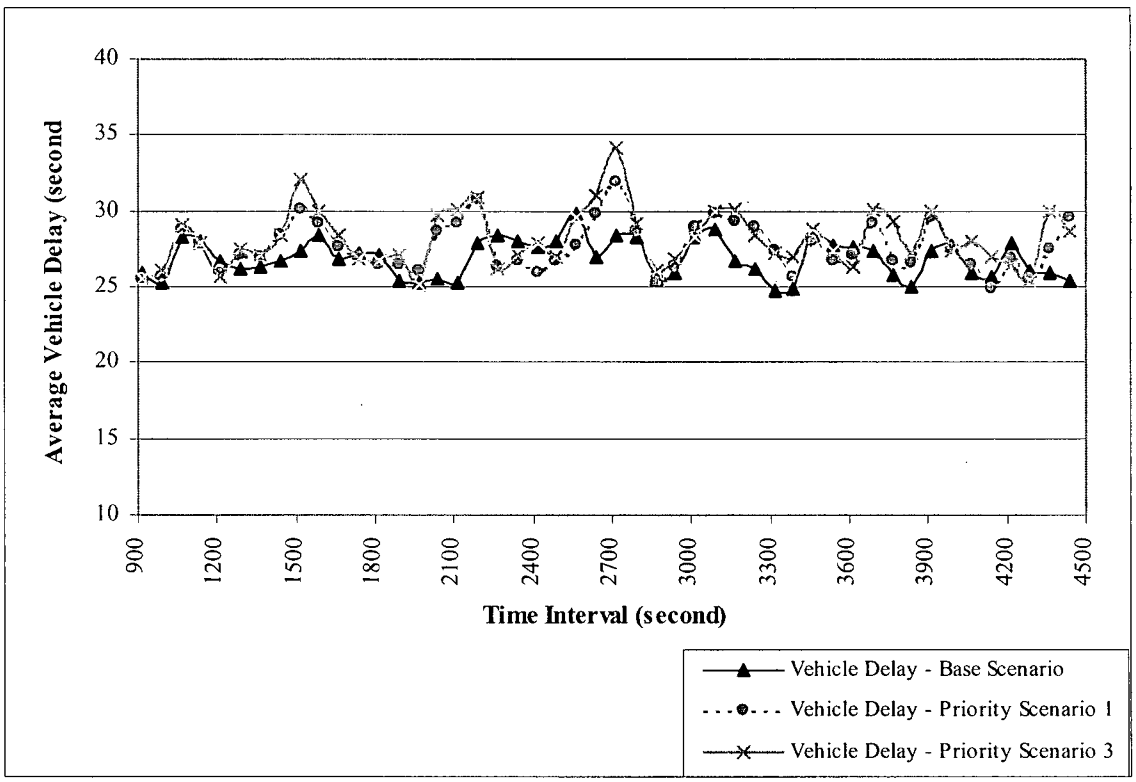

Figure 4.7. Vehicle delay at Westbound 25th Avenue - Average of 25 Random Seeds

Source: Table A-24 in Appendix.

Delay profiles were quite similar for scenarios 1 and 3 (Figure 4.7 and 4.8) along eastbound and west bound 25th avenue. The delay was more prominent with each successful priority call, especially for the westbound approach. Similar behaviour was noticed for the eastbound cross street traffic. At simulation second 1200, the delay experienced by vehicles along westbound 25th avenue indicated a recovery within 6 signal cycles for scenario 1 as well as 3 (Figure 4.7 and 4.8). Delay deterioration on other occasions usually recovered within 4 to 5 signal cycles for the eastbound as well as the westbound traffic.

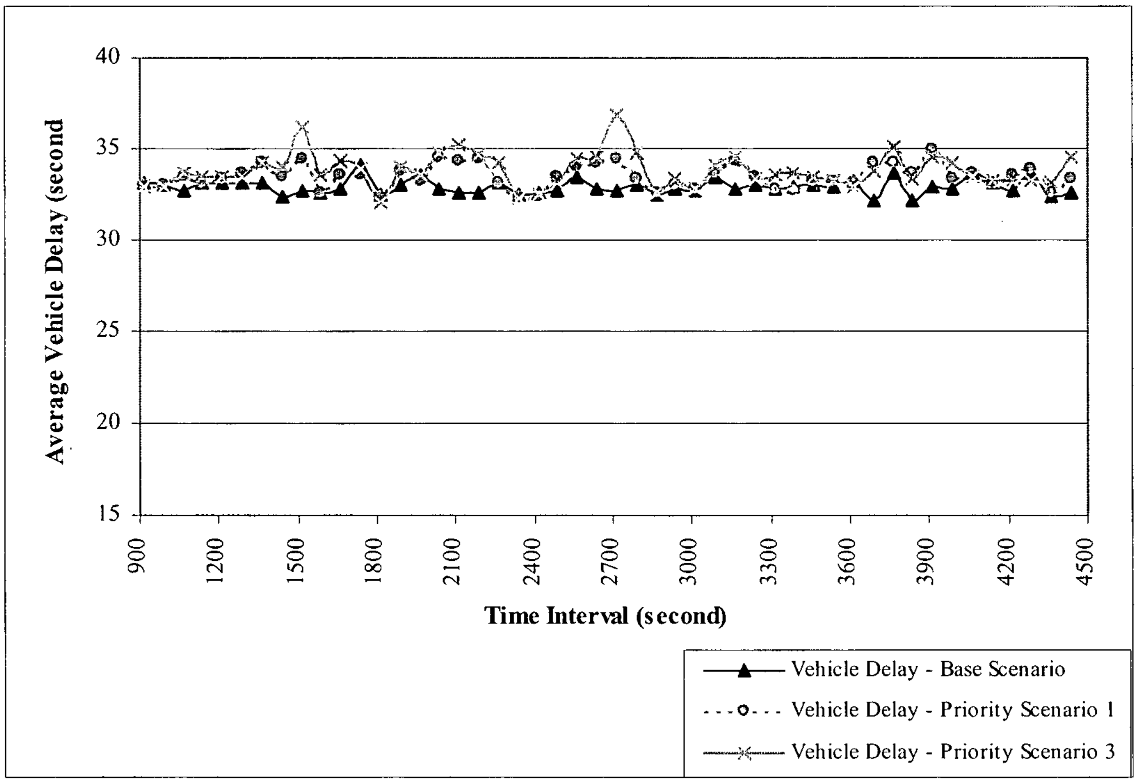

Figure 4.8. Vehicle delay at Eastbound 25th Avenue - Average of 25 Random Seeds

Source: Table A-24 in Appendix.

Summary:

Overall, priority was a success for the 25th avenue intersection in terms of improvement to express bus transit time and priority usage. Scenario 3 proved to be the better of the 2 strategies since it offered better and more consistent travel time improvements along the Granville corridor coupled with higher priority usage and longer priority time lengths. This improvement was achieved without significant impact to cross street delays through green extensions and red truncations. Majority of the successful green extensions were below 10 seconds. Successful red truncations were generally within the 6-10 second (scenario 1) or 11-15 second (scenario 3) interval. Owing to this, a green extension strategy allowing a maximum of 10 seconds along with a 15 second red truncation strategy might warrant an efficient performance for the intersection of 25th avenue as a whole.

Vehicles along 25th avenue did experience delays from the priority calls. All these delays recovered before the next priority call. The intersection indicated recoverable delays inspite of higher left turning volumes as compared to other cross streets along the Granville corridor. One major aspect governing this recovery was the sufficient gap between successful priority calls.

4.3.4. 49th Avenue and Granville Street

The 49th avenue intersection also exhibited a better priority usage as compared to the 16th and 12th avenue intersections. Amongst successful priority calls 49th avenue showed higher usage of red truncations as opposed to the green extension strategy for all

	Average Priority Usage per Simulation Run	Priority Usage Time					
		Green Extension			Red Truncation		
		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Priority Scenario 1	3.16	24%	19%	---------	29%	28%	---------
Priority Scenario 2	3.2	25%	19%	---------	29%	28%	---------
Priority Scenario 3	3.2	21%	18%	0%	28%	19%	15%
Priority Scenario 4	3.28	22%	15%	0%	26%	24%	15%

Table 4.8. Average priority usage at 49th Avenue based on 25 simulation runs

Source: Tables A-19 to A-22 in Appendix

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 2 (seconds)	Priority Scenario 3 (seconds)	Priority Scenario 4 (seconds)
B-Line Express						
57th Avenue to 49th Avenue (South - North)	1160	125	117	118	116	119
Variance		23	16	20	19	16
41st Ave to 49th Ave (North - South)	850	117	109	110	110	109
Variance		34	14	20	15	15
Non-express Bus						
57th Avenue to 49th Avenue (South - North)	1160	98	89	89	87	90
Variance		20	7	21	7	16
41st Ave to 49th Ave (North - South)	850	104	100	102	102	100
Variance		47	49	51	47	54

Table 4.9: Average travel time for express and non-express buses at 49th Avenue (peak non-peak direction)

Source: Tables A-1 to A-4 in Appendix

TSP scenarios (Table 4.8). Most of the successful red truncations were in the 1 to 5 second and 6 to 10 second interval. For green extensions, the frequency of successful priority calls was higher in the 1 to 5 second interval. Of the successful green extensions in scenarios 3 and 4, none required extended green times higher than 10 seconds for any of the scenarios.

