NOTE TO USERS

This reproduction is the best copy available.

UMI
Microsimulation Modeling and Advancements of Transit Priority Options at Major Arterials

BY

JINWOO LEE

A thesis submitted in conformity with requirements for the degree of Master of Applied Science

Graduate Department of Civil Engineering

University of Toronto

© Copyright by Jinwoo Lee, 2001
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.
Microsimulation Modeling and Advancements of
Transit Priority Options at Major Arterials

Master of Applied Science, 2001

Jinwoo Lee
Department of Civil Engineering
University of Toronto

ABSTRACT

The objective of this study is to examine the impacts of several transit priority strategies as well as to develop a conditional signal priority algorithm for a streetcar corridor in the city of Toronto. The 504 King streetcar was chosen for the study, a high frequency route with headway of 2 minutes. Six scenarios representing different levels of transit priority were considered, and a microsimulation model was developed to examine these scenarios. The model was enhanced by an Application Programming Interface (API) program to enable modeling passenger-related functions. Based on the selected set of MOEs, the simulation results were analyzed to assess the relative effectiveness of the scenarios. The simulation results also showed that conditional TSP algorithm was effective in reducing cross streets delay and headway variance. However, the tested conditional TSP algorithm failed to improve transit headway regularity on the network with near saturated condition.
ACKNOWLEDGEMENT

First of all, I would like to express my deep appreciation to my co-supervisors, Professor Baher Abdulhai and Professor Amer Shalaby for their consistent supports and cares for my research. Their encouragement always promoted me to overcome many difficulties in completing this research. I also would like to thank Asmus Georgi for many valuable advises and suggestions.

Special thanks go to my parents-in-law, brother and his family and especially to my parents for their loves and cares for my entire life.

With my love, I would like to present this small fruition to my beloved wife and our baby.

This work was funded in part by CITO (Communication and Information Technology)
TABLE OF CONTENTS

ABSTRACT ii
ACKNOWLEDGEMENT iii
TABLE OF CONTENTS iv
LIST OF TABLES vi
LIST OF FIGURES vii
LIST OF APPENDICES ix

1.0 INTRODUCTION 1

2.0 LITERATURE REVIEW 5

3.0 METHODOLOGY 10
  3.1 Development of the Base Network 10
    3.1.1 Skeleton Network Coding 10
    3.1.2 Network Refinement 11
    3.1.3 Traffic Demand 12
    3.1.4 Model Calibration 15
  3.2 Modeling of Traffic Signal System 20
    3.2.1 Unsignalized Intersections 22
    3.2.2 Signalized Intersections 22
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Travel time and speed of streetcar between simulated and real network</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>Streetcar Vehicle Specifications</td>
<td>42</td>
</tr>
<tr>
<td>4.1</td>
<td>Simulation results: summary of the base case with the capacity function and without the function</td>
<td>55</td>
</tr>
<tr>
<td>4.2</td>
<td>Simulation results: summary of scenarios 1, 2, 3 &amp; 4</td>
<td>55</td>
</tr>
<tr>
<td>4.3</td>
<td>Simulation results: summary of scenarios 1, 4, 5 &amp; 6</td>
<td>66</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Study Site: The 504 King street route</td>
<td>3</td>
</tr>
<tr>
<td>3.1</td>
<td>Downtown Toronto Sub-area in EMMU/2 Network</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>Assigned vs Observed volumes</td>
<td>15</td>
</tr>
<tr>
<td>3.3</td>
<td>Layout of Artificial Signal Stop</td>
<td>45</td>
</tr>
<tr>
<td>3.4</td>
<td>Procedure of Dwelling time Calculation</td>
<td>47</td>
</tr>
<tr>
<td>4.1</td>
<td>Transit cycle time (transit priority options, minutes)</td>
<td>56</td>
</tr>
<tr>
<td>4.2</td>
<td>Transit total travel distance (transit priority options, km)</td>
<td>57</td>
</tr>
<tr>
<td>4.3</td>
<td>Transit travel speed (transit priority options, km/h)</td>
<td>58</td>
</tr>
<tr>
<td>4.4</td>
<td>Average headway (transit priority options, seconds)</td>
<td>59</td>
</tr>
<tr>
<td>4.5</td>
<td>Headway standard deviation (transit priority options, seconds)</td>
<td>60</td>
</tr>
<tr>
<td>4.6</td>
<td>The percentage of headways that is less than 30 seconds and</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>more than 5 minutes (transit priority options, %)</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>Transit service frequency (transit priority options, vehicles per hour)</td>
<td>62</td>
</tr>
<tr>
<td>4.8</td>
<td>Average speed of all vehicles (transit priority options, km/h)</td>
<td>63</td>
</tr>
<tr>
<td>4.9</td>
<td>Average travel times on cross roads (transit priority options, sec)</td>
<td>64</td>
</tr>
<tr>
<td>4.10</td>
<td>Transit cycle time (conditional TSP, minutes)</td>
<td>66</td>
</tr>
<tr>
<td>4.11</td>
<td>Transit total travel distance (conditional TSP, km/h)</td>
<td>67</td>
</tr>
<tr>
<td>4.12</td>
<td>Transit travel speed (conditional TSP, km/h)</td>
<td>68</td>
</tr>
<tr>
<td>4.13</td>
<td>Average Headway (conditional TSP, seconds)</td>
<td>69</td>
</tr>
</tbody>
</table>
Figure 4.14 Headway standard deviation (conditional TSP, seconds) 69
Figure 4.15 The percentage of headways that is less than 30 seconds and more than 5 minutes (conditional TSP, %) 70
Figure 4.16 Transit service frequency (conditional TSP, vehicle per hour) 71
Figure 4.17 Average speed of all vehicles (conditional TSP, km/h) 71
Figure 4.18 Average travel times on cross roads (conditional TSP, sec) 72
### LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Turning Movements Counts</td>
<td>82</td>
</tr>
<tr>
<td>B.</td>
<td>Headway Variance Graphs</td>
<td>85</td>
</tr>
<tr>
<td>C.</td>
<td>Simulation Results Summary</td>
<td>89</td>
</tr>
<tr>
<td>D.</td>
<td>Examples of the Signal Plans</td>
<td>96</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Transit priority is defined as the provision of preferential treatment to transit vehicles in the design or control of transportation facilities. Transit priority schemes, such as transit exclusive lanes or transit roads, are typical examples of facility design based methods. Transit signal priority (TSP), on the other hand, provides priority by modifying signal timing; a typical method that changes the ways of control in transportation facilities [1].

Transit signal priority has been viewed as a potential option to improve the performance of transit by improving mobility, which is at a competitive disadvantage to the passenger vehicle. A large number of studies and experiments relating to transit signal priority has been conducted for the last several decades with some of the priority methods being implemented into signal systems. However, it has been found that unconditional provision of signal priority may cause serious disruptions in traffic coordination systems, may cause intensive delays on side streets, and may even cause damage to the transit operation.

Recently, conditional priority methods have been developed to ameliorate the loopholes concerning unconditional transit priority provision. In some instances where all vehicles are treated equally, it has been found that there are additional delays on the side streets and even more side effects to transit streets. Giving favorable treatments only to selected transit vehicles satisfying the pre-set conditions would result in less additional green time on
transit streets and reduce the loss of green time on cross roads. Thus, the conditional priority method is expected to solve the existing problems of the unconditional method by improving transit performance without causing serious harmful effects to cross roads.

The objective of this study was to examine the impacts of several transit priority strategies on a streetcar corridor in the city of Toronto. Six scenarios were focused on: (i) the status quo (including unconditional transit signal priority), (ii) the termination of the unconditional TSP, (iii) the provision of unconditional TSP while restricting vehicular left turn traffic, (iv) the provision of unconditional TSP while banning all traffic from King Street, (v) the status quo with conditional TSP, and the application of the conditional TSP while banning all traffic from King Street. It is clear that the last two scenarios replace the unconditional signal priority system in scenario (i) and (iv) with conditional TSP.

The 504 King streetcar route corridor in downtown Toronto was chosen for the study. Beginning at the Dundas West subway station and heading south, this consists of Dundas St. West, Roncesvalles Ave., King St., a short section of Queen St. East, and Broadview Ave., ending at the Broadview subway station. All crossroads up to the next intersection were also added. The 504 King streetcar route corridor is figure 1.1.
A microsimulation model was developed in Paramics (traffic simulator) to assess the various scenarios. The developed model was enhanced with an Application Programming Interface (API) program to enable modeling of streetcar capacity and as such represent appropriately instance of capacity spillover. Simulation results of the base network, prior to the development of the capacity and occupancy functions, were presented to demonstrate relative impacts of the streetcar vehicle capacity and occupancy function.

The simulation results of the six scenarios were analyzed with selected measures of effectiveness in order to assess the relative impact of the above scenarios. The selected MOEs include transit cycle time, transit total travel distance, transit travel speed, average transit headway, transit headway standard deviation, bunching rate of transit vehicles, transit service frequency, overall vehicle speed, and cross road traffic travel time.
A historical background of transit signal priority, transit priority methods, and some research results are presented in chapter 2. A detailed explanation of King Street route including the current signal system, the scenarios, the modeling method of the transit system, and the types of data used in the study are discussed in chapter 3. The scenario development procedures and the simulation results are discussed in chapter 4. The conclusion section states the findings from the simulation results and suggests future research.
CHAPTER 2

LITERATURE REVIEW

Travel times of transit vehicles are slower than those of passenger vehicles due to low acceleration rates and deceleration rates as well as the dwelling time incurred at stops for passenger boarding and alighting. The initial concept of transit signal priority, now called ‘passive priority strategies’, was to provide adjusted signal timing to accommodate the slow travel speed of transit vehicles. Passive priority strategies are relatively low-cost compared to active strategies, since detectors or communication equipment required to recognize the location of transit vehicles are not required. Passive priority strategies are most effective with high transit vehicle volumes and predictable transit arrivals [2].

Passive priority was developed and tested based on the SCOOT (Split. Cycle. Offset optimization Technique) system [3]. Weighting factors in SCOOT were used for preferential treatment on particular routes. The split weighting was modified to distribute more spare green time to weighted links. The offset weighting was used to produce signal offsets in a way that would give priority to the links, which had higher offset weighting values. The results for the passive signal priority test showed a slight increase of 1-2 percent in overall delay, while 5-8 percent of transit delay was reduced.

From the 1970s, a lot of research related to TSP with active priority strategies was conducted. Active priority is different from passive priority since priority is only given
when transit vehicles are approaching intersections. As a result, selective detection of transit vehicles is necessary. Extension of the priority phase, early truncation of the non-priority phase, omission of the non-priority phase, and inserting the transit exclusive phase are other widely used strategies of active transit signal priority.