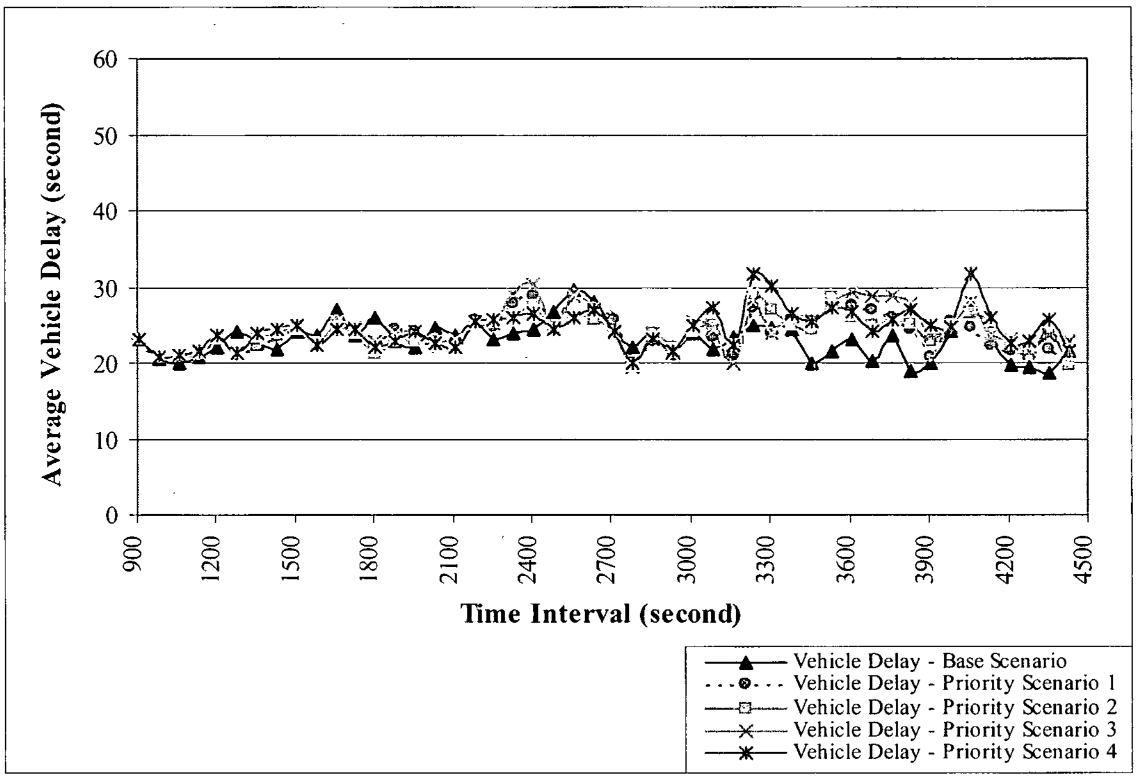

Figure 4.9. Vehicle delay at Westbound 49th Avenue - Average of 25 Random Seeds

Source: Table A-25 in Appendix.

Transit time for express buses decreased at the intersection of 49th avenue owing to higher priority usage (Table 4.9). Travel time improvements for the B-Line express ranged from 4.8% (scenario 4) to 7.2% (scenario 3) in the peak traffic direction. Non-express buses experienced improvements ranging from 8.2% (scenario 4) to 11.2% (scenario 3). In the off-peak directions express buses experienced reduced travel times of approximately 6% for all scenarios.

Once again, scenario 3 offered the best travel time benefits for express buses in the peak traffic direction (Table 4.9). Non-express buses too exhibited comparatively lower travel times upon the implementation of scenario 3. There was not much change in the variance for the bus travel times. The base scenario itself had a low variance indicating that transit travel time was quite consistent upstream and downstream of the intersection.

All 4 TSP strategies showed noticeable impacts on cross street delay (Figure 4.9). Delay deteriorations at 49th avenue were almost similar for all priority scenarios (Figure 4.9). Every successful priority call at the intersection allowed the cross street to recover to the base scenario delay before the next priority was offered. Delay usually recovered within 3 to 4 signal cycles. Priority given at simulation second 3400 was the only exception. Recovery to the base delay profile at this time step took 7 to 8 signal cycles. Majority of the red truncations with priority times between the 11 to 15 second interval occurred during this part of the simulation. Also, scenario 3 showed a higher deterioration in delay at simulation second 3400 amongst the priority scenarios analyzed.

Summary:

Implementation of transit priority at the 49th avenue intersection offered substantial opportunities for improvement in express bus travel times through higher number of successful priority calls. Although the priority times used were shorter as compared to the 25th avenue intersection (Table 4.6 and 4.8), it still resulted in significant improvements to the express as well as the non-express bus travel times.

The deteriorations in delay during the different priority scenarios were recoverable to the base scenario inspite of the higher frequency of priority calls. Red truncations that were in the 11 to 15 second interval, caused a higher deterioration to the cross street delay which was still recoverable. As a whole, priority implementation at 49th avenue was in favour of the express buses without lasting impacts on cross street traffic.

4.4. Level of Service (LOS)

Most cross streets analyzed during this study were operating at LOS D, with an exception of 49th Avenue eastbound, which operated at LOS C (Table 4.10). Intersections did not exhibit any change in the LOS. However, the average delay increased within the same LOS. Average delay for 12th avenue eastbound, 16th avenue westbound, 25th avenue eastbound, and 25th avenue westbound showed minor increments under the different priority scenarios. Average delay increased by two seconds at 49th avenue eastbound for scenarios 3 and 4. This deterioration is justified based on the higher usage of longer priority times under these two scenarios at the intersection of 49th avenue.

Although priority usage was comparatively higher for the intersections of 25th and 49th avenue, the cross streets did not experience much deterioration in average cross street delays. This indicated that the intersections could accommodate a higher priority usage with recoverable delays and amenable LOS.

Delay Section	Base Scenario		Priority							
			Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Average Delay	LOS*	Average Delay	LOS*	Average Delay	LOS*	Average Delay	LOS*	Average Delay	LOS*
12th Ave EB	27	D	28	D	28	D	28	D	28	D
16th Ave WB	36	D	37	D	37	D	37	D	37	D
25th Ave EB	33	D	33	D	-----	-----	34	D	-----	-----
25th Ave WB	27	D	28	D	-----	-----	28	D	-----	-----
49th Ave EB	23	C	24	C	24	C	25	C	25	C

Table 4.10. Level of Service for the 4 cross streets analyzed.

Source: Tables A-22 to A-25 in Appendix

*Level of Service (LOS) classification for delays:

LOS A: Delays less than 5.0 seconds per vehicle

LOS B: Delays between 5.1 to 15 seconds per vehicle

LOS C: Delays between 15.1 to 25 seconds per vehicle.

LOS D: Delays between 25.1 to 40 seconds per vehicle

LOS E: Delays between 40.1 to 60 seconds per vehicle.

LOS F: Delays above 60 seconds per vehicle.

4.5. Checkout Detector Usage

Checkout detector usage was an important aspect of this study since this would not only ensure efficient usage of green extensions but would also facilitate lower impact to cross street delays. According to Table 4.11, majority of successful green extensions utilized the checkout detector for all priority scenarios at respective study intersections. As a result, the recovery to the base scenario delay was within fewer signal cycles for the TSP scenarios. 25th Avenue showed lower checkout detector usage as compared to the other intersections, since there were a few instances when priority times were used up to the maximum assigned limit (Table 4.6).

	12th Avenue	16th Avenue	25th Avenue	49th Avenue
Priority Scenario 1	100%	100%	85%	100%
Priority Scenario 2	100%	100%	---------	100%
Priority Scenario 3	100%	100%	94%	100%
Priority Scenario 4	100%	100%	---------	100%

Table 4.11. Checkout detector usage during green extensions.

Source: Tables A-7 to A-20 in Appendix

Based on Table 4.11 and the signal distribution observed for each simulation run within individual priority scenarios for 25th Avenue, it was found that on a few occasions the express bus utilized the entire 10 or 15 seconds provided and still failed to clear the intersection. The checkout detector was ineffective in such cases (Tables A-15 and A-16 in Appendix). As a whole, the checkout detector usage was significant for all intersections analyzed.

4.6. Priority Analysis with Uncoordinated Signal Logic

As mentioned in earlier sections, all signals along the Granville corridor were coordinated to facilitate lower travel times for peak hour traffic. The TSP strategies developed offered priority to transit without significantly impacting the coordination between signals. This control logic led to a few instances, especially during green extensions; where the express bus successfully cleared the intersection offering green extension but it encountered the cross street phase upon arrival at the downstream intersection. Buses arriving towards the latter part of the cross street phase could not warrant a red truncation at the downstream intersection since the pedestrian flash don't walk phase was already active and could not be shortened.

The main idea behind analyzing the uncoordinated logic was to capture any additional improvements in bus arrival times at downstream intersections, which would further reduce transit travel times. The logic might facilitate buses arrivals at the downstream intersections during the transit phase or earlier part of the cross street phase to allow the cross street phase reduction through red truncations.

Scenario 3 was chosen as the strategy to offer priority since it showed the best results with the coordinated logic. Express bus travel time was used to analyze the effectiveness of this strategy.

4.7. TSP strategy using Uncoordinated Signals

For uncoordinated logic all offsets along the Granville corridor were removed. The constraint to maintain a 75 second signal cycle while offering priority was also neglected. If the express bus was detected during the latter part of the transit phase then the TSP logic would offer priority through green extensions. However the surplus green time used by the transit bus to clear the intersection would not be deducted from the following cross street phase. The cross street phase would get its allotted green time without any deductions. At the same time, during red truncations the truncated green time from the cross street phase would not be given to the transit phase.

4.8. Travel Time Analysis for Uncoordinated Logic:

Average travel times for B-Line express buses were 2.2% higher under the base scenario when signals were uncoordinated (Tables 4.1 and 4.12).

Simulation Scenario	Direction of Traffic Flow	Length of Section (m)	Average B-Line Express Travel Time (sec)	Variance (sec^2)	Average Bus Travel Time (sec)	Variance (sec^2)
Base Scenario	South-North	7099	876	546	899	584
Priority Scenario3		7099	844	523	877	414
Base Scenario	North-South	7644	883	536	832	1293
Priority Scenario 3		7644	832	466	804	1154

Table 4.12. Table of Average Total Travel Time – Uncoordinated Signal Logic

Source: Tables A-5 and A-6 in Appendix.