In 1970, the green extension method was tested in Los Angeles under actual traffic conditions with the aim of introducing the bus priority system. This priority system let drivers who are approaching signalized intersections indicate whether they intend to stop or not. The test result showed that 5% - 7% of portal to portal trip time was reduced, as well as a 15% - 20% reduction of bus riding time [4].

In 1975, J. S. Ludwick reported simulation results of the unconditional transit priority with the use of the Urban Traffic Control System model. A simple bus priority algorithm was tested on a traffic network with a number of combinations of various bus headways, bus stop locations, and number of routes. The bus priority provided benefits to buses as well as other vehicles on the bus streets. Unfortunately, the results found that additional delay had occurred to cross road traffic, especially with short bus headways or near side bus stops [5].

In 1983, D. A. Benevelli et al studied the effects of implementing a bus preemption strategy on an arterial corridor. They used the UTCS/BPS microscopic traffic simulation model to simulate the bus preemption system operation for various bus flow rates and bus stop locations. The simulation results showed that the benefits of bus preemption were greatly dependent on the preemption algorithm structure and the bus stop location [6].
A number of transit signal priority strategies were tested to promote the transit operation efficiency of SCATS (Sydney Coordinated Adaptive Traffic System). [7,8] SCRAM (Signal Coordination of Regional Area in Melbourne) was also proposed to improve SCATS, especially in the area of transit operations. Both active and passive transit signal priority strategies have been tested in the studies. The transit exclusive phase, the minimization of cycle length, and the provision of offsets based on transit vehicles are typical methods of passive transit priority. Also green extension and red truncation methods were tested as active strategies. The test results indicated that the system failed to deal with the scenarios where more than two transit vehicles approached at the same time [9,10].

The SPPORT (Signal Priority Procedure for Optimization in Real Time) model was developed to analyze transit operations, general flow of traffic, and the integration of transit signal priority methods into its optimization process. This model optimization process is based on lists of rules that allocate different priority to key traffic events. The events are projected in advance by using a discrete-event traffic microscopic simulator, and phase plans are generated in order to accommodate the events as effectively as possible [11,12,13].

In recent years, the emphasis of TSP strategies has been shifting away from unconditional priority to conditional priority with improved technologies in communication such as the Automated Vehicle Location (AVL) system, Automated Vehicle Identification (AVI) system, and the Global Positioning System (GPS).
G. Chang et al developed integrated models for an adaptive control system with bus preemption. The decision of the control system was based on the performance index incorporating vehicle delay. The model without AVL systems employed bus detectors to identify the location of the buses in a mixed traffic stream. Real-time traffic variables from the output of TRAF-NETSIM were used to test the performance of the algorithm. The experimental results showed that the proposed model performed better than the actual control logic simulated by NETSIM; under various traffic conditions [14].

Alexander Skabardonis reviewed the existing transit priority strategies, identified the major factors affecting transit priority, and described the formulation of three conditional transit priority schemes. Criteria for providing the priority included the availability of space green time in the system cycle length, progression, and schedule adherence [1].

K. N. Balke et al proposed an intelligent bus priority concept. The concept used bus position information to predict when in the cycle a bus would arrive at the bus stop and stop line of a signalized intersection and to evaluate if a bus needed priority. The concept was developed in an environment that assumed the bus stops were located nearby. Priority strategies including phase extension, phase insertion, and early return were tested. The results were very effective in reducing transit delay without causing interruption to the coordination of the system. The performance of the intelligent bus priority was examined with three different volume-to-capacity levels: 0.5, 0.8, and 0.95. The results indicated significant reduction in bus travel times at all three levels, and minor increases in the total system stop delay and individual approach stop delays at the 0.5 and 0.8 v/c levels [15].
It is not clear from the literature whether conditional transit signal priority yields significant benefits to transit operation along high frequency route with minimum impact on other traffic. It is not also clear were those benefits and impacts compared to other priority methods. This study will explore those questions.
CHAPTER 3

METHODOLOGY

3.1. Development of the Base Network

As the initial step of the study, the base network was developed with the microsimulation program, Paramics. The data used in this study were obtained from a variety of sources. Various sections of the Toronto Works and Emergency Services Department provided the Toronto Centreline data, base plans, traffic signal data, and turning movement counts. Transit-related information such as routes, schedules, streetcar operations, stop locations, passenger boardings and alightings, transit vehicle specifications, as well as speed travel time data was provided directly by the Toronto Transit Commission (TTC). Further data such as turning restrictions, speed limits were collected on a number of site visits. All data pertain to the morning peak period.

3.1.1. Skeleton Network Coding

The first step in coding a Paramics microsimulation model is to build a skeleton network, which defines the position of the main nodes and links in the model. This can be achieved by direct conversion of coordinate data to the correct Paramics network text file format. Alternatively, an AutoCAD (DXF) file can be loaded and displayed within Paramics to function as an overlay for manual network coding. This latter approach was chosen for this study.
The City of Toronto Centreline data (TCL), from Toronto Survey and Mapping Services, provided the basis for the skeleton network coding. This data was provided in ArcView Shapefile format. It was necessary to import the file into ArcInfo and discard superfluous display layers. From ArcInfo, it was then possible to export the file to the DXF format. During this step, appropriate DXF colour specifications were chosen that would be correctly displayed in Paramics, and would not conflict with colours used to display other features.

The original TCL file, as well as the resulting DXF, is projected in the Universal Transverse Mercator (UTM) coordinate system (NAD 27), which uses 1 metre units. This DXF was loaded as an overlay in Paramics, with a scale of 1:1 and in the proper position, and used as a guideline for manually adding the main nodes and links of the microsimulation network. The result was a Paramics network in the proper scale and with the proper UTM coordinates. This simplifies the incorporation of data from other sources, as features will match spatially as long as the same coordinate system is used.

3.1.2. Network Refinement

The accuracy of the microsimulation model is generally improved by replicating the roadway geometrics as closely as possible. To provide more detail, base plans for the King Street corridor were also used. These are Microstation digital files based on the Property Data Sheet series, which is maintained by Survey and Mapping Services. The Topographic Mapping section of Survey and Mapping Services provided assistance by converting the Microstation files to AutoCAD format.
Using AutoCAD, it was then possible to discard the layers that were not needed and create DXF files with appropriate DXF colour specifications. Based on the resulting DXF overlay, the skeleton network within Paramics was refined by correcting the roadway widths, number of lanes as well as exact intersection layouts including curb locations. Intermediate nodes could also be added to better replicate the actual roadway geometry. In addition, Paramics allows for the definition of curved links, which were chosen where appropriate to provide a better match with either of the overlays (TCL or base plan).

3.1.3. Traffic Demand: Developing the Origin-Destination Matrix

As described above, the study network includes the 504 King streetcar route corridor along Roncesvalles Ave., King St. and Broadview Ave., as well as all cross roads up to the next intersection. No parallel roads to this corridor were included, as this was deemed beyond the scope (and resources) of this study. The simulation represents the traffic and transit operations in the study network during the morning rush hour on a typical weekday of Fall 2000. As such, the input traffic demand should represent the same time period.

In order to simulate vehicle traffic in the study network, Paramics requires as input the vehicle traffic demand between each pair of terminal nodes of the network. For this study, the only source of origin-destination trip data is the Transportation Tomorrow Survey (TTS), the most recent of which was conducted in 1996. Obviously, this data is inconsistent with the desired simulation of fall 2000 conditions. This study used a "reverse traffic assignment" approach to adjust the relevant 1996 O-D matrix in order to represent the
actual fall 2000 traffic conditions. In contrast to the conventional traffic assignment which assigns an input O-D matrix to the road network producing link and turn volumes, this approach uses actual link and turn volumes (fall 2000) to adjust the input O-D matrix (the 1996 O-D matrix). An iterative process involves several traffic assignments, so as to cause the new adjusted O-D matrix reproduce the actual observed volumes. This approach has been implemented in study using the gradient-based model developed by Spiess (1990). In more detail, the following steps were followed in our study:

- Traffic movement counts along the study corridor were obtained from the City of Toronto. The counts were representative of traffic mainly during the morning rush hour on a typical weekday in year 2000, though some of them were collected earlier.

- A traversal matrix for the downtown area was created in EMME/2. This is an origin-destination trip matrix for all zones in the downtown sub-area, including the downtown internal zones plus other zones (or “gates”) which were created at the downtown periphery. The Figure 3.1 shows the downtown sub-area. The traversal matrix was created from a traffic assignment of the 1996 morning vehicle trips to the GTA road network. As such, the traversal matrix represents intra-downtown traffic and traffic entering/Exiting downtown during the morning rush hour of a typical weekday of Fall 1996.
Figure 3.1 Downtown Sub-area in EMMU/2 Network

- Using the "Gradient Approach For The O-D Matrix Adjustment Problem", the traversal matrix was updated based on the traffic counts to produce an adjusted O-D matrix that represents year 2000 conditions along King St.. This was done using a macro available from the support center web-site of INRO (the developer and maintainer of EMME/2). The resulting R2 (measuring how close the traffic movement volumes from the procedure are to the actual traffic volumes) was 0.853, which compares favourably with other reported results (Spiess. 1990). The Figure 3.2 shows the actual vs the assigned volumes.
3.1.4. Model Calibration

A process of calibrating network geometry was necessary to avoid unusual behaviour and simulation results, which may be due to inexact modeling of the network. This was done visually, by observing the individual vehicles, signals, etc, via the Paramics graphical user interface. In addition, a variety of statistical outputs can be gathered to support this calibration effort [17.18].

Problems that can often be observed include unrealistically long queues, complete network breakdown, or perhaps unreasonably short queues or high speeds. Initially, one must review all the previous coding steps, from basic network construction, to traffic signals and transit
coding, and identify possible coding errors. A few additional features will be mentioned here, that were used in this study in an attempt to address problems at individual locations in the network.

- Curbs and Stop lines
Each link has an inside and outside curb point, both at the start of the link and at the end. By default, in Paramics, locus points are defined along a line joining each pair of curbs so that for each lane on a link a locus point is drawn at the centre of the lane. Vehicles have to pass through these locus points as they move through a junction. For example, if locus points for the in and out links of a 90 degree turn are very close to each other then vehicles making that turn are forced to traverse the curve very slowly. It is therefore important that curbs are positioned to reflect the actual road layout as accurately as possible. For geometric network calibration, individual locus points were adjusted by matching the points with information from the overlay files. In addition, unusually slow or jerky turning movements were rectified.

- Next lanes
When a vehicle reaches the end of a link, Paramics calculates the range of lanes suitable for the vehicle on the next link. However, it is possible for the user to override this default range and specify the exact lane on the next link for each lane on the current link. Collected lane usage and turning restriction information were used to rectify any lane choice problems that were observed initially.
• Gradient

A gradient can be specified for each link. The value can be either positive or negative, and will affect the acceleration and deceleration of vehicles, dependant on their weight.

• Visibility

This is the distance back along the link from a downstream intersection, at which the conflicting streams of traffic are initially seen by oncoming traffic. If no conflicting traffic is seen while the oncoming traffic is within the visibility distance, then that vehicle may travel through the downstream junction without slowing to give way to higher-priority movements.

• Headway factor

The target headway for all vehicles on a selected link can be modulated using the headway factor. Certain locations in a network may in reality prompt drivers to accept a headway that is longer or shorter than the average (bridges with reduced visibility, important merging areas, tunnels, etc.).

• End speed

To simulate traffic calming measures and stop signs, a terminal speed can be defined for a link.

A number of system-wide simulation parameters exist which were also used to calibrate the network. For this purpose, outputs generated by the simulation were compared with real-
life data. The primary statistics used for the calibration were the turning movement counts as well as streetcar travel time. The following system-wide parameters were adjusted during the calibration procedure:

- Time-step per second

The default time step in Paramics is 0.5 seconds (i.e., 2 time steps per second). Paramics is a discrete simulation, and as such is always an approximation compared with the reality of continuous motion. In order to achieve accurate results from the loop detectors, a time step of 0.1 seconds was chosen. Among other things, this signifies that the signal plans will be executed 10 times per second, and that the sample rate of loop detectors is also 10 times per second. In addition, this will cause vehicles to move much more smoothly through the network, but it also significantly increases the computational load and run time of each simulation.

- Driver Behaviour

Paramics use a model where each driver-vehicle unit is assigned a number of behaviour parameters. Awareness and aggression can be assigned to individual drivers when the vehicle is released into the network according to the researcher’s specified distributions, including square distribution and normal distribution. In this study, the behaviour of drivers was assigned to follow a square distribution.

- Mean headway

This is the headway for all vehicles on all links (not to be confused with transit vehicle headway), around which individual vehicles will be distributed. After a number of tests, the
Mean headway was set back to the default value of 1 second, as this has been calibrated in other studies by the software developers.

- Mean reaction time
This parameter affects the average reaction time to changes in front of a driver, for example, a vehicle braking. After more testing, it was also set back to the recommended value of 1 second.

- Seed number
This can be used to set the seed value for the random number generator. If the seed number is not specified, the current system time will be used. This would guarantee a different outcome from each simulation run, even if all the other input parameters are not changed. Numerous runs with various seed values were completed in all cases, to ensure the validity of the results.

After the model calibration process, eleven signalized intersections were chosen for the purpose of comparing turning vehicle counts between real network and simulation network. The results are shown in the appendix A.

Travel time and travel speed of streetcar also compared for the same purpose. The following table shows travel time and speed of streetcar between calibrated network and real.
<table>
<thead>
<tr>
<th>Travel time (min)</th>
<th>Real Network</th>
<th>Simulation Network</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eastbound</td>
<td>Westbound</td>
</tr>
<tr>
<td>55.4</td>
<td>56.9</td>
<td>58.9</td>
</tr>
<tr>
<td>Travel speed (km/h)</td>
<td>13.4</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Table 3.1 Travel time and speed of streetcar between simulated network and real

3.2. Modeling of Traffic Signal System

The 504 King streetcar route traverses 32 signalized and 80 unsignalized intersections. The lane usage at intersections, turning restrictions, and traffic signals were coded at this stage.

The exact implementation of the traffic signal control system is crucial for the performance of downtown arterial roads. As such, the signal system needs to be properly reproduced within a microsimulation model. Due to the significance of signal preemption as a transit priority measure, the traffic signals are an especially important component within this study. Researching, documenting, and implementing the existing signal system within Paramics, and reproducing the necessary algorithms for actuated signals with the plan language that Paramics provides, was perhaps the most demanding portion of this work. As such, the relevant components of the Toronto traffic signal control system are documented here.

Although the City of Toronto operates a total of three different signal systems, all the traffic signals along the 504 King streetcar route are controlled by only one of these systems: the
Main Traffic Signal System (MTSS). MTSS is an interval-based traffic signal control system, and it was reproduced successfully in the phase-based system that is used within Paramics.

For each of the 32 signalized intersections in the network model, the Toronto Traffic Signal Control Section provided an MTSS Intersection Timing Report, as well as a timing card. The Timing Report provides such information as control mode, controller type, transit preemption type, transit preemption interval, number of detectors, timing plans and schedules, intervals, aspects, cycle lengths, offsets, minimum green times, and extensions. The timing card provides additional information that is often necessary in order to understand the signal algorithm at an intersection, such as the differences between system and local controller intervals, extension methods, etc. Further remarks are often included on both the Timing Report and the timing card that may be of special interest for transit signal priority.

The timing plan schedules of signalized intersections usually feature at least three different plans for morning peak, afternoon peak, and off peak time, with different cycle lengths, offset values, interval lengths, etc. “Shoulder” time plans as well as special function plans may also exist. Only the AM peak timing plan was implemented in all cases for this study.

For many of the intersections that feature transit signal priority, an additional document was provided, with a written description of the existing priority algorithms.
3.2.1. Unsignalized Intersections

At unsignalized intersections, every turning movement is assigned a priority of Major, Medium, Minor, or Barred. Major movements are free flow and do not need to yield to other streams of traffic. In the network, through and right-turn movements from a major road are given the designation Major. A Medium priority movement yields right-of-way to Major streams of traffic but has priority over Minor traffic movements. The left-turn movements from a major street onto a minor side street have Medium priority at unsignalized intersections in the network (i.e., they must yield to the opposing traffic, but have right-of-way over vehicles exiting from the minor side street). Minor priority gives way to both Major and Medium traffic flows while Barred indicates the turn is banned to all vehicle movements. Traffic flows exiting minor side streets, as well as right-turn flows on red, are assigned the minor priority.

3.2.2. Signalized Intersections

Traffic flows at signalized intersections use the same Major, Medium, Minor, or Barred designation, but the designation for each turning movement can change with each of the phases that are offered at a signal.

The modeling of actuated signals and transit signal priority algorithms were executed in the Paramics plan language, which is similar to a C programming language. The plan language associates particular detectors with specific signals and defines the control parameters for changing the signal settings. A single signal plan can be used for a number of intersections.
which have the same signal control algorithm, yet have their own parameters such as minimum green and maximum number of extensions. However, a different signal plan must be defined for every unique signal algorithm (i.e., different decision point).

3.2.2.1. Detectors Implementation

Within Paramics, a generic detector object can be defined. A detector can be placed anywhere on a link between the “entry point” at the upstream end of the link and the stop line at the downstream end of the link. Actuated signals and transit signal priority algorithms required different types of detectors, while other types of detectors were implemented for the purpose of collecting simulation results. Loop detectors in Paramics can classify vehicle types, and therefore are able to distinguish a streetcar from other vehicles. In this study, the following types of detectors were used, (though several more types of detectors are available additionally such as speed, headway, gap or edge detectors.):

- Occupancy detector – the “on” or occupied time flow
- Count detector – the total number of vehicles crossing the loop
- Type-count detector – a count of each type crossing the loop

Transit signal priority request loops, as describe in the following, were implemented at their exact locations. Priority cancel loops and detectors for semi-actuated signals were located at stop lines.
3.2.2.2. Traffic Control Modes for Signalized Intersections

The 32 signalized intersections within the study area exhibit a variety of modes of signal operations. Four basic "Modes" can be found, and all of these modes and associated algorithms were implemented within the traffic microsimulation model. The simulation of pedestrian signals was beyond the scope of this study, yet a description of the handling of pedestrians by the signal algorithms is included.

*FXT Mode*

Of the signalized intersections in the study area, 20 are under FXT mode of control. At FXT signals, both main-street green as well as side-street green (and/or other normal aspects) is served during every cycle. Beyond that, a limited amount of signal actuation does in fact occur at FXT intersections, and will be described below in more detail. In addition to transit-preemption functions, vehicle detectors may be used to call special aspects for the purpose of protected left-turns, i.e., actuated flashing advanced green or left-turn arrow.

*SAP on Recall*

Additional 7 signalized intersections use "SAP on Recall," and are actually FXT signals/controllers. There is no side-street actuation, and the side street will receive green in every cycle. For the most part, these intersections function exactly like FXT, except their treatment during offset recovery is following the method of semi-actuated mode.
**Semi-actuated Modes**

There are two types of semi-actuated signals within MTSS, and 5 of the signals in the study area use one of these modes. Many of the characteristics of these two modes are identical, and are described in the following.

At intersections controlled by semi-actuated signals, side street green will only be given if there is a side-street actuation. These intersections will always have side-street vehicle detectors at the stop line. There is no maximum limit of main street green, so the side-street green will never be served if there is no actuation. Vehicle detectors are designed to “fail safe”: if they fail, then the side street will receive green during every cycle. However, the “fail-safe” function does not always work. Algorithms have been implemented within MTSS to check for “faulty full” errors (in the middle of the night) and “faulty empty” errors (during the afternoon peak period).

If there is no side-street actuation, the signal controller will remain in the hang interval. This is the main street major interval (the first capitalized aspect string on the MTSS Intersection Timing Report). The main street will therefore receive a continuous green signal. When there is a side-street actuation, the controller will wait until the proper time has been reached in the cycle, and then begin advancing. It will serve any main street green intervals that may follow the main street major interval, and continue on to main street yellow, all-red, side-street green, etc. until the hang interval is reached again.
The shortest possible delay between side-street actuation and provision of side-street green will occur if the side-street actuation is received one second before the end of the main-street major interval. In this case, the controller will immediately advance beyond the hang interval, and will provide side-street green shortly thereafter.

The longest possible delay before the provision of side-street green will occur if the side-street actuation is registered shortly after the end of the main street major interval. In fact, there will be a wait of more than one full cycle length before the side street receives green. This maximum delay is significant, given the prevalent cycle length of 70 seconds at the semi-actuated signals within the study area. Transit signal priority and offset recovery, as described below, can cause an additional time lag before the side-street green is served.

As can be seen in the following, there are two significant differences between the two types of semi-actuated signals within MTSS: the provision of per-vehicle side-street extensions.