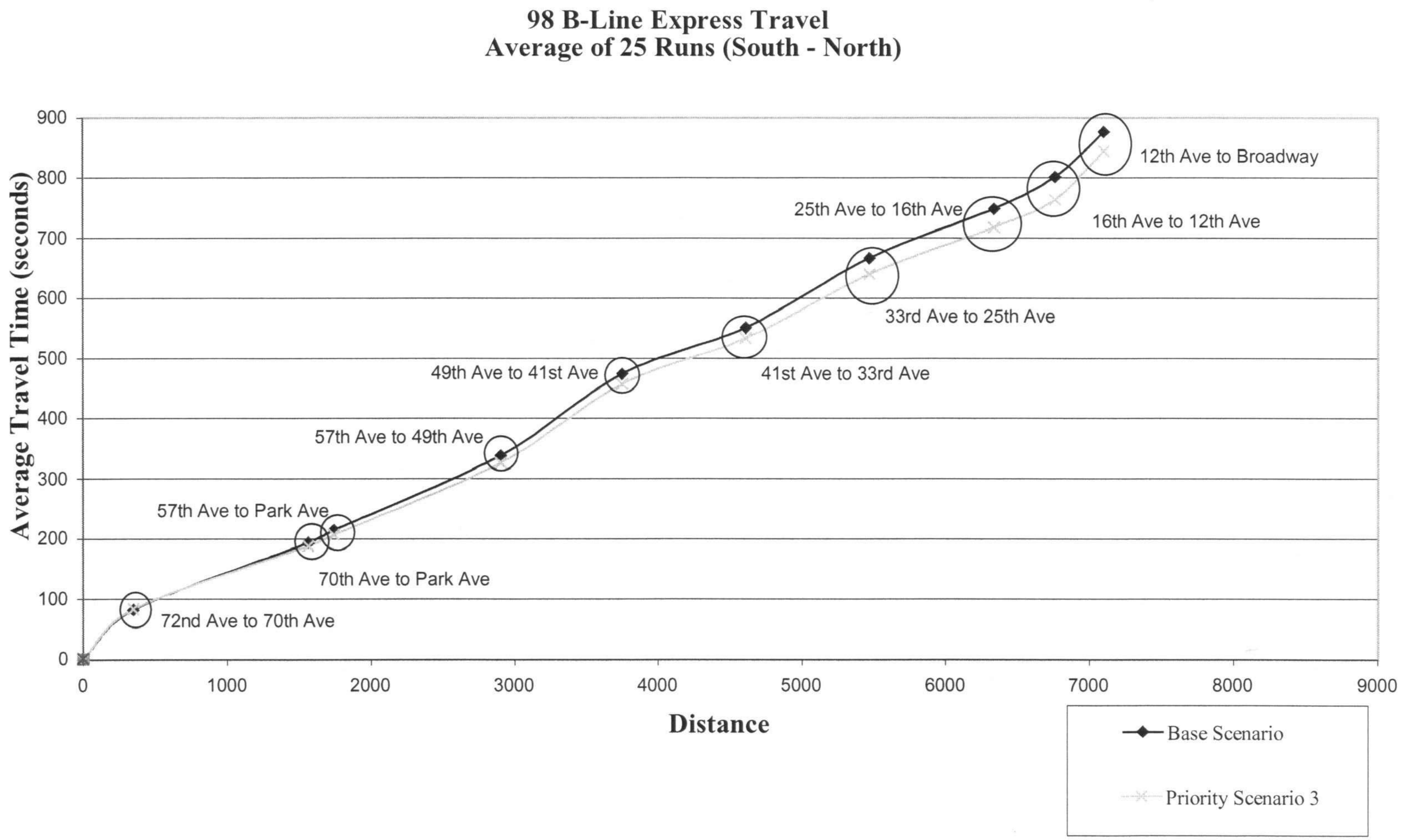

Figure 4.10. Travel Time comparison for B-Line Express (Base and Priority Scenario 3 – Uncoordinated) in the peak direction.

Source: Table A-5 in Appendix

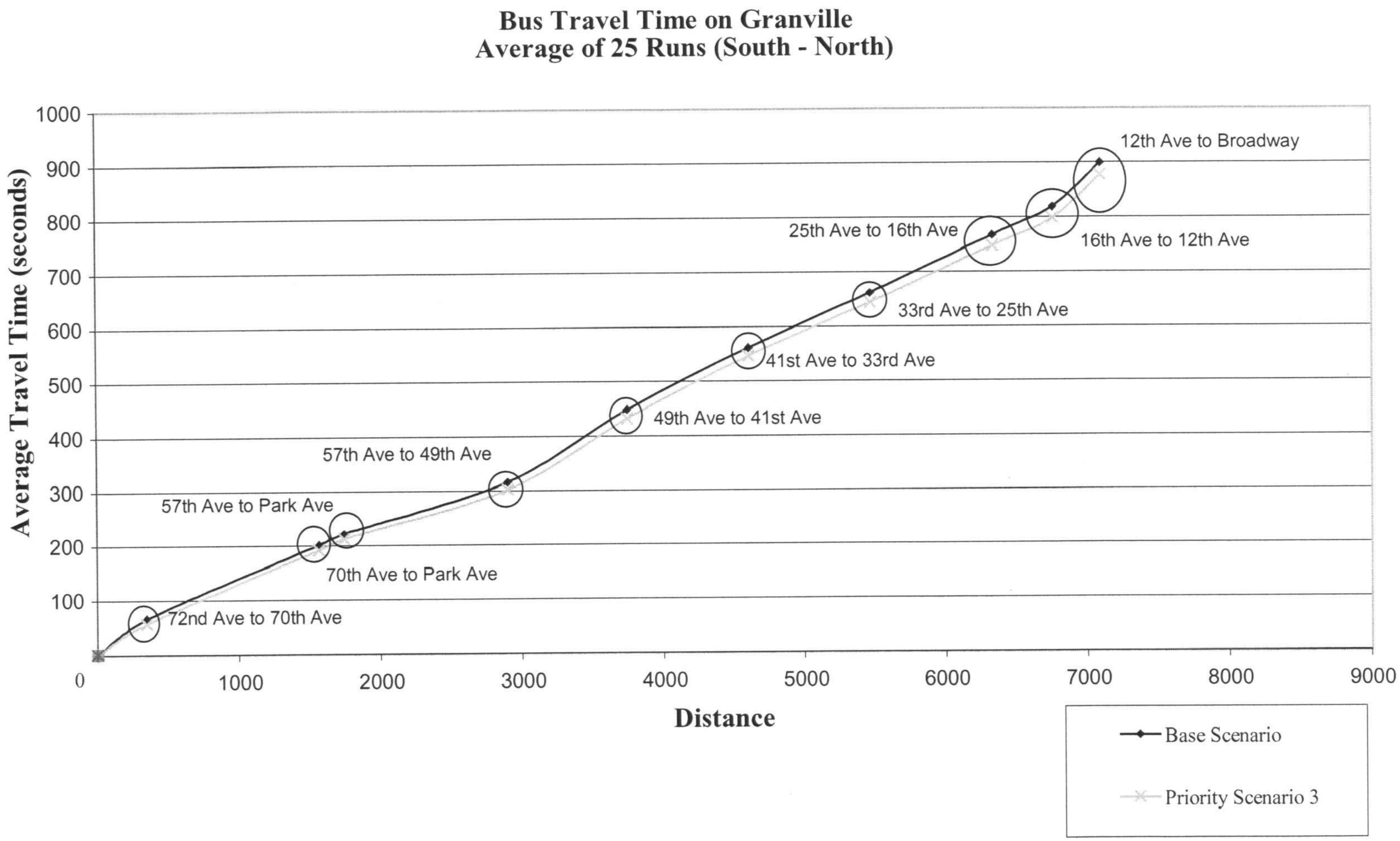

Figure 4.11. Travel Time comparison for Non-Express buses (Base and Priority Scenario 3 – Uncoordinated) in the peak direction.

Source: Table A-6 in Appendix

Transit time for express buses improved by 3.7% in the peak direction (Table 4.12). This improvement was still lower than the one offered with the coordinated logic (Table 4.1). Average travel time for express buses in the off-peak direction showed an improvement of 5.7%.

Non-express buses experienced travel time improvements of 2.5% and 3.4% in the peak and non-peak directions respectively. For the base scenario, non express bus travel times were the same in the peak direction with and without signal coordination. However priority scenario 3 offered better improvements for non-express buses with coordination between the signals (Table 4.1).

Individual travel time sections along major intersections did not show higher improvements in transit time with the uncoordinated logic (Figure 4.10 and 4.11). Overall transit travel time thus deteriorated when the signals were not in coordination. In order to see the effect of priority on individual uncoordinated intersections, 25th was analyzed for cross street delay as well as transit travel time. The lower improvements offered by scenario 3 were complemented by a higher variance in travel time for express as well as non-express buses.

4.9. Intersection Analysis

4.9.1. 25th Avenue and Granville Street

Delay and travel time data were compiled for the intersection of 25th avenue as it exhibited a higher frequency of priority usage (Table 4.6) coupled with consistent cross street delays (Figure 4.7) under the coordinated logic. If there were any additional benefits by using the uncoordinated they would be captured by the MOEs compiled for 25th Avenue.

	Average Priority Usage per Simulation Run	Priority Usage Time					
		Green Extension			Red Truncation		
		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Priority Scenario 3	2.88	28%	33%	10%	10%	0%	19%

Table 4.13. Average priority usage at 25th Avenue (Uncoordinated) based on 25 simulation runs

Source: Table A-21 in Appendix

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 3 (seconds)
B-Line Express			
33rd Ave to 25th Ave (South - North)	860	115	106
Variance		128	58
16th Ave to 25th Ave (North - South)	894	131	126
Variance		300	55
Non B-Line Express			
33rd Avenue to 25th Avenue (South - North)	860	100	97
Variance		72	71
16th Ave to 25th Ave (North - South)	894	90	95
Variance		2201	114

Table 4.14. Average travel time for express and non-express buses at 25th Avenue (Uncoordinated)

Source: Table A-6 and A-7 in Appendix

Priority usage of 2.88 at the 25th avenue intersection was comparatively lower for priority scenario 3 with the uncoordinated logic (Table 4.13). The priority usage table shows that green extensions were used more often than red truncations. Majority of the green extensions were within the 6-10 second interval. Only 19% of the red truncations were within the 11-15 second interval as opposed to the 42% with the coordinated signals (Table 4.6).