*SAP ("SAPLO")*

This is an older type of semi-actuated signal within MTSS, and a total of 3 signalized intersections in the study area use this mode of control. Pedestrian and vehicle side-street detection are treated the same at these intersections. If the side-street green is called, both a side-street green and a pedestrian "Walk" will always be displayed simultaneously. The same amount of green time will be given for the side street, regardless of whether a vehicle actuation, a pedestrian actuation, or both were received. In fact, the minimum amount of time that needs to be provided for pedestrians to cross the main street is usually greater than
the minimum amount of time that would be necessary for side-street vehicles. Therefore, a SAP controller may be providing a longer side-street green time than is necessary if only a side-street vehicle actuation was received. In addition, there are no per-vehicle extensions for the side street: the same amount of side-street green is always given, regardless of how many vehicles are attempting to exit from the side streets.

SA2

This is a newer type of semi-actuated signal within MTSS, and only two of these signals exist in the study area. In this case, pedestrian and vehicle side-street actuation are wired separately. If there is a vehicle actuation, but no pedestrian actuation, a side-street green will be served without a side-street "Walk." If the side-street pedestrian minimum is longer than the side-street green minimum, the side street green only needs to be as long as the vehicle minimum green in this case.

If on the other hand the pedestrian button is pushed, but no vehicle is detected on the side street, both a side-street "Walk" and a side-street green will be displayed.

SA2 intersections allow for per-vehicle extensions. An initial time for side-street green will always be served after a side-street actuation. Then an extension side-street green interval is served for a minimum time period. If an additional vehicle is detected at the end of those initial seconds in the extension interval, the controller will start serving per-vehicle extensions.
For the per-vehicle extensions, the controller will start counting down. If it reaches 0 without an additional vehicle being detected, the controller will advance to the next interval (side-street yellow). If however an additional vehicle is detected while counting down from the per-vehicle extension, the controller will immediately reset back to the per-vehicle extension and start counting down again. In addition, a maximum vehicle extension is defined for each SA2 intersection. Regardless of how often vehicles are detected, extensions will only be served up to this maximum.

Protected left turns

A number of the signalized intersections within the study area have provisions for protected left-turn movements. These may be implemented via flashing advanced green signals or left-turn arrows. Such signals may be provided as one of the "normal" aspects, i.e., the aspect is served in a normal signal cycle, and does not rely on vehicle actuation.

In other cases, the protected left turn may be a "callable" aspect, which is only served if a vehicle has been detected within the left lane. This type of vehicle actuation can exist at signalized intersections under any of the modes of control, including FXT.

3.2.2.3. Transit Signal Priority

The 504 King St. route corridor was the first location where transit signal preemption was implemented in Toronto. As of Fall 2000, transit signal preemption was active at 27 of the 32 signalized intersections in the study area. Only the following five locations are excluded: Queen at Roncesvalles and King, Spadina at King, University at King, Bay at
King, and Yonge at King. All five of these feature very important cross streets, leading to concerns that transit signal priority would have an unacceptable impact on motorists.

For the implementation of transit signal priority, it was possible to make use of some pre-existing transit infrastructure. All TTC streetcars are equipped with transmitters that are used to control the position of track switches, via antennas, which receive these requests. For transit signal priority, additional antennas were installed as loops cut in the road surface between the streetcar tracks. For the signal controllers, these are implemented as presence detectors, which detect only transit vehicles.

A pair of detector loops is required for each direction at a signalized intersection with transit signal preemption. A first "request loop" is situated upstream of the intersection. In the study area, the average distance from the request loop to the stop line is approx. 80 metres, with extremes of 20 metres and 174 metres. The TTC provided information about the request loop locations for each of the signals with transit priority. For each direction, an additional "cancel loop" is located just past the stop line.

At an intersection with transit signal priority, if a streetcar has been detected at the upstream request loop, and has not yet crossed the cancel loop at the stop line, the controller considers the "zone" to be "active" for this transit route direction. Two basic algorithms are used to provide signal priority for transit vehicles: transit-corridor green extension, and cross-street green early truncation. In addition to the exact signal timings, the choice of algorithms varies from intersection to intersection, but at least green extension is
implemented at every intersection where transit signal priority is active within the study area.

Green extension

For transit-corridor green extension, a decision point is defined on the intersection timing report and/or the timing card. In the signal data, the decision point may be defined as a value in seconds (e.g., “11 seconds”), in which case this refers to the number of seconds before the end of the transit-corridor green. Alternately, the decision point may be defined based on an interval number.

If either of the “zones is active” (i.e., for either transit route direction) at the time of the decision point for transit-corridor green extension, transit preemption is initiated and the signal switches to local control. The exact type of green extension employed at each intersection depends heavily on whether or not “Flashing Don’t Walk” signals have been implemented.

Over half of the signalized intersections in the study area do not display “Flashing Don’t Walk” for pedestrians. At these intersections the green extension algorithm will begin with an initial fixed green time period for the transit corridor which is equivalent to the green time which would have been provided by default without a transit preemption call. This is followed by 2-second demand-dependant extensions for the transit-corridor green. Parallel pedestrians will typically still have “Walk” during these extensions if separate pedestrian signals are installed. The extensions are served consecutively until the zone is cleared (i.e.,
streetcar passes the cancel loop) or until a maximum value is reached. This maximum value is defined per intersection, and tends to be 30 seconds at minor cross streets and 16 seconds at major cross streets. After the end of the demand-dependant extensions, amber will be served for the transit corridor, followed by all-red. The transit preemption then comes to an end, and the signal returns to system control, generally for the cross-street green.

At intersections with “Flashing Don’t Walk” signals, the green-extension algorithm may also begin with an initial fixed green time period for the transit corridor which is equivalent to the green time which would have been provided by default without a transit preemption call. In this case, this period will coincide with the “Flashing Don’t Walk” signal parallel to the transit route. The transit preemption algorithm will then continue with 1 or 2 second demand-dependent extensions of transit-corridor green, again until the zone is cleared or a maximum extension is reached (14, 16 or 30 seconds within the study area). The demand-dependent extensions will coincide with a “Don’t Walk” signal parallel to the transit route. The end of signal preemption will be similar to above.

At other intersections with “Flashing Don’t Walk” signals, the green-extension algorithm begins with the demand-dependent extensions, coinciding with a “Walk” signal parallel to the transit route. After the demand-dependant extensions are over (zone clears or a maximum of 30 seconds is reached), a fixed time period of transit-corridor green will follow, coinciding with the parallel “Flashing Don’t Walk” signals. Subsequently, transit-corridor amber and parallel “Don’t Walk” is served, followed by all-red and the end of signal preemption.
The differentiation between the two methods of integrating transit signal priority with “Flashing Don’t Walk” signals is quite important. In the former case, transit signal preemption comes to an end quickly after the end of the demand-dependent extensions, minimizing adverse impacts on cross-street traffic. However, the effective pedestrian “all-red” time is potentially very long, as a “Don’t Walk” signal coincides with the demand-dependent extensions. This creates greater negative effects for pedestrian, and could potentially increase the rate of jaywalking. However, the extended “Don’t Walk” may also be intended, to allow more turning vehicles to clear the intersection during this time.

In the latter method of integrating transit signal priority with “Flashing Don’t Walk” signals, adverse impacts on pedestrians are minimized. as the demand-dependent extensions occur during a “Walk” signal. However, it will take a significant amount of time for transit signal preemption to end after the extensions are over, as “Flashing Don’t Walk” still has to be served. This additional transit-corridor green time is potentially wasted. as the streetcar may have already cleared the intersection. Adverse impacts on cross-street are greater in this case.

Although the interactions between pedestrians and transit signal priority were not explicitly included in this study. this choice of signal priority algorithms must be considered for a comprehensive evaluation of benefits and disbenefits.
In addition to the standard transit-corridor green extension, transit signal preemption is also used to extend protected left-turn aspects at a few intersections in the study area. Unlike the other types of transit signal preemption, this algorithm will only be valid for one direction of the streetcar route at this intersection. Examples are King & Bathurst, as well as Danforth & Broadview. As left-turning vehicles share the centre lane with streetcars at these intersections, the extended "flashing advance green" signals ensure that vehicles blocking the streetcar can complete their turns and allow the streetcar to proceed. In either case, an additional decision point and maximum extension are defined for the "flashing advanced green" preemption. As in all cases of transit signal preemption, this algorithm only checks if a streetcar is in the "zone" at the time of the decision point. This is quite different from the normal callable protected left turn aspect, controlled by a standard vehicle detector loop.

*Early truncation*

The second basic method to provide signal priority for transit vehicles is cross-street green truncation, which is implemented at about one half of the signalized intersections in the study area. An additional decision point is defined for the truncation. If the zone is active at the time of this decision point (streetcar between request loop and cancel loop), the signal will also switch to local control. The signal timing will be altered to shorten the cross-street green time, and hasten the provision of green to the transit corridor. The amount of green time that will be subtracted from the cross street is a set value defined per intersection, ranging from 2 seconds to 6 seconds in the study area. One should note that green extension and red truncation are able to be combined in the same cycle.
Cross-street green truncation is impossible if the cross street is already operating at minimum pedestrian requirements (e.g., pedestrian minimum green). At the two SA2 intersections within the study area, cross-street green truncation is also not provided. Truncation is probably not as crucial at these types of intersections, as the cross street is only given green upon demand, and the use of demand-dependant vehicle or pedestrian extensions limits the provision of unnecessarily long cross-street green.

The treatment of opposing transit vehicle movements is important for the simulation of transit signal priority. At any signalized intersection, transit signal preemption will be provided if streetcars are between the request loop and the cancel loop in either or both directions at the respective decision point. For green extensions, if the zones are active for both directions at the time of the decision point, then both directions will have to clear in order to end the provision of demand-dependent extensions.

The manner in which transit signal priority handles streetcars, which are closely following one another should also be discussed. As soon as the first streetcar in a group crosses the cancel loop, any following streetcars that have already crossed the matching request loop will become invisible to the preemption algorithms. The zone will be considered inactive: transit preemption will never be called if this happens before the time of a decision point. Otherwise, if this occurs during the provision of demand-dependent extensions, the extensions will cease.
At Danforth & Broadview, a request loop is situated 20m before the northbound stop line, and a second one is at 85m before the southbound stop line. This pair of loops is used to control the provision of north/south (transit-corridor) extensions, as well as east/west (cross-street) truncation. As mentioned above, this intersection also features a northbound flashing advanced green, which can be extended via transit preemption. The northbound flashing advanced green extension is however controlled by a whole set of request loops, at 120m, 98m, 75m and 55m before the northbound stopline. The principal effect of these multiple request loops is that after the first streetcar in a group crosses the cancel loop, the zone will only be inactive for a short time. As soon as any following streetcar crosses one of the other request loops, the zone will be re-activated, so that the extended flashing advanced green can again be provided.