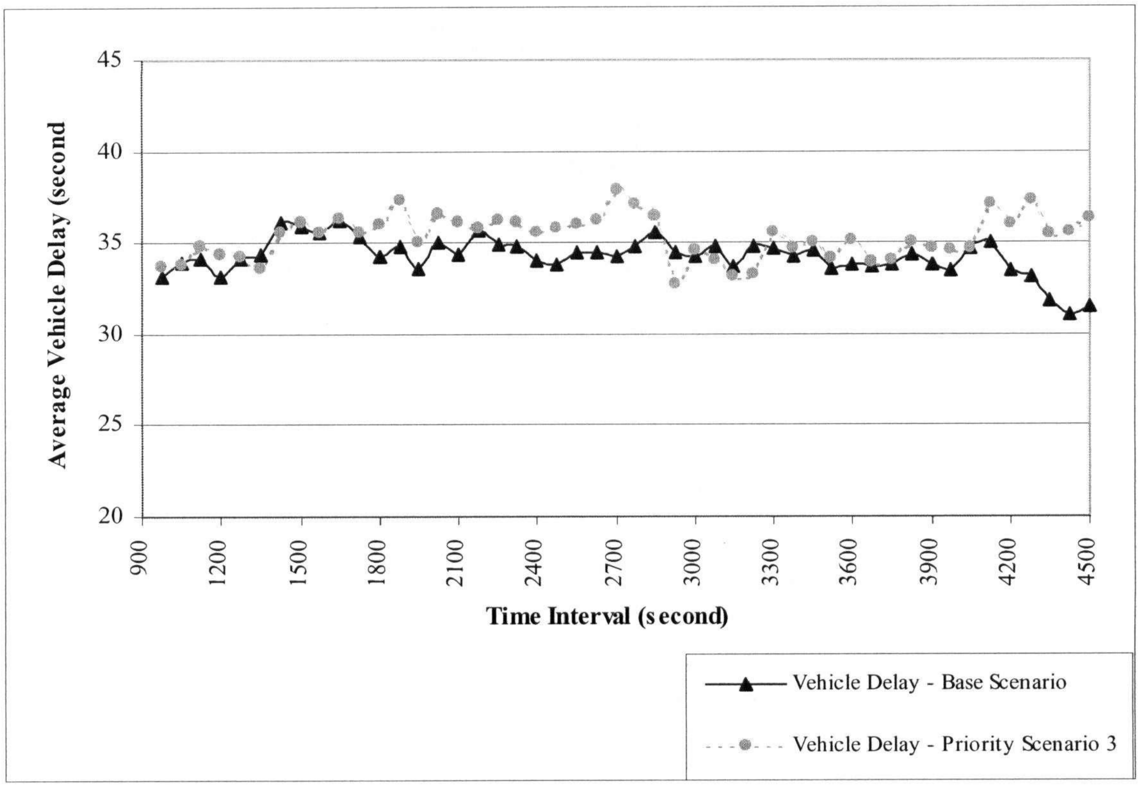

Figure 4.12. Vehicle delay at Westbound 25th Avenue - Average of 25 Random Seeds

Source: Table A-26 in Appendix

Based on the priority usage, travel time improvements for buses despite being noticeable at the 25th avenue intersection, were lower with uncoordinated signals. In the peak direction, express buses showed a 7.8% improvement in transit time. Transit time for non-express buses improved by 3% in the same direction. The travel time improvements with signals working in coordination were higher, offering a decrease of 10.4% and 5.2% in the peak direction for express and non-express buses respectively (Table 4.8). In the off-peak direction express bus travel time experienced a 3.8% improvement while transit time deteriorated for non-express buses (Table 4.15). The variance in transit travel time (express and non-express) in the peak as well as non-peak directions were almost the same or higher for the base and priority scenarios during the uncoordinated logic as compared to the coordinated logic.

Similar to travel time, base scenario cross street delay in the westbound direction increased without the coordinated logic (Figure 4.8 and 4.13). On the other hand, cross street delays in the eastbound direction showed a reduction under the base scenario with uncoordinated logic. Average delay reduced to 18 seconds in the eastbound directions without coordination as compared to 33 seconds with coordination (Table A-23 and A-26 in Appendix). Since delay increased along the westbound approach, the data was analyzed graphically in order to identify deteriorations caused by priority.

Priority offered at simulation second 2100 caused delays that did not recover till simulation second 2800 along the westbound approach. Delay for this approach needed more time to recover to the base scenario inspite of low priority usage (Fig 4.8 and 4.13).

Summary:

From the 25th avenue intersection analysis with uncoordinated logic it can be inferred that TSP along the Granville corridor worked in favour of transit when signals were coordinated. Coordination fetched better results in terms of priority usage, transit travel time, and timeliness. Cross street delays indicated higher deterioration under the uncoordinated logic for the westbound approach. In addition, the deterioration in delay needed longer recovery times.

There was significant reduction in the westbound delay when signals were uncoordinated. With improved TSP usage the reduced delay would work favour of the intersection. However, benefits from the uncoordinated signals may be limited due to increased travel times for non-transit vehicles along the transit approach.

4.10. Summary of TSP Analysis

The priority logic adopted for the Granville corridor used dynamic green extensions and red truncations. This gave signals the flexibility to work efficiently in favour of transit inspite of constraints such as pedestrian walk and flash don't walk times. The TSP strategy used checkout detectors which displayed their effectiveness during successful green extensions by allowing efficient usage of priority time lengths and causing minimal impacts to cross street delays during green extensions. Since green extensions were used more often than red truncations, the checkout detectors were a significant part of the TSP strategy. Also, the dynamic red truncation logic adopted for each priority scenario offered higher opportunities towards successful priority calls, especially when the transit and cross street phase shared almost equal green times (25th avenue intersection).

Amongst the four intersections studied two (25th avenue and 49th avenue) showed prominent benefits to transit while the other two (12th avenue and 16th avenue) had displayed minor improvements from the implementation of the TSP strategies. Priority usage was a governing factor for all intersections. Intersections demonstrating higher priority usage, offered greater improvements to transit travel time and improved transit timeliness. But these improvements were accompanied by frequent deterioration in cross street delays.

The TSP strategy used in scenario 3 offered best improvements in terms of express as well as non-express bus transit times (Table 4.2). The 15 seconds of priority time length offered by scenario 3 was however seldom utilized to the fullest at majority of the intersections, especially for green extensions. The 25th avenue intersection indicated highest usage of priority time lengths to their fullest for red truncations (Table 4.7). The comparatively higher usage of longer green extensions and red truncations caused noticeable delays to cross street vehicles along 25th avenue (Figure 4.8 and 4.9). However, delay for all scenarios at respective intersections were recoverable. The time gap between two successive priority calls allowed sufficient time for the cross streets to recover to the base scenario.

Each intersection had some unique characteristics and differed from the others. Therefore, a priority strategy imparting uniform priority time lengths at all intersections might not be the best option. Assigning different priority lengths (10 seconds and 15 seconds) and classifying them accordingly (5 second intervals) while conducting the analysis, built a good platform to decide as to what priority time lengths would achieve the best results for the respective intersection (refer priority usage table for the 4 intersections). Depending on the priority usage, appropriate TSP plans can be developed for each intersection along the transit corridor. For instance, based on the priority usage at the 25th avenue intersection, a priority strategy could be implemented that offers 10 seconds of maximum green extension time coupled with 15 seconds of maximum red truncation time (Table 4.7).

Another observation made during the analysis was that the frequency of successful priority calls was dependant upon the green time distribution at the intersection as well as the distance between two intersections. The longer the cross street phase length, higher was the probability of detecting the bus during the cross street phase (12th avenue and 16th avenue) and greater was the priority usage.

Using the 2 second pedestrian "walk" time in priority scenarios 2 and 4 did not offer much change to the benefits to buses. The 5 second pedestrian 'Walk' time requirement used in scenarios 1 and 3 offered better results (Table 4.2).

Uncoordinated signals did not create any additional benefits for the express as well as non-express buses over coordinated signals. With the uncoordinated signal logic average travel times for buses increased along with an increase in their timeliness. Priority usage too was fairly low in the absence of coordination between signals. The low priority usage had mixed effects on thee cross street delays, which showed higher deterioration along one approach. The high delays were observed inspite of the low frequency of successful priority call.

Chapter 5. Conclusions

This research investigated the feasibility of different active TSP strategies during peak hours and the impacts of various traffic parameters on the success of these strategies. The Granville corridor was used as a case study to conduct detailed analysis. The main findings of the study are listed below:

1. Active priority strategies offer better overall results during time-sensitive peak hour flows. The two active priority strategies used in this study were green extensions and red truncation with two different maximum priority time lengths (10 and 15 seconds). Detailed analysis of the strategies indicated that the intersections responded well to strategies using dynamic or variable priority times. Dynamic priority times facilitated curtailment of the priority phase as soon as the transit had cleared the intersection imparting priority. In addition, the priority strategies improved bus transit times with lower variance in the travel times for different random seeds. This ensured improved and timely service to transit users.

2. Green extensions are well complemented by checkout detectors. The detectors ensure curtailment of priority green times once the candidate bus has successfully cleared the intersection. This allows an earlier return of the cross street phase resulting in recoverable cross street delays. Also, dynamic red truncation times

working in conjunction with pedestrian phases increase the probability of early return of the transit phase.

3. During peak hour traffic flows, TSP offers greater benefits to transit buses when the signals are coordinated. Uncoordinated signals are not as effective as coordinated signals. Pedestrian phases play a significant role in such coordinated TSP strategies. Concurrently, successful priority usage depends in signal phase lengths as well as signal distances. Intersections having shorter cross street phases reduce the frequency of successful priority calls. For closely spaced intersections, green extension at the upstream intersection will usually be followed by red truncations at the downstream intersection.

4. TSP strategies show significant benefits to corridors having higher transit usage. Although priority strategies might be dedicated to a particular transit service, they cause a ripple effect benefiting other transit services using the same corridor, especially if the corridor boasts of a higher transit volume.

5. Impacts on cross street delays increase with an increase in successful priority calls. Cross street delays are also dependant on the frequency of priority calls and the period between two calls. Longer the period between two calls, greater are the chances for the intersection to recover before the next priority call.

Future scope:

This study indicated that dynamic priority strategies work well during peak hours with coordinated signals. Since most of the signals used along the corridor were fixed type, future analysis using actuated signals would build more insight into using dynamic priority strategies. In addition, the priority strategies in this study were used on express buses with 10 minute headways. Changing the bus headways would affect priority usage. Shorter headways would increase priority usage but at the same time cause deterioration to the cross street traffic. (Bus Lanes)

The 98 B-Line express runs between Downtown Vancouver (along Granville Street) and Richmond (along No. 3 Street). This study analyzed a section of the Vancouver corridor. The Richmond corridor offers dedicated bus lanes. Since the bus-only lanes were not operational during the inception of this study the analysis was limited to the Granville corridor. Bus-only lanes would work in favour of express buses by offering more consistent bus arrivals at intersections, thereby improving transit timeliness. A study to analyze the Richmond corridor with similar priority strategies would complement the current study.

Certain sections of the Granville corridor have designated HOV (High Occupancy Vehicle) lanes. Since transit as well as other HOVs use these lanes, TSP strategies can be developed to benefit both. The combined benefits to transit as well as the HOVs using the corridor would be higher and encourage more users to commute by transit or HOVs.

LRTs display a higher schedule adherence and more consistent arrival times as compared to buses. TSP strategies used in this study might bring out added benefits if used on LRT vehicles.

VISSIM allowed the flexibility to program many different traffic signals (fixed, semi-actuated, fully-actuated.), including a logic that controls signals on a network wide basis. Such logic would grant priority to buses after evaluating the state of the intersection with respect to cross streets and other vehicles, an important contingency being people occupancy. Using this logic would offer better network wide benefits and reduce impacts on the non-transit users.

This study evaluated TSP strategies based on fixed dwell times at bus stops. In reality the dwell times at bus stops are variable and depend on the number of passengers either boarding or de-boarding the bus. Future studies can include variable bus stop dwell times as an added parameter to analyze TSP strategies.

A significant number of transit routes used the Granville corridor in addition to the 98 B-Line express. Some of the other routes along Granville street run express buses too, especially the intercity buses (New Westminister-Vancouver, Surrey-Vancouver). Since the priority granted to 98 B-Line did not have much impact on the delay to major cross streets, granting priority to a few or all of the other express routes might further maximize the improvement to transit travel times.

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Appendix.