A number of signalized intersections also feature merging or crossing transit routes, with additional transit signal preemption defined in an attempt to also provide benefits to the crossing routes. Examples are Dundas & Roncesvalles, Roncesvalles & Howard Park, King & Dufferin, Bathurst & King, Queen & Broadview, Broadview & Dundas, as well as Broadview & Gerrard. The modelling of cross-street transit was beyond the scope of this study. Therefore, only the preemption algorithms directly related to the 504 King St route were modeled at these intersections.

The interaction between transit signal priority and semi-actuated signals also had to be taken into account while creating the microsimulation network. At semi-actuated intersections, the streetcar will of course always be travelling along the main street. The
side-street green is only served if there was a side-street actuation. As mentioned above, if there is no side-street actuation, the controller remains on the hang interval. In this case there is no need for transit priority, since the main street with the transit route is already receiving 100% green. Therefore, transit preemption is only active at semi-actuated intersections if there has been a side-street actuation.

**Offset Recovery**

All signalized intersections within MTSS are assigned an offset value in seconds. This offset is in reference to the master system clock, and is valid for the beginning of the first interval. (This is not necessarily equivalent to the beginning of the main street green, as the main street green may already begin in the last few intervals of a cycle and carry over to the first interval.) These offset values are generally used to preserve some kind of offset progression for vehicles travelling along a major corridor.

There are a number of situations that may lead to a traffic signal temporarily having the wrong offset value. An example is when a signalized intersection switches from one timing plan to another, e.g., from off-peak to AM-peak. However, the most common cause for incorrect offset values within the study area will in fact be a transit priority event. The offset recovery routine is initiated at the start of interval 1. Every time the system starts interval 1 it checks the cycle clock against the desired offset and makes necessary adjustments.

Most of the signals that provide for cross-street truncation along the 504 King route use a
truncation algorithm that in fact will not have an effect on the offset. In these cases, the
green time taken from the cross street is immediately balanced by an additional transit-
corridor green interval at the end of the same cycle. The offset will therefore be correct at
the start of interval 1, and no adjustment is necessary.
In a few cases (e.g., King & Strachan, King & Peter, Danforth & Broadview) the cross-
street truncation is not balanced immediately, and can cause the offset to be wrong by a few
seconds at the start of the next cycle. However, transit-corridor green extension has a far
more serious effect on the offset value, as demand-dependent extensions of up to 30
seconds can occur. A significant amount of adjustment is often necessary to return the
signal to the correct offset value.

If the system detects an incorrect offset value at the beginning of interval 1 (i.e., if the
difference is greater than 1.0 second), the transition algorithm proceeds as follows:

- If the actual offset is up to 1/4 of the cycle length behind the proper offset, offset
  recovery can occur by shortening the transition intervals to the minimum (Minimum
  CGI_GREEN). In addition, the total amount of time subtracted during a cycle may not be
  more than 1/8 of the regular cycle length. Note that the transition intervals are equivalent to
  the major green intervals, with capitalized aspect strings on the MTSS Intersection Timing
  Report.
- The algorithm will also check if this method (shortening green) would take more than 2
cycles to return to the proper offset: if this is the case, the lengthening method will instead
  be chosen (explained below).
• If the actual offset is ahead of the proper offset by up to $3/4$ of the cycle length (or in the special case mentioned above), offset recovery will take place by extending the transition intervals by a total of no more than $3/8$ of the cycle length.

• In the case of an FXT signal, both the main street and the side street green will be adjusted (shortened or extended) for the purpose of offset transitioning. The amount of adjustment applied to the two directions will be proportional to the default lengths of the major green intervals for these directions.

• At semi-actuated signals (SAP and SA2), and FXT signals coded as semi-actuated on recall, offset recovery only happens on the main street green. Due to the prevalent cycle lengths and the design of the transitioning algorithm, the lengthening method of offset recovery is most commonly used. In the case of SAP, SA2, and SAP on Recall, this has the additional side effect of providing significantly more green time and capacity to the transit corridor. In fact, the reason many signals which are actually FXT are coded as SAP on Recall is to achieve this benefit of additional transit-corridor green time.

• As is evident from these descriptions, it sometimes takes more than one cycle to return to the correct offset value. Occasionally a second transit priority preempt request is received before the proper offset has been restored. The utility of attempting to correct the offset along a transit route running at 2 minute headway in each direction, and therefore requesting transit preemption very frequently, should be examined in more detail.

• A special case of offset transitioning occurs at the SA2 intersections: Any pedestrian or per-vehicle extensions for the side street will make the offset wrong at the start of the next cycle. These SA2 side-street extensions will immediately be subtracted from the following main street major interval.
It should be noted that the combined effect of the default semi-actuation algorithm, transit signal priority, and offset transitioning can lead to extremely long delays for side-street traffic and pedestrians. An example would be King & Shaw, which operates as SAP. As mentioned above, the longest possible delay before the provision of side-street green will occur if the side-street actuation is registered shortly after the end of the main street major interval. In this example, this would occur if the side-street actuation is received just at the beginning of interval 3. Even without transit signal priority or offset transitioning, a vehicle or pedestrian would have to wait up to 89 seconds before receiving a green signal.

However, if a streetcar on King St. is between request loop and cancel loop one full cycle later (i.e., 70 seconds later; the decision point for green extension is at the beginning of interval 3), then an additional 30 seconds of demand-dependent east-west-green extension could be added.

On the other hand, offset transitioning occurs only on the main street major green interval at this SAP intersection. Therefore, offset transitioning alone could theoretically add a delay of 26 seconds (3/8 of 70 seconds). Without transit signal priority, the maximum delay for a side-street vehicle or pedestrian could therefore reach 96 seconds.

In fact, offset recovery and transit signal priority are independent events, and can both take place within the same cycle. Before interval 1, the offset transition algorithm may specify that interval 2 (transition interval) be lengthened by 26 seconds. The decision point for east-
west-green extension is after interval 2, and up to 30 seconds of demand-dependent extensions may be added. As a result, a maximum delay of 145 seconds for north-south pedestrian or vehicle movements is theoretically possible.

3.3. Modeling of Transit System

The 504 King streetcar route was modeled within Paramics using two separate transit routes: the eastbound route from the Dundas West subway station via Roncesvalle, King and Broadview to Broadview station, as well as the westbound route from Broadview station to Dundas West station.

3.3.1. Transit Route

The King streetcar travels in the centre lane in mixed traffic. This was replicated within Paramics using lane restrictions. Link and lane restrictions are very versatile within Paramics, allowing for transit-only links/lanes, or restrictions by individual vehicle type, as well as by vehicle characteristics such as weight, height, and/or width. In this case, the streetcar vehicle type was banned from the curb lanes in order to force the streetcars to use only the centre lane. For the most part, other vehicles were permitted to use all lanes, in order to emulate the mixed traffic conditions.

Two sections of King St. have designated streetcar-exclusive lanes: from Dufferin St. to John St., and from Jarvis St. to Parliament St. The restrictions are in effect from 7 to 9 AM and from 4 to 6 PM, Monday to Friday.
However, the compliance rate is not very high in reality. Simply using Paramics lane restrictions to ban all vehicles except for streetcars from the centre lane would not be realistic, as this would be reproducing a 100% compliance rate. Therefore, the general vehicle population was divided into two groups, with 50% being in a vehicle type that was banned from the exclusive streetcar lanes, and the other 50% not being restricted.

Many of the non-restricted vehicles continued to use the curb lane in free-flow conditions, while a higher percentage would select the lane designated as “streetcar exclusive” if the curb lane experienced congestion. The resulting behaviour was quite realistic, with an actual compliance rate of approximately 70%. In discussions with City and TTC staff, this was seen as a reasonable representation of reality.

3.3.2. Transit Vehicle Specification

In addition to the default vehicle types, the definition of exact streetcar specifications was used in the study. As Paramics only features buses as pre-defined transit vehicles, the streetcars were in fact implemented as a user-defined type. Only the TTC’s CLRV (non-articulated) vehicle type was modeled in Paramics, as this was the only vehicle available for service on the 504 King route in the fall of 2000, the base period for this study. (In the meantime, seven longer ALRV vehicles have been reallocated from the 511 Bathurst route to 504 King, however, that service change is beyond the scope of this work.) The following streetcar specifications were used in the model.
### Table 3.2 Streetcar Vehicle Specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Length</td>
<td>15 metre</td>
</tr>
<tr>
<td>Vehicle Width</td>
<td>2.6 metre</td>
</tr>
<tr>
<td>Acceleration Rate</td>
<td>1.47 m/s²</td>
</tr>
<tr>
<td>Deceleration Rate</td>
<td>1.6 m/s²</td>
</tr>
<tr>
<td>Max. Occupancy</td>
<td>75 passengers</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>50 mph</td>
</tr>
</tbody>
</table>

3.3.3. Streetcar Operations

The streetcar schedule was based on information provided by the TTC, and streetcars were released from the origin stations at the peak headway of 2 minutes in each direction.

Transit speed and delay data including travel time from origination to destination, passenger service time, signal delay, congestion delay, and trip speed were provided by the TTC. This speed and delay survey was performed from 7:30 AM to 8:30 AM on Nov. 30, 2000. This data was useful while coding the streetcar route, in order to understand how the route operates, but its primary application was in the calibration of the network, as described below.

3.4. Modeling of Streetcar Stop with Vehicle Capacity Function

There are a total of 114 streetcar stops on the 504 King route. Most of these stops are located at the near-side of intersections. The exceptions are 3 stops on the eastbound route
and 4 stops westbound which are located at the far-side, with streetcar platforms. The TTC provided information on stops, including the exact location of the stops in terms of distance from the cross-street curb, as well as distance from the previous stop.

Proper modeling of the streetcar stops was a critical part of this work, because streetcars have different operational characteristics from other transit vehicles. Paramics, as is the case with many other traffic microsimulation programs, does not have the built-in capability to properly reproduce the behavior of streetcars at stops in mixed traffic.

Although it was relatively easy to force the streetcars to travel in the center lane, using lane restrictions as described above, the normal Paramics transit stop will actually not function properly for a streetcar in the center lane. In addition, other vehicles should not pass a streetcar in the curb lane while passengers are boarding and alighting. This has major implications on roadway capacity; again, Paramics cannot replicate this behavior using a normal transit stop.

3.4.1. Artificial Signal Stop

A viable solution to this dilemma was found as part of this study. Artificial traffic signals were implemented at all streetcar stops in the model, instead of using actual transit stops. For this purpose, additional nodes were added at the streetcar stop locations, and traffic signals could then be associated with these nodes. The artificial signals force streetcars to stop by providing a red phase, according to the calculated passenger boarding and alighting time. The artificial signals in the model are actuated signals, and are controlled by loop
detectors that are programmed to only detect streetcars. As is the case for normal signalized intersections, a special programming language for actuated signals is available within the base Paramics Modeller software module, and can be used to implement these special streetcar-stop signals.

The streetcar-specific detectors are usually located 10 meters before the artificial signals. This ensures that, under free-flow conditions, the streetcar will have enough reaction time to be able to stop after being detected at the special streetcar detector and calling the red phase at the artificial signal. In addition, if other vehicles are queued ahead of the streetcar at the adjacent crossroad, and the streetcar cannot advance all the way to the proper streetcar stop location, it will nevertheless be able to service passengers as soon as it has reached the streetcar-specific detector. In other words, streetcars will let passenger board and alight up to 10 metres back of the proper stop location if other vehicles are queued ahead. This was found to be a reasonable reproduction of actual conditions, as discussed with TTC staff, and observed in the field.

In the curb lane, the stop line associated with the artificial signal is 7 – 8 metres behind the streetcar stop location, forcing vehicles to stop approximately half-way back along the streetcar while passengers are boarding and alighting at the stop. The following figure shows a typical near side streetcar stop with an artificial signal.
The TTC also provided data for passenger on and off counts for each stop. These statistics were collected from 8:00 AM to 9:00 AM on January 10, 2000, and were the most recent values available for this study. The passenger counts were used to implement the artificial signals at streetcar stops.

Once a streetcar activates the special loop detector, the artificial signal will provide a red phase to this roadway direction for the calculated dwell time. The default boarding time at a streetcar stop was set to 3 seconds per passenger, with an additional 4 seconds per stop. The default alighting time was set to 2 seconds per passenger, and 4 seconds of extra time. The actual streetcar dwelling time at a stop will be the maximum of the calculated boarding time and the calculated alighting time.
The passenger boarding time at a stop will have variable values, depending on the actual headway from the previous streetcar. Therefore, a streetcar which has arrived after a longer headway will require more time to board passengers. However, the number of alighting passenger at a stop is calculated as a proportion of the total passengers in a streetcar. For example, one could perhaps calculate that 20 percent of the passengers on a streetcar alight at a specific stop rather than a fixed number, as more passengers will obviously exit a fully occupied streetcar when compared with a streetcar with a lower passenger load. The alighting rates at the streetcar stops were calculated from the passenger on and off counts for each stop.

3.4.2. Streetcar Capacity Function
Since the artificial traffic signals were implemented instead to model appropriately operation at streetcar stops, a special function was developed and added to the model. The function incorporates streetcar capacity constraints to represent realistically streetcar occupancy and spillover instances. The function was coded in Visual C++ version 6.0 and added to the Paramics modeller as API overload function.

The API program grants streetcar id to every streetcar in the network, save the current occupancy of every streetcar, and calculates boarding and alighting taking into consideration vehicle capacity. Passengers beyond the capacity of the streetcar will stay at the stop and take the next one. Dwelling time at streetcar stop is calculated by the following procedure.
After the Paramics modeler initializes the API function, the program is on standby until streetcar detected in the network. When a streetcar leaves the origin, the program retrieves its pointer value and grants a streetcar index for the identification purpose. Every streetcar will have fixed initial occupancy, representing the passengers who boarded the streetcar at the origin. The initial vehicle occupancy is fixed, because all the streetcars are assumed to have same departure headway.

If a streetcar is detected by the loops for the artificial signals, the program will retrieve its streetcar index, so that the vehicle's current occupancy is determined. The next step is retrieving the network-wide detector index of the detector, which is occupied by the streetcar.
The detector index is associated with node number. For example, if the retrieved detector index is 10 and its associated node number is 5, then the red phase will be shown at the node 5 representing dwell time. The Paramics modeler automatically grants network-wide id to every detector.

As the next step, the program calculates the headway and expected boarding and alighting passengers. Passenger arrival rate and alighting rate at the stop are retrieved at this stage and used to calculate numbers of boarding and alighting passengers at the stop.

If the calculated number of expected boarding passengers is greater than the available occupancy of the streetcar at the stop, the difference is saved as leftovers at the stop, and added to the next expected boarding passengers.

The total boarding and alighting times and the dwell time will be calculated as the next stage. As mentioned earlier, the default boarding time was 3 seconds per passenger, with an additional 4 seconds per stop, and the default alighting time was set to 2 seconds per passenger, and 4 seconds of extra time. The actually provided dwelling time will be the maximum of the calculated boarding time and the calculated alighting time.
CHAPTER 4

MODEL APPLICATIONS AND DISCUSSION OF RESULTS

4.1. Scenario Development

The developed microsimulation model is very flexible and can in fact be used to examine a wide array of operational scenarios. As mentioned earlier, the purpose of this study was to examine the effects of various transit priority schemes and evaluate the performance of conditional transit signal priority on the network. Thus, several scenarios deployed different transit priority options in order to assess their relative advantages and disadvantages. Also, the conditional signal priority scheme was evaluated on two different networks. These scenarios are described as follows:

- **Scenario 1: Base Case**
  The status quo of streetcar operations on the King line is represented here, and it includes the already existing transit signal priority system.

  The following three scenarios (scenarios 2, 3, & 4) implemented different transit priority options. The simulation results will be used to compare with the results from the base case network.

- **Scenario 2: Turning off the signal priority**
  This scenario is the same as the base case except that the signal priority system is turned off.
A comparison of this scenario with the base case will be indicative of the merits of the already deployed priority system.

- Scenario 3: Banning of left-turns at all intersections in the base case

Left turn traffic can block the streetcar track for a significant length of time as vehicles wait for an acceptable gap in the opposing through traffic. This wait could be serious impedance to streetcar movement. Banning left turn movement is therefore expected to improve streetcar operations along King Street.

- Scenario 4: Banning all vehicles from King Street in the base case

The most aggressive scenario examined in this study is to ban traffic entirely from King Street to ensure an uninterrupted flow of streetcars along the King route. It should be noted, however, that this scenario does not necessarily indicate the adverse effect of diverted traffic on parallel roads (for instance, traffic that is diverted onto Queen Street). The model used in this study focuses solely on King Street, and no parallel arterials are modeled.

Scenario 5 and scenario 6 examine the application of the conditional signal priority.

- Scenario 5: Base case with conditional transit signal priority

This scenario adds a conditional signal priority scheme to the base network. The purpose of this scenario is to investigate the effects of conditional provision of signal priority to the real world network conditioned on selected measures of effectiveness such as cross road traffic travel times, transit headway, transit travel time.

- Scenario 6: Conditional Transit Signal Priority applied to the network where all traffic is banned from King Street
Provision of transit signal priority includes green extension, red truncation, and offset recovery to restore co-ordination along Broadview Ave., King St., and the Roncesvalles Ave. at most signalized intersections. For scenario 2 (i.e. no transit signal priority), all transit signal priority plan files in Paramics are eliminated except the plans for semi-actuated control and offset recovery.

For scenario 3 (i.e. left turn prohibition), Paramics automatically eliminates the zone-to-zone trips if they do not have any appropriate route between the origin and destination. Therefore, all the zone-to-zone trips, which have no options but to make a left turn, are set to zero in this case. This change caused about a 10% reduction in the total number of trips. In order to compensate for such an artificial reduction caused by the nature of the model, 10% of total demand is added to the model before the elimination of left-turning trips. The overall level of ‘traffic usage/congestion’ is therefore restored to normal/typical.

For scenario 4 (i.e. full traffic banning), all traffic destined to any zone on King St. is set to zero. Vehicles are allowed only on Roncesvalles Ave., Broadview Ave., and the side streets of King Street in this scenario. The only type of vehicle that is granted access to King Street is streetcar.

The fifth and sixth scenario replaced the deployed unconditional signal priority with a conditional transit signal priority. The concept of the conditional transit priority is to provide priority to selected transit vehicles which satisfy pre-set conditions related to the performance of the transit line and/or the cross traffic. In this study, signal priority is only
given to the streetcars that are behind schedule by more than 2 minutes, which is the
departure headway from the origin. The difference between scenario 6 and scenario 5 is
that all vehicles, which are headed to their destination zones on King Street, are deleted
from the zone-to-zone demand file.

4.2. Measures of Effectiveness
The following measures of effectiveness are selected to assess the relative impact of the
above scenarios.

- Cycle time is the time for a streetcar to complete a round trip, both in absolute
  minutes and as a percentage change relative to the status quo except for scenario 6, which is
  simulated to observe the effects of conditional transit signal priority. Transit cycle times
  are collected from the streetcars that finished their trips. Thus, the travel times of streetcars
  that did not arrive at the destination are not included.
- Transit total travel distance is a summation of each streetcar’s traveled distance for
  the simulation period. This shows the effects of transit priority on transit performance in
  terms of transit mobility.
- Average transit travel speed (km/h) demonstrates the performance of transit mobility
  with the use of transit travel time and travel distance.
- Average headway is the average time gap in seconds between successive streetcars.
  Note that the release headway of streetcars from the terminal is fixed at 2 minutes for all
  scenarios. However, for each scenario, the actual headways along the line vary due to a
  combination of interrupting factors (i.e. if there is no interruption, streetcars would arrive at
  each stop every two minutes). Therefore, the average headway captures the effective
  headway for the entire route under the considered scenario.
- Headway standard deviation indicates the variability around the mean headway.
- Headway spread is loosely interpreted as the percentage of transit vehicles following
too close and too far from each other (i.e. with very short or long headways). To quantify
this very subjective measure, transit vehicles are counted only if the headway is less than 30 seconds or more than 5 minutes.

- Average service frequency in streetcars per hour is defined as the number of streetcar finished trip for one hour, bearing in mind that the scheduled headway is fixed at 2 minutes for all scenarios, as discussed above.
- Overall vehicle average speed in km/hr is the average of the speeds generated by every vehicle in the network during the study period. It is used to assess the performance of the entire network which includes all types of vehicles as well as transit vehicles.
- Cross road Traffic Travel time is defined as through traffic only from cross road zone to cross road zone (i.e., from University Ave. north to University Ave. south). Transit priority impacts on cross roads must be quantified, because transit signal priority modifies signals in favour of transit roads rather than cross roads.

4.3. Simulation Results and Discussion

The purposes of developed scenarios fall into two categories: assessing the effects of transit priority options and the effects of conditional transit signal priority. Thus, the simulation results of the base network are compared to the results of the different scenarios, those implemented transit priority options (scenarios 2, 3, & and 4) independently. The scenarios deploying the conditional signal priority (scenarios 5 & and 6) are also compared with the results of scenario 1 and scenario 4. Prior to any comparison between the scenarios, the simulation results of the base network without the streetcar capacity or occupancy function are presented to show the effectiveness of the added capacity function.