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 2 (seconds)	Priority Scenario 3 (seconds)	Priority Scenario 4 (seconds)
72nd Avenue to 70th Avenue	350	82	72	72	72	71
72nd Avenue to Park Avenue	1567	186	172	173	168	169
72nd Avenue to 57th Avenue	1744	206	193	195	187	189
72nd Avenue to 49th Avenue	2904	331	310	313	304	308
72nd Avenue to 41st Avenue	3749	469	434	439	431	432
72nd Avenue to 33rd Avenue	4611	548	510	514	507	505
72nd Avenue to 25th Avenue	5471	658	609	612	602	602
72nd Avenue to 16th Avenue	6338	734	682	684	676	676
72nd Avenue to 12th Avenue	6761	774	721	722	713	716
72nd Avenue to Broadway	7099	857	803	806	793	796
Total	7099	857	803	806	793	796

Table A-1. Cumulative travel time for 98 B-Line in peak direction (Average of 25 runs)

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 2 (seconds)	Priority Scenario 3 (seconds)	Priority Scenario 4 (seconds)
7th Ave to Broadway	240	61	60	60	60	60
7th Ave to 12th Ave	559	89	89	89	89	89
7th Ave to 16th Ave	973	158	158	158	158	158
7th Ave to 25th Ave	1867	285	279	279	276	277
7th Ave to 33rd Ave	3137	363	355	358	352	354
7th Ave to 41st Ave	4002	506	490	494	482	486
7th Ave to 49th Ave	4852	623	599	604	592	595
7th Ave to 57th Ave	6238	696	671	678	664	667
7th Ave to Park Ave	6432	718	691	698	683	686
7th Ave. to 70th Ave	7644	842	800	805	792	797
Total	7644	842	800	805	792	797

Table A-2. Cumulative travel time for 98 B-Line in off-peak direction (Average of 25 runs)

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 2 (seconds)	Priority Scenario 3 (seconds)	Priority Scenario 4 (seconds)
72nd Avenue to 70th Avenue	350	81	76	77	77	76
72nd Avenue to Park Avenue	1567	211	200	206	201	205
72nd Avenue to 57th Avenue	1744	231	220	227	221	225
72nd Avenue to 49th Avenue	2904	329	309	316	308	316
72nd Avenue to 41st Avenue	3749	462	429	441	428	441
72nd Avenue to 33rd Avenue	4611	578	541	556	538	555
72nd Avenue to 25th Avenue	5471	673	633	648	630	651
72nd Avenue to 16th Avenue	6338	775	731	749	727	752
72nd Avenue to 12th Avenue	6761	815	771	789	766	792
72nd Avenue to Broadway	7099	899	853	874	846	876
Total	7099	899	853	874	846	876

Table A-3. Cumulative travel time for non-express buses in peak direction (Average of 25 runs)

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 1 (seconds)	Priority Scenario 2 (seconds)	Priority Scenario 3 (seconds)	Priority Scenario 4 (seconds)
7th Ave to Broadway	240	35	34	34	33	34
7th Ave to 12th Ave	559	89	90	88	88	89
7th Ave to 16th Ave	973	155	156	154	154	155
7th Ave to 25th Ave	1867	262	243	246	245	244
7th Ave to 33rd Ave	3137	359	339	341	341	345
7th Ave to 41st Ave	4002	465	442	444	443	447
7th Ave to 49th Ave	4852	569	542	546	546	547
7th Ave to 57th Ave	6238	674	644	648	649	647
7th Ave to Park Ave	6432	696	665	670	670	667
7th Ave. to 70th Ave	7644	832	797	801	804	803
Total	7644	832	797	801	804	803

Table A-4: Cumulative travel time for non-express buses in off-peak direction (Average of 25 runs)

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 3 (seconds)
	0	0	0
72nd Avenue to 70th Avenue	350	82	83
72nd Avenue to Park Avenue	1567	193	188
72nd Avenue to 57th Avenue	1744	214	206
72nd Avenue to 49th Avenue	2904	338	326
72nd Avenue to 41st Avenue	3749	474	457
72nd Avenue to 33rd Avenue	4611	551	533
72nd Avenue to 25th Avenue	5471	666	639
72nd Avenue to 16th Avenue	6338	748	717
72nd Avenue to 12th Avenue	6761	801	763
72nd Avenue to Broadway	7099	876	844
Total	7099	876	844

Table A-5. Cumulative travel time for express buses in peak direction - Average of 25 runs

Travel Time Section	Section Length (m)	Base Scenario (seconds)	Priority Scenario 3 (seconds)
	0	0	0
72nd Avenue to 70th Avenue	350	65	56
72nd Avenue to Park Avenue	1567	201	191
72nd Avenue to 57th Avenue	1744	221	212
72nd Avenue to 49th Avenue	2904	315	301
72nd Avenue to 41st Avenue	3749	448	431
72nd Avenue to 33rd Avenue	4611	561	546
72nd Avenue to 25th Avenue	5471	661	643
72nd Avenue to 16th Avenue	6338	767	747
72nd Avenue to 12th Avenue	6761	819	798
72nd Avenue to Broadway	7099	899	877
Total	7099	899	846

Table A-6. Cumulative travel time for express buses in peak direction - Average of 25 runs

	Frequency of Green Extension		Frequency of Checkout Detector Usage	Frequency of Red Truncation	
	1 to 5 seconds	6 to 10 seconds		1 to 5 seconds	6 to 10 seconds
Simulation Run 1					
Simulation Run 2	1		1		1
Simulation Run 3					
Simulation Run 4					
Simulation Run 5	1		1		2
Simulation Run 6	1	1	2		
Simulation Run 7	1	1	2		
Simulation Run 8		1	1		
Simulation Run 9					1
Simulation Run 10					
Simulation Run 11					1
Simulation Run 12		1	1		
Simulation Run 13					
Simulation Run 14		2	2		
Simulation Run 15		1	1		
Simulation Run 16		1	1		
Simulation Run 17		1	1	1	
Simulation Run 18					1
Simulation Run 19					
Simulation Run 20		1	1		
Simulation Run 21	1		1		
Simulation Run 22	2	1	3		
Simulation Run 23	2		2		
Simulation Run 24	1		1		1
Simulation Run 25	2	1	3		1
Total	12	12	24	1	8

Table A-7. Priority usage counts based on priority strategy and priority time lengths for 12th Ave – Priority Scenario 1

	Frequency of Green Extension		Frequency of Checkout Detector Usage	Frequency of Red Truncation	
	1 to 5 seconds	6 to 10 seconds		1 to 5 seconds	6 to 10 seconds
Simulation Run 1					
Simulation Run 2	1		1		1
Simulation Run 3					
Simulation Run 4					
Simulation Run 5	1		1		2
Simulation Run 6	1	1	2		
Simulation Run 7	1	1	2		
Simulation Run 8		1	1		
Simulation Run 9					1
Simulation Run 10					
Simulation Run 11					1
Simulation Run 12		1	1		
Simulation Run 13					
Simulation Run 14		2	2		
Simulation Run 15		1	1		
Simulation Run 16		1	1		
Simulation Run 17		1	1	1	
Simulation Run 18					1
Simulation Run 19					
Simulation Run 20		1	1		
Simulation Run 21	1		1		
Simulation Run 22	2	1	3		
Simulation Run 23	2		2		
Simulation Run 24	1		1		1
Simulation Run 25	2	1	3		1
Total	12	12	24	1	8

Table A-8. Priority usage counts based on priority strategy and priority time lengths for 12th Ave – Priority Scenario 2

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1							
Simulation Run 2						2	
Simulation Run 3							
Simulation Run 4							
Simulation Run 5		1		1			1
Simulation Run 6	1	1		2			
Simulation Run 7	1	1		2			
Simulation Run 8		1		1			
Simulation Run 9		1		1			1
Simulation Run 10							
Simulation Run 11							1
Simulation Run 12		1		1			
Simulation Run 13							
Simulation Run 14		2		2			
Simulation Run 15		1		1			
Simulation Run 16		1		1			
Simulation Run 17		1		1	1		
Simulation Run 18						1	
Simulation Run 19							
Simulation Run 20		1		1			
Simulation Run 21	1			1			
Simulation Run 22	2	1		3			
Simulation Run 23	2			2			
Simulation Run 24	1			1			1
Simulation Run 25		1		1			2
Total	8	14		22	1	3	6

Table A-9. Priority usage counts based on priority strategy and priority time lengths for 12th Ave – Priority Scenario 3

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1							
Simulation Run 2		1		1			1
Simulation Run 3							
Simulation Run 4							
Simulation Run 5		1		1			1
Simulation Run 6	1	1		2			
Simulation Run 7	1	1		2			
Simulation Run 8		1		1			
Simulation Run 9		1		1			1
Simulation Run 10							
Simulation Run 11							1
Simulation Run 12		1		1			
Simulation Run 13							
Simulation Run 14		2		2			
Simulation Run 15		1		1			
Simulation Run 16		1		1			
Simulation Run 17		1		1	1		
Simulation Run 18							1
Simulation Run 19							
Simulation Run 20		1		1			
Simulation Run 21	1			1			
Simulation Run 22	2	1		3			
Simulation Run 23	2			2			
Simulation Run 24	1			1			1
Simulation Run 25		1		1			2
Total	8	15		23	1	0	8

Table A-10. Priority usage counts based on priority strategy and priority time lengths for 12th Ave – Priority Scenario 4

	Frequency of Green Extension		Frequency of Checkout Detector Usage	Frequency of Red Truncation	
	1 to 5 seconds	6 to 10 seconds		1 to 5 seconds	6 to 10 seconds
Simulation Run 1	2	1	3	1	
Simulation Run 2	1		1		1
Simulation Run 3		1	1		
Simulation Run 4		1	1		2
Simulation Run 5	1		1		1
Simulation Run 6					1
Simulation Run 7	1	1	2		
Simulation Run 8		1	1	1	
Simulation Run 9	2		2	1	
Simulation Run 10	2	1	3		1
Simulation Run 11		1	1	1	1
Simulation Run 12	2	1	3		
Simulation Run 13	2		2	1	
Simulation Run 14		1	1		1
Simulation Run 15	1	1	2		
Simulation Run 16					
Simulation Run 17	1		1		1
Simulation Run 18					1
Simulation Run 19	1		1	1	
Simulation Run 20	1	1	2		
Simulation Run 21		1	1		
Simulation Run 22	1		1	1	1
Simulation Run 23		1	1		
Simulation Run 24		1	1		2
Simulation Run 25	1		1		
Total	19	14	33	7	13

Table A-11. Priority usage counts based on priority strategy and priority time lengths for 16th Ave – Priority Scenario 1

	Frequency of Green Extension		Frequency of Checkout Detector Usage	Frequency of Red Truncation	
	1 to 5 seconds	6 to 10 seconds		1 to 5 seconds	6 to 10 seconds
Simulation Run 1				1	3
Simulation Run 2		1	1	1	1
Simulation Run 3		1	1		
Simulation Run 4		1	1		2
Simulation Run 5	1		1		1
Simulation Run 6					1
Simulation Run 7	1	1	2		
Simulation Run 8		1	1		1
Simulation Run 9	1		1	1	1
Simulation Run 10	2	1	3		1
Simulation Run 11		1	1	1	1
Simulation Run 12	2	1	3		
Simulation Run 13	2		2	1	
Simulation Run 14		1	1		1
Simulation Run 15	1	1	2		
Simulation Run 16					
Simulation Run 17	1		1		1
Simulation Run 18					1
Simulation Run 19	1		1	1	
Simulation Run 20	1	1	2		
Simulation Run 21		1	1		1
Simulation Run 22		2	2		1
Simulation Run 23		1	1		
Simulation Run 24		1	1		2
Simulation Run 25	1		1		
Total	14	16	30	6	19

Table A-12. Priority usage counts based on priority strategy and priority time lengths for 16th Ave – Priority Scenario 2

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1	1	2		3	1		
Simulation Run 2	1			1			2
Simulation Run 3		1	1	2			
Simulation Run 4		1		1			1
Simulation Run 5	1			1	1		1
Simulation Run 6	1			1			2
Simulation Run 7	1	1		2			
Simulation Run 8		1		1	1		
Simulation Run 9	2			2	1		
Simulation Run 10	2	1		3			1
Simulation Run 11		1		1	1		1
Simulation Run 12	2	1		3			
Simulation Run 13	2	1		3	1		
Simulation Run 14							1
Simulation Run 15	1	1		2			
Simulation Run 16							
Simulation Run 17	1			1			1
Simulation Run 18		1		1			1
Simulation Run 19	1			1	1		
Simulation Run 20	1	1		2			
Simulation Run 21		1		1	1		
Simulation Run 22	1			1	1		1
Simulation Run 23		1		1			
Simulation Run 24	1	1		2			1
Simulation Run 25	1			1			
Total	20	16	1	37	9	0	13

Table A-13. Priority usage counts based on priority strategy and priority time lengths for 16th Ave – Priority Scenario 3.

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1						1	3
Simulation Run 2		1		1			1
Simulation Run 3		1	1	2			1
Simulation Run 4		1		1	1		1
Simulation Run 5	1			1	1		2
Simulation Run 6	1			1			2
Simulation Run 7	1	1		2			
Simulation Run 8		1		1		1	
Simulation Run 9	2			2		2	
Simulation Run 10	2	1		3			1
Simulation Run 11		1		1	1		1
Simulation Run 12	2	1		3			
Simulation Run 13	3			3		1	
Simulation Run 14							1
Simulation Run 15	1	1		2			
Simulation Run 16							
Simulation Run 17	1			1			1
Simulation Run 18		1		1			
Simulation Run 19	1			1	1		
Simulation Run 20	1	1		2			
Simulation Run 21	1			1		2	
Simulation Run 22	1	1		2		1	
Simulation Run 23		1		1			
Simulation Run 24	1	1		2			1
Simulation Run 25	1			1			
Total	20	14	1	35	4	8	15

Table A-14. Priority usage counts based on priority strategy and priority time lengths for 16th Ave – Priority Scenario 4

	Frequency of Green Extension		Frequency of Checkout Detector Usage	Frequency of Red Truncation	
	1 to 5 seconds	6 to 10 seconds		1 to 5 seconds	6 to 10 seconds
Simulation Run 1	1	4	4		1
Simulation Run 2					4
Simulation Run 3		1	1		
Simulation Run 4	1	1	2		2
Simulation Run 5	2	2	2		
Simulation Run 6		2	2		
Simulation Run 7	1	3	3		1
Simulation Run 8	1	1	2		1
Simulation Run 9	1		1		1
Simulation Run 10		2	2		2
Simulation Run 11	1	1	1		2
Simulation Run 12	2	1	3		1
Simulation Run 13		2	2		2
Simulation Run 14	1	1	2		2
Simulation Run 15	1	1	2		2
Simulation Run 16	1	3	3		
Simulation Run 17	1	1	2		2
Simulation Run 18	1	1	2		3
Simulation Run 19					3
Simulation Run 20	2	1	3		2
Simulation Run 21	2	1	2		1
Simulation Run 22	2	1	3		1
Simulation Run 23					1
Simulation Run 24	1	1	2		
Simulation Run 25	1	1	1		2
Total	23	32	47		36

Table A-15. Priority usage counts based on priority strategy and priority time lengths for 25th Ave – Priority Scenario 1

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1	1		1	1	1		3
Simulation Run 2	2	1		3			2
Simulation Run 3		1		1			
Simulation Run 4		1		1			2
Simulation Run 5		1	1	2			
Simulation Run 6		2		2			
Simulation Run 7	1	2	1	4			
Simulation Run 8		1		1			1
Simulation Run 9	1			1			1
Simulation Run 10		2		2			2
Simulation Run 11			3	3			2
Simulation Run 12	2	1		3			1
Simulation Run 13	1			1			3
Simulation Run 14	2			2			2
Simulation Run 15							3
Simulation Run 16	2		1	2			1
Simulation Run 17	1	1		2			1
Simulation Run 18	1	1		2			2
Simulation Run 19							3
Simulation Run 20	3	1		4			4
Simulation Run 21	2	1		3			1
Simulation Run 22	3			3			2
Simulation Run 23		1		1			1
Simulation Run 24	2	1		3			
Simulation Run 25	2	1		2			2
Total	26	19	7	49	1		39

Table A-16. Priority usage counts based on priority strategy and priority time lengths for 25th Ave – Priority Scenario 3

	Frequency of Green Extension		Frequency of Checkout Detector Usage	Frequency of Red Truncation	
	1 to 5 seconds	6 to 10 seconds		1 to 5 seconds	6 to 10 seconds
Simulation Run 1	2		2		
Simulation Run 2	1	2	3	1	1
Simulation Run 3		2	2		1
Simulation Run 4	1	1	2		1
Simulation Run 5				2	
Simulation Run 6	2		2	1	
Simulation Run 7	1	1	2	1	
Simulation Run 8	1		1		1
Simulation Run 9	1		1	2	1
Simulation Run 10				3	
Simulation Run 11		1	1	2	2
Simulation Run 12		1	1	1	1
Simulation Run 13					1
Simulation Run 14		1	1	1	1
Simulation Run 15	1	1	2	1	
Simulation Run 16	1	1	2		1
Simulation Run 17				1	
Simulation Run 18				2	
Simulation Run 19	2	1	3	2	
Simulation Run 20		2	2	1	2
Simulation Run 21	1	1	2		2
Simulation Run 22	2		2	1	2
Simulation Run 23	2		2		1
Simulation Run 24	1		1	1	2
Simulation Run 25					2
Total	19	15	34	23	22

Table A-17. Priority usage counts based on priority strategy and priority time lengths for 49th Ave – Priority Scenario 1

	Frequency of Green Extension		Frequency of Checkout Detector Usage	Frequency of Red Truncation	
	1 to 5 seconds	6 to 10 seconds		1 to 5 seconds	6 to 10 seconds
Simulation Run 1	2		2		
Simulation Run 2	1	2	3	1	1
Simulation Run 3		1	1	1	2
Simulation Run 4	1	1	2	2	1
Simulation Run 5				2	
Simulation Run 6	2		2	1	
Simulation Run 7	1	1	2	1	
Simulation Run 8					1
Simulation Run 9	1		1	2	1
Simulation Run 10		1	1	2	
Simulation Run 11		1	1	2	2
Simulation Run 12		1	1	1	1
Simulation Run 13					1
Simulation Run 14		1	1		1
Simulation Run 15	1	1	2	1	
Simulation Run 16	1	1	2		1
Simulation Run 17	1		1	1	
Simulation Run 18				2	
Simulation Run 19	2		2	1	
Simulation Run 20				1	2
Simulation Run 21	2	1	3		2
Simulation Run 22	2		2		3
Simulation Run 23	2		2		1
Simulation Run 24	1	1	2	2	
Simulation Run 25					2
Total	20	13	33	23	22

Table A-18. Priority usage counts based on priority strategy and priority time lengths for 49th Ave – Priority Scenario 2

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1	2			2			
Simulation Run 2	1	1		2		1	1
Simulation Run 3		2		2		1	
Simulation Run 4	1	1		2	1		1
Simulation Run 5					2	1	2
Simulation Run 6	2			2	1		
Simulation Run 7		1		1	2		1
Simulation Run 8	1			1		1	
Simulation Run 9	1			1	2	1	
Simulation Run 10		1		1	1	1	
Simulation Run 11		1		1	2		1
Simulation Run 12		1		1	1		1
Simulation Run 13						1	1
Simulation Run 14		1		1	1		
Simulation Run 15	1			1	1	1	
Simulation Run 16	1	1		2		1	
Simulation Run 17					1		
Simulation Run 18					3		
Simulation Run 19	2			2	1		
Simulation Run 20		2		2			2
Simulation Run 21	1	1		2	1	1	
Simulation Run 22	2			2	1	1	1
Simulation Run 23	2			2			1
Simulation Run 24		1		1	1	2	
Simulation Run 25						2	
Total	17	14		31	22	15	12

Table A-19. Priority usage counts based on priority strategy and priority time lengths for 49th Ave – Priority Scenario 3

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1	2			2			
Simulation Run 2	1	1		2		1	1
Simulation Run 3		2		2		1	
Simulation Run 4					1		1
Simulation Run 5					2	1	2
Simulation Run 6	2			2	1		
Simulation Run 7		1		1	2		1
Simulation Run 8	1			1		1	
Simulation Run 9	1			1	2	1	
Simulation Run 10		1		1	1	1	
Simulation Run 11		1		1	2		1
Simulation Run 12		1		1	1		1
Simulation Run 13						1	1
Simulation Run 14		1		1		2	
Simulation Run 15	1			1		1	
Simulation Run 16	1	1		2		1	
Simulation Run 17					1		
Simulation Run 18					3		
Simulation Run 19	2			2	1		
Simulation Run 20					2	1	
Simulation Run 21	2	1		3		2	
Simulation Run 22	1	1		2		2	1
Simulation Run 23	2			2			1
Simulation Run 24		1		1	2	1	
Simulation Run 25	2			2		1	
Total	18	12		30	21	18	10

Table A-20. Priority usage counts based on priority strategy and priority time lengths for 49th Ave – Priority Scenario 4