4.3.1. Preliminary investigations

The simulation results of the base case network before the implementation of the transit capacity and occupancy function were collected to show the effectiveness of this function.
The detailed simulation results were presented by another report [16]. Table 4.1 shows the different simulation results between the base case with the capacity function and without the function. No significant difference was found except for the headway standard deviation and the headway spread rate. Headway standard deviation increased by 13 seconds (or 17%).

It is evident that the transit capacity function helps to reduce the unrealistically long dwelling time at stops. As a result of a long dwelling time, the distance and headway between the prior streetcar and the current streetcar, which is serving at a stop, will increase and the distance to the approaching streetcar will decrease. Extended distances between the prior vehicle and the serving vehicle will then contribute to an increase in the headway standard deviation while shortened distances between the serving vehicle and the following vehicle will result in a bunching of streetcars. It should be noted that other types of vehicles between the serving streetcar and the following streetcar act as a ‘cushion’, preventing a complete bunching of streetcars.

<table>
<thead>
<tr>
<th></th>
<th>Base case with the capacity function</th>
<th>Base case without the capacity function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit cycle time (sec)</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Transit travel distance (km)</td>
<td>1840</td>
<td>1824</td>
</tr>
<tr>
<td>Transit travel speed (km/h)</td>
<td>13.1</td>
<td>12.8</td>
</tr>
<tr>
<td>Avg. Headway (sec)</td>
<td>134</td>
<td>137</td>
</tr>
<tr>
<td>Headway standard deviation (sec)</td>
<td>107</td>
<td>120</td>
</tr>
</tbody>
</table>
### Table 4.1 Simulation results: summary of the base case with the capacity function and without the function

<table>
<thead>
<tr>
<th>Headway spread</th>
<th>6.0 / 6.2</th>
<th>6.4 / 6.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(LT 30sec / MT 5min) (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service frequency (vph)</td>
<td>32.8</td>
<td>31.3</td>
</tr>
<tr>
<td>Overall vehicle speed (km/h)</td>
<td>6.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

### 4.3.2. Transit Priority Options

Table 4.2 shows the summary of the simulation results of the base network and the other networks, which implemented transit priority options.

<table>
<thead>
<tr>
<th></th>
<th>Base network</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Cycle time (min)</td>
<td>115</td>
<td>133</td>
<td>113</td>
<td>80</td>
</tr>
<tr>
<td>Transit total travel distance (km)</td>
<td>1840</td>
<td>1756</td>
<td>1854</td>
<td>2101</td>
</tr>
<tr>
<td>Avg. Transit travel speed (km/h)</td>
<td>13.1</td>
<td>11.2</td>
<td>13.5</td>
<td>19.7</td>
</tr>
<tr>
<td>Average headway (sec)</td>
<td>134</td>
<td>140</td>
<td>136</td>
<td>121</td>
</tr>
<tr>
<td>Headway STDEV</td>
<td>107</td>
<td>147</td>
<td>108</td>
<td>101</td>
</tr>
<tr>
<td>Headway spread</td>
<td>6.0 / 6.2 (12.2)</td>
<td>9.7 / 7.1 (16.8)</td>
<td>5.6 / 6.3 (11.9)</td>
<td>12.0 / 5.0 (17)</td>
</tr>
<tr>
<td>(LT 30sec / MT 5min) (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service frequency (vph)</td>
<td>32.8</td>
<td>28.3</td>
<td>34.5</td>
<td>44.2</td>
</tr>
<tr>
<td>Overall vehicle speed (km/h)</td>
<td>6.5</td>
<td>6.1</td>
<td>6.5</td>
<td>19.8</td>
</tr>
<tr>
<td>Cross road traffic travel time (sec)</td>
<td>70.0</td>
<td>73.0</td>
<td>72.1</td>
<td>44.2</td>
</tr>
</tbody>
</table>

Table 4.2 Simulation results: summary of scenarios 1, 2, 3 & 4
One of the measures of effectiveness shown in Figure 4.1 is the absolute transit cycle time in minutes. It is evident that the current method of transit priority is beneficial to transit operations along the line relative to the case where no priority is assigned to transit vehicles. Termination of the transit priority assignment would result in an 18 minutes (or 16%) increase in transit cycle time. Left turn banning provides an improvement in transit cycle time by 2 minutes (or 2%). Total traffic ban on the route, no doubt, shows significant reduction in round-trip time by 35 minutes (or 30%) over the base case.

![Figure 4.1 Transit cycle time (transit priority options, minutes)](image)

It should be noted though that transit travel times are only collected from the streetcars, which finished their trips. Thus streetcars that could not arrive at their destinations are ignored, despite the longer travel time than the average case.
Transit total travel distance is chosen as a complementary measure of effectiveness in terms of transit mobility and is shown in Figure 4.2. Similar to transit travel time, the current transit signal priority results in an 84km (or 5%) benefit in travel distance. Banning left turning movements improves current status by only 14km (or 1%), and banning all traffic from King Street definitely improves the travel distance by 161km (or 9%). It can be seen that the travel distances are not as significantly improved as the travel times.

![Figure 4.2 Transit total travel distance (transit priority options, km)](image)

Average transit travel speeds are shown in Figure 4.3. The figure indicates a systematic upward pattern in speeds due to the addition of transit priority, left turn banning, and the exclusive dedication of King Street to transit. It is notable that transit priority alone is less effective compared to the additional left turn banning, which is consistent with the expectations that streetcar travel time savings at traffic lights due to priority could very well
be reduced as a result of being stranded behind a left turning vehicle waiting for an acceptable gap.

![Figure 4.3 Transit travel speed (transit priority options, km/h)](image)

Figure 4.3 Transit travel speed (transit priority options, km/h)

Figure 4.4 shows the average headway in seconds. Opposite to speeds, the results show a systematic downward pattern in average headways due to the addition of transit priority, left turn banning, and the exclusive dedication of King Street to transit. It is notable that the “No Traffic” scenario results in a 121 seconds average headway, which is very close to the scheduled headway of 120 sec. It is evident that transit priority has a positive influence on the average headway of transit vehicles.
Figure 4.4 Average headway (transit priority options, seconds)

Figure 4.5 shows headway standard deviation, which indicates the variability around the mean headway. It is important to realize that reduction in the headway variation is as important as a reduction in the headway itself, if not more important. From a transit rider perspective, the unpredictability of the streetcar arrival is the most frustrating. The results show that the transit signal priority significantly reduces headway standard deviation by 40 seconds (or 37%). The signal priority with no traffic on King Street is also more effective in decreasing the transit headway standard deviation. Without any traffic on King Street, the headway standard deviation is decreased by 46 seconds (or 46%) compared to the scenario 2, which turns off the current transit signal priority.
As an indication of transit vehicle bunching, Figure 4.6 shows the percentage of headways that are less than 30 seconds and more than 5 minutes. Bunching is a critical problem in line operations, and results need careful interpretation.

It is clear that transit priority and further banning of left turns both reduce the level of bunching which is also intuitive. It seems, however, that full traffic prohibition significantly increases the proportion of headways less than 30 seconds by 6%, and decreases the proportion of headways that are more than 5 minutes by 1.2%. One possible explanation could be that vehicular traffic on the route acts like a ‘cushion’, separating streetcars. In the absence of such a cushion, once a streetcar is interrupted, say at a traffic signal, the streetcars behind will eventually catch up, which is obviously not the case if there is
vehicular traffic between the two. It should also be noted that despite transit priority, some streetcars still get caught at some intersections, as priority assignment (or not) depends on the streetcar arrival time at the priority call detector relative to the traffic light cycle.

Figure 4.6 The percentage of headways that is less than 30 seconds and more than 5 minutes (transit priority options, %)

Figure 4.7 shows the average service frequency measured in transit vehicles per hour. The service frequency is yielded from the number of streetcars arriving at their destinations during the simulation period (150 minutes). The total number of streetcars, those reached their destinations, is divided by 2.5 to yield service frequency per hour. The figure shows
significant changes in the service frequency due to the signal priority alone, but higher frequencies can be achieved due to banning of left turns (1.7 more streetcars per hour over the base case) or traffic banning (11.4 more streetcars per hour over the base case). Turning off the transit signal priority reduces service frequency by 4.5 vehicles per hour or 14%.

Figure 4.7 Transit service frequency (transit priority options, vehicles per hour)

Figure 4.8 shows the overall average speed including transit as well as traffic in km/hr. The figure shows that the implementation of the transit priority causes a slight decrease in overall combined average speeds, since the additional green on the transit road increases both transit vehicles as well as other vehicles. In the case where traffic is fully prohibited access to King Street, further improvements in speed take place, which may be counter-intuitive. However, this seems to be more of a modeling artifact than representative of
Due to the absence of alternate routes in the model, banned traffic not only 'disappears' from King Street but from the entire network. In reality, this traffic would actually divert to parallel routes causing travel time to increase on such routes, and potentially appearing as cross traffic on King Street intersections causing some delays to streetcars. The only way to capture the true effect on traffic, therefore, should then be to expand the network to include several parallel routes north and south of King Street.

Figure 4.8 Average speed of all vehicles (transit priority options, km/h)

Figure 4.9 shows the average travel times of only cross road traffic. Implementation of transit priority schemes is a very sensitive issue, because it traditionally favors transit vehicles over other vehicles. However, turning off the transit signal priority results in an increase in travel time for the traffic at the cross roads, even though more green time must
have been provided to the cross roads compared to the base case. This unexpected result may be caused by spillbacks from the transit road. Reduced green time on the transit street increases queue length, which encroaches on intersections leading to hindered movements at the cross roads. Turning vehicles that are hindered will increase the delay of cross road traffic, especially on a single lane cross road. Banning all traffic on King Street dramatically decreases travel times on cross roads. These results, however, are a little biased since the decrease in average travel times are mainly produced by the removal of turning movements from cross roads, which is modeled in scenario 4.

![Figure 4.9 Average travel times on cross roads (transit priority options, sec)](image-url)
4.3.3. Conditional Transit Signal Priority

The expected advantages of the conditional provision of signal priority is the maximization of the effects of the transit signal priority and the minimization of the side effects of priority provision, such as additional delay on cross streets and transit vehicle bunching. In this study, a simple conditional signal priority scheme is developed and tested. Transit vehicles are only given signal priority if they satisfy the condition of 2 minutes headway (departure headway at origin). Scenario 5 implements conditional TSP on the base network in order to assess its effects on the network, which is almost saturated. Conditional TSP is also deployed for scenario 6, which bans all traffic on King Street except for streetcars. The simulation results of scenario 5 & and 6 are compared to those of scenario 1, the base network, and scenario 4, the banning of traffic on King Street. The analysis of the simulation results focuses on transit performance, cross road effects, and transit vehicle bunching.