	Frequency of Green Extension			Frequency of Checkout Detector Usage	Frequency of Red Truncation		
	1 to 5 seconds	6 to 10 seconds	11 to 15 seconds		1 to 5 seconds	6 to 10 seconds	11 to 15 seconds
Simulation Run 1	2	1		3			1
Simulation Run 2							
Simulation Run 3		1		1		2	2
Simulation Run 4		1		1			
Simulation Run 5							1
Simulation Run 6		2		2			1
Simulation Run 7	1	1		2			
Simulation Run 8		1	2	1		1	1
Simulation Run 9	2	1		3	1		
Simulation Run 10			1	1	1		
Simulation Run 11							
Simulation Run 12	2			2			1
Simulation Run 13		1		1	1		
Simulation Run 14	1	1	1	3			1
Simulation Run 15	1			1			
Simulation Run 16	1	1		2			
Simulation Run 17		2	1	3		1	1
Simulation Run 18	2		1	3			1
Simulation Run 19	1	1		2		1	1
Simulation Run 20	1	1		2			
Simulation Run 21	1	6		7	1		
Simulation Run 22	2	1		3	1		
Simulation Run 23	1	1	1	3	1		
Simulation Run 24	2	1		3	1		1
Simulation Run 25							2
	20	24	7	49	7		14

Table A-21. Priority usage counts based on priority strategy and priority time lengths for 25th Ave – Priority Scenario 4 (Uncoordinated Signal Logic)

Base Scenario

Time	Vehicle Delay EB	Vehicle Delay WB
929	28	19
1004	28	18
1079	28	18
1154	26	22
1229	28	19
1304	28	21
1379	32	22
1454	34	23
1529	34	19
1604	30	19
1679	28	17
1754	28	19
1829	33	19
1904	32	18
1979	27	16
2054	25	17
2129	26	17
2204	24	19
2279	25	19
2354	24	20
2429	26	20
2504	29	19
2579	29	20
2654	29	19

Priority Scenario 1

Time	Vehicle Delay EB	Vehicle Delay WB
929	28	19
1004	28	18
1079	29	17
1154	28	22
1229	27	19
1304	29	21
1379	32	21
1454	33	22
1529	33	19
1604	30	20
1679	30	18
1754	28	20
1829	35	19
1904	36	17
1979	33	16
2054	27	16
2129	26	15
2204	27	18
2279	29	20
2354	26	19
2429	26	18
2504	30	19
2579	27	20
2654	29	21

Priority Scenario 2

Time	Vehicle Delay EB	Vehicle Delay WB
929	28	19
1004	28	18
1079	29	17
1154	28	22
1229	27	19
1304	29	21
1379	32	21
1454	33	22
1529	33	19
1604	30	20
1679	30	18
1754	28	20
1829	34	19
1904	34	17
1979	32	16
2054	26	16
2129	26	15
2204	26	18
2279	28	20
2354	27	19
2429	27	18
2504	29	19
2579	27	20
2654	30	22

Priority Scenario 3

Time	Vehicle Delay EB	Vehicle Delay WB
929	28	19
1004	28	19
1079	30	19
1154	28	24
1229	27	20
1304	30	22
1379	32	22
1454	33	23
1529	33	20
1604	30	21
1679	31	18
1754	28	18
1829	34	18
1904	34	17
1979	31	16
2054	26	16
2129	27	16
2204	27	19
2279	30	21
2354	29	19
2429	27	18
2504	31	18
2579	29	20
2654	31	20

Priority Scenario 4

Time	Vehicle Delay EB	Vehicle Delay WB
929	28	19
1004	28	19
1079	30	19
1154	28	24
1229	28	19
1304	30	22
1379	32	23
1454	33	23
1529	33	20
1604	31	21
1679	31	18
1754	28	18
1829	34	18
1904	34	17
1979	32	16
2054	27	16
2129	27	16
2204	27	19
2279	30	21
2354	29	19
2429	27	18
2504	31	18
2579	28	20
2654	30	20

	Base Scenario			Priority Scenario 1			Priority Scenario 2			Priority Scenario 3			Priority Scenario 4		
Time	Vehicle Delay EB	Vehicle Delay WB	Time	Vehicle Delay EB	Vehicle Delay WB	Time	Vehicle Delay EB	Vehicle Delay WB	Time	Vehicle Delay EB	Vehicle Delay WB	Time	Vehicle Delay EB	Vehicle Delay WB
2729	29	20	2729	28	16	2729	30	16	2729	30	17	2729	30	17
2804	28	17	2804	27	16	2804	28	16	2804	28	17	2804	28	17
2879	30	16	2879	29	17	2879	30	17	2879	30	17	2879	30	17
2954	26	17	2954	23	17	2954	23	17	2954	24	17	2954	24	18
3029	22	15	3029	21	15	3029	21	16	3029	21	16	3029	21	17
3104	25	17	3104	23	17	3104	23	17	3104	24	17	3104	24	17
3179	25	16	3179	24	15	3179	24	15	3179	25	15	3179	25	15
3254	23	17	3254	24	15	3254	26	16	3254	25	16	3254	26	17
3329	30	17	3329	28	16	3329	30	17	3329	28	17	3329	29	17
3404	25	15	3404	25	17	3404	25	16	3404	26	15	3404	26	15
3479	23	17	3479	27	19	3479	27	19	3479	29	19	3479	28	19
3554	22	18	3554	27	15	3554	27	15	3554	27	16	3554	26	15
3629	21	22	3629	25	18	3629	25	17	3629	25	18	3629	25	18
3704	24	20	3704	26	17	3704	26	16	3704	27	19	3704	27	19
3779	26	19	3779	26	18	3779	26	17	3779	27	22	3779	26	21
3854	25	18	3854	24	17	3854	26	17	3854	25	22	3854	26	22
3929	25	17	3929	24	16	3929	25	16	3929	24	18	3929	25	17
4004	24	21	4004	26	17	4004	26	19	4004	28	19	4004	28	19
4079	28	20	4079	27	19	4079	27	19	4079	30	23	4079	30	21
4154	29	19	4154	30	18	4154	31	17	4154	31	19	4154	32	17
4229	36	18	4229	30	16	4229	30	17	4229	31	18	4229	30	18
4304	29	16	4304	27	15	4304	29	16	4304	29	17	4304	31	17
4379	25	18	4379	23	16	4379	25	17	4379	23	17	4379	25	18
4454	26	16	4454	25	17	4454	25	17	4454	24	18	4454	24	18
Average for Simulation	27	18	Average for Simulation	28	18	Average for Simulation	28	18	Average for Simulation	28	19	Average for Simulation	28	19

Table A-22. Average Delay at 12th Avenue based on 25 simulation runs

Base Scenario

Time	Vehicle Delay EB	Vehicle Delay WB
926	20	35
1001	21	33
1076	20	36
1151	21	36
1226	20	35
1301	21	38
1376	22	33
1451	21	36
1526	19	35
1601	19	36
1676	19	35
1751	21	37
1826	22	36
1901	21	37
1976	20	38
2051	20	36
2126	21	37
2201	19	37
2276	20	35
2351	20	33
2426	22	37
2501	21	37
2576	21	35
2651	21	37

Priority Scenario 1

Time	Vehicle Delay EB	Vehicle Delay WB
926	20	35
1001	22	35
1076	21	38
1151	20	35
1226	21	36
1301	20	38
1376	22	35
1451	21	36
1526	20	36
1601	21	37
1676	20	36
1751	23	36
1826	22	37
1901	19	38
1976	20	38
2051	20	35
2126	23	37
2201	22	37
2276	22	38
2351	19	34
2426	21	37
2501	20	38
2576	21	35
2651	20	37

Priority Scenario 2

Time	Vehicle Delay EB	Vehicle Delay WB
926	20	35
1001	22	35
1076	21	38
1151	20	35
1226	20	36
1301	20	38
1376	22	35
1451	21	36
1526	20	36
1601	21	37
1676	21	37
1751	22	37
1826	22	36
1901	19	39
1976	20	37
2051	20	35
2126	23	38
2201	23	37
2276	22	39
2351	19	34
2426	21	37
2501	21	37
2576	21	35
2651	20	37

Priority Scenario 3

Time	Vehicle Delay EB	Vehicle Delay WB
926	20	35
1001	22	35
1076	21	38
1151	20	35
1226	20	36
1301	20	38
1376	22	35
1451	20	36
1526	20	36
1601	21	38
1676	22	37
1751	23	36
1826	22	36
1901	20	39
1976	19	38
2051	20	35
2126	23	39
2201	22	38
2276	22	37
2351	18	34
2426	21	37
2501	21	38
2576	21	35
2651	21	37

Priority Scenario 4

Time	Vehicle Delay EB	Vehicle Delay WB
926	20	35
1001	22	35
1076	21	38
1151	21	35
1226	20	36
1301	20	38
1376	22	35
1451	21	36
1526	19	37
1601	21	38
1676	22	37
1751	22	37
1826	23	36
1901	20	40
1976	20	38
2051	20	35
2126	23	39
2201	23	39
2276	22	38
2351	18	33
2426	20	37
2501	22	38
2576	21	34
2651	21	37

Base Scenario

Time	Vehicle Delay EB	Vehicle Delay WB
2726	18	36
2801	20	36
2876	21	37
2951	20	33
3026	22	32
3101	20	36
3176	20	34
3251	20	39
3326	19	35
3401	20	37
3476	20	37
3551	22	39
3626	19	35
3701	19	42
3776	21	35
3851	19	36
3926	21	35
4001	19	34
4076	19	36
4151	20	37
4226	21	37
4301	20	37
4376	22	36
4451	21	37
Average for Simulation	20	36

Priority Scenario 1

Time	Vehicle Delay EB	Vehicle Delay WB
2726	20	42
2801	21	37
2876	20	38
2951	21	37
3026	20	33
3101	21	37
3176	19	35
3251	20	38
3326	21	35
3401	23	37
3476	24	41
3551	21	38
3626	20	35
3701	22	42
3776	22	36
3851	21	37
3926	21	36
4001	20	38
4076	21	38
4151	20	37
4226	20	36
4301	20	35
4376	23	37
4451	20	36
Average for Simulation	21	37

Priority Scenario 2

Time	Vehicle Delay EB	Vehicle Delay WB
2726	20	42
2801	21	39
2876	20	38
2951	21	37
3026	20	34
3101	22	36
3176	21	35
3251	20	37
3326	20	35
3401	22	38
3476	22	39
3551	22	37
3626	20	35
3701	23	41
3776	22	36
3851	21	37
3926	22	38
4001	19	37
4076	20	37
4151	20	38
4226	20	36
4301	21	35
4376	23	40
4451	21	37
Average for Simulation	21	37

Priority Scenario 3

Time	Vehicle Delay EB	Vehicle Delay WB
2726	20	37
2801	21	37
2876	20	38
2951	22	38
3026	20	36
3101	20	37
3176	19	35
3251	21	37
3326	19	35
3401	21	40
3476	23	36
3551	21	37
3626	20	35
3701	20	39
3776	21	36
3851	21	37
3926	21	34
4001	19	40
4076	22	39
4151	19	36
4226	21	36
4301	20	35
4376	23	41
4451	19	38
Average for Simulation	21	37

Priority Scenario 4

Time	Vehicle Delay EB	Vehicle Delay WB
2726	19	37
2801	22	38
2876	21	38
2951	23	38
3026	20	37
3101	20	38
3176	20	35
3251	20	37
3326	19	34
3401	20	41
3476	21	37
3551	21	37
3626	20	37
3701	19	39
3776	20	36
3851	21	37
3926	21	36
4001	20	40
4076	22	39
4151	19	36
4226	21	35
4301	21	35
4376	23	44
4451	20	38
Average for Simulation	21	37

Table A-23. Average Delay at 16th Avenue based on 25 simulation runs

Base Scenario

	Delay EB	Delay WB
915	33	26
990	33	25
1065	33	28
1140	33	28
1215	33	27
1290	33	26
1365	33	26
1440	32	27
1515	33	27
1590	33	28
1665	33	27
1740	34	27
1815	32	27
1890	33	25
1965	34	25
2040	33	26
2115	33	25
2190	33	28
2265	33	28
2340	33	28
2415	33	28
2490	33	28
2565	33	30
2640	33	27
2715	33	28

Priority Scenario 1

	Delay EB	Delay WB
915	33	26
990	33	26
1065	33	29
1140	33	28
1215	33	26
1290	34	27
1365	34	27
1440	34	28
1515	34	30
1590	33	29
1665	34	28
1740	34	27
1815	32	26
1890	34	26
1965	33	26
2040	35	29
2115	34	29
2190	34	31
2265	33	26
2340	32	27
2415	32	26
2490	33	27
2565	34	28
2640	34	30
2715	34	32

Priority Scenario 2

	Delay EB	Delay WB
915	33	26
990	33	26
1065	34	29
1140	33	28
1215	33	26
1290	33	28
1365	34	27
1440	34	28
1515	36	32
1590	34	30
1665	34	28
1740	34	27
1815	32	27
1890	34	27
1965	34	25
2040	35	30
2115	35	30
2190	35	31
2265	34	26
2340	32	27
2415	33	28
2490	33	27
2565	34	30
2640	35	31
2715	37	34

Base Scenario

	Delay EB	Delay WB
915	33	26
2790	33	28
2865	33	26
2940	33	26
3015	33	28
3090	33	29
3165	33	27
3240	33	26
3315	33	25
3390	33	25
3465	33	28
3540	33	28
3615	33	28
3690	32	27
3765	34	26
3840	32	25
3915	33	27
3990	33	28
4065	34	26
4140	33	26
4215	33	28
4290	34	26
4365	32	26
4440	33	25
Average for Simulation	33	27

Priority Scenario 1

	Delay EB	Delay WB
915	33	26
2790	33	29
2865	33	25
2940	33	26
3015	33	29
3090	34	30
3165	34	29
3240	33	29
3315	33	27
3390	33	26
3465	33	28
3540	33	27
3615	33	27
3690	34	29
3765	34	27
3840	34	27
3915	35	30
3990	33	27
4065	34	26
4140	33	25
4215	34	27
4290	34	26
4365	33	27
4440	33	30
Average for Simulation	33	28

Priority Scenario 2

	Delay EB	Delay WB
915	33	26
2790	35	29
2865	33	26
2940	33	27
3015	33	28
3090	34	30
3165	35	30
3240	33	28
3315	34	27
3390	34	27
3465	34	29
3540	33	27
3615	33	26
3690	34	30
3765	35	29
3840	33	27
3915	35	30
3990	34	27
4065	33	28
4140	33	27
4215	33	26
4290	33	25
4365	33	30
4440	35	29
Average for Simulation	34	28

Table A-24. Average Delay at 25th Avenue based on 25 simulation runs

Base Scenario

Time	Vehicle Delay EB	Vehicle Delay WB
908	23	7
983	21	6
1058	20	6
1133	21	7
1208	22	9
1283	24	10
1358	22	9
1433	22	9
1508	24	7
1583	24	6
1658	27	6
1733	24	5
1808	26	6
1883	23	7
1958	22	5
2033	25	4
2108	24	6
2183	25	6
2258	23	9
2333	24	8
2408	24	7
2483	27	10
2558	30	9
2633	28	7

Priority Scenario 1

Time	Vehicle Delay EB	Vehicle Delay WB
908	23	7
983	21	6
1058	21	8
1133	21	9
1208	23	11
1283	21	12
1358	22	7
1433	23	8
1508	24	10
1583	22	8
1658	26	9
1733	24	5
1808	22	7
1883	24	8
1958	24	5
2033	23	4
2108	22	6
2183	26	5
2258	25	8
2333	28	11
2408	29	10
2483	25	12
2558	29	9
2633	27	6

Priority Scenario 2

Time	Vehicle Delay EB	Vehicle Delay WB
908	23	7
983	21	6
1058	21	8
1133	21	8
1208	23	12
1283	21	12
1358	23	8
1433	24	8
1508	25	10
1583	23	9
1658	25	10
1733	24	5
1808	21	7
1883	23	8
1958	23	5
2033	22	3
2108	22	6
2183	25	5
2258	25	8
2333	26	11
2408	27	10
2483	24	12
2558	26	9
2633	26	6

Priority Scenario 3

Time	Vehicle Delay EB	Vehicle Delay WB
908	23	7
983	21	6
1058	21	8
1133	21	8
1208	23	12
1283	21	11
1358	24	7
1433	24	7
1508	25	10
1583	22	8
1658	25	9
1733	25	5
1808	23	8
1883	24	9
1958	24	6
2033	23	3
2108	23	6
2183	25	5
2258	25	8
2333	29	10
2408	30	9
2483	25	13
2558	29	9
2633	27	7

Priority Scenario 4

Time	Vehicle Delay EB	Vehicle Delay WB
908	23	7
983	21	6
1058	21	8
1133	22	8
1208	24	13
1283	21	12
1358	24	8
1433	24	8
1508	25	10
1583	22	9
1658	24	10
1733	25	5
1808	22	8
1883	23	9
1958	24	6
2033	23	4
2108	22	6
2183	25	5
2258	26	9
2333	26	11
2408	26	9
2483	25	12
2558	26	9
2633	27	7

Base Scenario

Time	Vehicle Delay EB	Vehicle Delay WB
2708	24	5
2783	22	8
2858	24	5
2933	21	8
3008	24	6
3083	22	8
3158	23	7
3233	25	8
3308	25	4
3383	24	8
3458	20	7
3533	22	7
3608	23	6
3683	20	8
3758	24	8
3833	19	6
3908	20	10
3983	24	10
4058	28	7
4133	23	10
4208	20	6
4283	20	5
4358	19	5
4433	22	4
Average for Simulation	23	7

Priority Scenario 1

Time	Vehicle Delay EB	Vehicle Delay WB
2708	26	7
2783	20	6
2858	23	7
2933	21	6
3008	24	7
3083	23	6
3158	21	5
3233	27	6
3308	24	7
3383	26	8
3458	25	5
3533	27	6
3608	28	9
3683	27	8
3758	26	6
3833	24	7
3908	21	10
3983	25	9
4058	25	8
4133	22	10
4208	22	9
4283	21	9
4358	22	7
4433	20	7
Average for Simulation	24	8

Priority Scenario 2

Time	Vehicle Delay EB	Vehicle Delay WB
2708	24	7
2783	20	5
2858	24	7
2933	22	7
3008	24	8
3083	25	7
3158	22	6
3233	29	6
3308	27	5
3383	25	7
3458	24	5
3533	29	6
3608	26	7
3683	25	9
3758	25	9
3833	25	9
3908	23	11
3983	25	10
4058	26	11
4133	25	13
4208	22	10
4283	21	10
4358	24	7
4433	20	5
Average for Simulation	24	8

Priority Scenario 3

Time	Vehicle Delay EB	Vehicle Delay WB
2708	24	7
2783	20	5
2858	24	8
2933	21	6
3008	25	8
3083	24	10
3158	20	7
3233	28	7
3308	24	7
3383	27	9
3458	26	6
3533	28	7
3608	29	10
3683	29	9
3758	29	8
3833	28	8
3908	24	9
3983	25	11
4058	28	8
4133	24	12
4208	23	11
4283	21	10
4358	24	8
4433	23	6
Average for Simulation	25	8

Priority Scenario 4

Time	Vehicle Delay EB	Vehicle Delay WB
2708	24	8
2783	20	5
2858	23	6
2933	22	7
3008	25	8
3083	27	10
3158	22	7
3233	32	6
3308	30	5
3383	26	8
3458	26	5
3533	27	7
3608	27	9
3683	24	10
3758	26	10
3833	27	10
3908	25	10
3983	25	11
4058	32	12
4133	26	12
4208	23	10
4283	23	10
4358	26	7
4433	22	6
Average for Simulation	25	8

Table A-25. Average Delay at 49th Avenue based on 25 simulation runs

Base Scenario		
Time	Vehicle Delay EB (sec)	Vehicle Delay WB (sec)
975	18	33
1050	18	34
1125	18	34
1200	18	33
1275	18	34
1350	18	34
1425	17	36
1500	18	36
1575	18	36
1650	18	36
1725	19	35
1800	18	34
1875	18	35
1950	19	34
2025	18	35
2100	18	34
2175	18	36
2250	18	35
2325	18	35
2400	18	34
2475	18	34
2550	19	34
2625	19	35
2700	18	34
2775	18	35
2850	18	36
2925	17	34
3000	18	34
3075	18	35
3150	18	34
3225	18	35
3300	18	35
3375	17	34
3450	18	35
3525	18	34
3600	18	34
3675	18	34
3750	18	34
3825	18	34
3900	18	34
3975	18	34
4050	19	35
4125	18	35
4200	18	34
4275	18	35
4350	17	34
4425	18	35
4500	18	34
Average for Simulation	18	34

Priority Sacenario 3		
Time	Vehicle Delay EB (sec)	Vehicle Delay WB (sec)
975	18	34
1050	18	34
1125	18	35
1200	18	34
1275	17	34
1350	17	34
1425	18	36
1500	20	36
1575	17	36
1650	18	36
1725	18	37
1800	18	35
1875	18	37
1950	18	36
2025	19	36
2100	22	36
2175	18	36
2250	19	36
2325	18	36
2400	18	36
2475	18	36
2550	19	39
2625	20	37
2700	21	36
2775	19	33
2850	17	35
2925	18	34
3000	18	33
3075	19	33
3150	19	36
3225	19	35
3300	19	35
3375	19	34
3450	19	35
3525	18	34
3600	18	34
3675	18	35
3750	19	35
3825	19	35
3900	20	35
3975	18	35
4050	19	35
4125	19	37
4200	18	36
4275	18	37
4350	18	35
4425	19	36
4500	22	36
Average for Simulation	19	35

Table A-26 Average Delay at 25th Avenue based on 25 simulation runs (Uncoordinated Logic)