Table 4.3 shows the summary of simulation results of the base network and the networks, which implemented transit priority options.

<table>
<thead>
<tr>
<th></th>
<th>Base network</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
<th>Scenario 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Cycle time (min)</td>
<td>115</td>
<td>80</td>
<td>122</td>
<td>81</td>
</tr>
<tr>
<td>Transit total travel distance (km)</td>
<td>1840</td>
<td>2101</td>
<td>1872</td>
<td>2123</td>
</tr>
<tr>
<td>Avg. Transit travel speed (km/h)</td>
<td>13.1</td>
<td>19.7</td>
<td>12.8</td>
<td>19.6</td>
</tr>
<tr>
<td>Average headway (sec)</td>
<td>134</td>
<td>121</td>
<td>136</td>
<td>122</td>
</tr>
</tbody>
</table>
Headway STDEV

<table>
<thead>
<tr>
<th></th>
<th>107</th>
<th>101</th>
<th>127</th>
<th>87</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit vehicle bunching (LT 30sec / MT 5min) (%)</td>
<td>6.0 / 6.2 (12.2)</td>
<td>12.0 / 5.0 (17)</td>
<td>7.3 / 5.8 (13.1)</td>
<td>9.7 / 4.1 (13.8)</td>
</tr>
<tr>
<td>Service frequency (vph)</td>
<td>32.8</td>
<td>44.2</td>
<td>32.8</td>
<td>43.8</td>
</tr>
<tr>
<td>Overall vehicle speed (km/h)</td>
<td>6.5</td>
<td>19.8</td>
<td>6.8</td>
<td>20.6</td>
</tr>
<tr>
<td>Cross road traffic travel time (sec)</td>
<td>70.0</td>
<td>44.2</td>
<td>63.8</td>
<td>31.4</td>
</tr>
</tbody>
</table>

Table 4.3 Simulation results: summary of scenarios 1, 4, 5 & 6

Figure 4.10 shows the average transit travel times. Deploying conditional TSP in the base network and in scenario 4 increases the transit travel time by 7 minutes (or 6%) and 1 minute (or 1%), respectively. The results are reasonable, since transit vehicles are only given signal priority if they satisfy the condition of 2 minutes headway.

Figure 4.10 Transit cycle time (conditional TSP, minutes)
Total travel distances for transit vehicles are shown in Figure 4.11. The application of conditional TSP leads to an increase in travel distance of 32km (or 2%) in base case and a 22km (or 1%) increase in scenario 4.

![Figure 4.11 Transit total travel distance (conditional TSP, km/h)](image)

Figure 4.11 shows average transit travel speeds. The figure indicates that the networks, those implemented conditional TSP produce slightly lower travel speeds than the original scenarios. Scenario 5 simulates an average speed of 12.8 km/h, which is 0.3 km/h (or 2%) less than the travel time of the base network. The transit vehicles in scenario 6 have an average speed of 19.6 km/h, which is 0.1 km/h (or 1%) less than the average travel time in scenario 4. These results show that the implementation of the conditional TSP to the two scenarios did not have a large adverse impact to the average travel time or distance.
Average headways are shown in the Figure 4.13. The conditional TSP slightly increases average headways by 2 seconds (or 1%) and 1 second (or 1%) for scenarios 1 and 4, respectively. Implementation of the conditional TSP did not lead to a significant increase in transit average headway.
Figure 4.14 depicts the different headway standard deviations. It should be noted that scenario 5, which implements conditional TSP into the base case, significantly increases the headway standard deviation by 11 seconds (or 10%). However, the implementation of conditional TSP to scenario 6, which bans all traffic from King Street, decreases headway standard deviation by 14 seconds (or 14%). This difference seems to be caused by the fact that vehicles with headways less than 120 seconds did not receive signal priority, but had to wait for the next green time. Headway variance graphs are provided in Appendix B.

![Figure 4.14 Headway standard deviation (conditional TSP, seconds)](image-url)
Figure 4.15 shows the percentage of the headways that are less than 30 seconds and more than 5 minutes. The application of conditional TSP to the base case and the banned traffic case increase the percentage of transit headway that is less than 30 seconds by 1.3% and decreases it by 2.3%, respectively. It should be noted that the conditional provision of transit priority is not effective in reducing bunching in a network, since it is almost saturated. The percentage of headways that is more than 5 minutes decreases by 0.4% in scenario 5 and decreases by 0.9% (in scenario 6).

![Bar chart showing the percentage of headways less than 30 seconds and more than 5 minutes across different scenarios.](image)

**Figure 4.15** The percentage of headways that is less than 30 seconds and more than 5 minutes (conditional TSP, %)

The following Figure 4.16 shows the transit service frequency per hour. The figure shows no significant changes in the service frequency after the implementation of the conditional signal priority.
Figure 4.16 Transit service frequency (conditional TSP, vehicle per hour)

Figure 4.17 Average speed of all vehicles (conditional TSP, km/h)

Figure 4.17 shows the overall average speed of vehicles and transit in km/hr. The Figure shows that the implementation of conditional transit priority increases the overall travel...
speed of all vehicles in both networks. In the base case, conditional TSP improves traffic travel speed by 0.3 km/h (or 5%) and increases the traffic travel speed by 0.8 km/h (or 4%) in the network that ban all traffic from King Street. The major difference in travel speeds between the base network and the network that bans all traffic on King Street is caused by the inclusion or exclusion of turning movements from the cross roads.

Finally, Figure 4.18 shows the cross road traffic travel times. The conditional TSP reduces the travel times of cross road traffic by 6 seconds per vehicle (or 9%) in the base case. There is also a significant effect of the conditional TSP on scenario 6 as 13 seconds (or 30%) average travel time is saved. It should be noted though that the less saturated network (scenario 6) is more effective in deploying the conditional TSP scheme than the nearly saturated network (or base case).

![Figure 4.18 Average travel times on cross roads (conditional TSP, sec)](image-url)
CHAPTER 5

CONCLUSIONS

This study was focused on quantifying the impact of adopting selected transit priority schemes on streetcar operations along King Street in the city of Toronto. Six pressing scenarios were analyzed including the status quo (with existing transit priority), no transit signal priority, the prohibition of all left-turning traffic case and finally, the full traffic ban. A simple conditional transit signal priority algorithm was also tested on the transit route under different circumstances. In order to quantify the impact of any of the above scenarios, a set of measures of effectiveness were used that included transit travel time, distance, speed, headways, service frequency, cross road traffic travel time, transit vehicle bunching rate, and overall traffic and transit average speeds.

The study was concentrated on the peak-hours case with higher streetcar frequency (2 minutes per vehicle) and higher passenger load factor. Based on the integrated microsimulation model results outlined in this study, the following conclusions can be drawn:

First of all, the developed transit capacity and occupancy model aided in modeling transit stops more realistically. In the base network with the function implemented, headway standard deviation, which may be caused by unrealistically long dwelling times, decreased significantly compared to the network without the capacity function.
Secondly, the currently operated transit signal priority was very effective in improving transit performance, in terms of mobility, compared to the network without transit signal priority. Turning off the transit signal priority resulted in an 18 seconds (or 16%) decrease in transit cycle time, an 86 km (or 5%) increase in travel distance, and a 1.9 km/h (or 15%) increase in transit travel speed. Transit signal priority on the transit route also made improvements in headway-related MOEs, such as average transit headway (an increase of 4%), transit headway standard deviation (an increase of 37%), as well as a proportion of transit headways that were less than 30 seconds (or 62%) and more than 5 minutes (15%). In addition, transit service frequency was improved by 4.5 vph (or 14%) and overall vehicle speed was increased by 0.4 km/h (or 6%) with transit signal priority. Finally, turning off signal priority produced a 3 seconds (or 4%) decrease in average travel time of cross road traffic. In fact reduced cross road travel time was not an expected effect of transit signal priority because the total green time provided to cross the road was assumed to increase by turning off the signal priority. One possible explanation of this result was that spillbacks on the transit street, which were caused by reduced green time on transit streets by turning off signal priority, may block intersections so that the vehicles on the cross roads experience additional delay. Furthermore the transit route approached a near saturation condition during the morning peak period. Because of the spillbacks on transit streets, there may have been a possibility of serious effects on the cross roads since they are mostly single lane streets.

Banning left turns at all intersections on the transit route was another option that was expected to improve transit performance. By banning the left turns, transit performance
improved slightly in all the selected MOEs. Transit cycle time, travel distance, and travel speeds were improved by approximately 5%. In headway-related MOEs, transit vehicle bunching was reduced by 7%. The banning of left turns also improved service frequency by 5%. The rest of the MOEs, however, such as average headway, headway standard deviation, cross road travel time, and overall speed were not significantly influenced. Most changes were less than 3%. It was evident then that the effectiveness of this option completely depended on the degree of left turn flow in the network. More left turn movements would block transit movements that would lead to disadvantages in transit operations such as a loss in transit mobility, irregular arrivals of transit vehicles, and lower service frequency.

The banning of all traffic on King Street resulted in significant improvements in almost every MOEs except for transit vehicle bunching. However, it should be noted that several MOEs such as cross road traffic travel time and overall traffic speed were not applicable in this scenario. Absence of alternate routes in the modeled network and banned traffic, such as turning movements from cross roads to transit streets, were automatically deleted by the Paramics modeler. Thus, the rest of the traffic (i.e., through traffic from cross roads to cross roads) experiences much less delay with a faster travel speed. Transit cycle time and speeds were reduced by 35 minutes (or 30%) and 6.6 km/h (or 50%). Travel distances were also increased by 261 km (or 14%). This scenario made significant changes in headway-related MOEs. The scenario generated 13 seconds (or 10%) of reduced average transit headway and 6 seconds (or 6%) of decreased headway standard deviation. The only exception was the bunching rate of transit vehicles. The percentage of headways that were less than 30 seconds increased by 6%, while the headways that were more than 5 minutes decreased by
1.2%. As mentioned above, the vehicles between streetcars were likely to act as a 'cushion', keeping streetcars apart. Lastly, the banning of all traffic led to an improvement in transit service frequency by 11.4 vph (or 35%).

Conditional transit signal priority was implemented onto the streetcar route under two different scenarios: with traffic, the base case and conditional TSP, and without traffic, scenario 4 and conditional TSP on King Street. The implementation of the conditional signal priority method resulted in an increase in transit cycle time by 7 seconds (or 6%) as well as an increase in transit travel distance by 32 km (or 2%). It also resulted in a minor decrease in transit travel speed by 0.3 km/h (or 2%). The implementation of conditional TSP did not cause serious differences in average transit headway and service frequency. The most significant differences were found in transit headway standard deviation and cross road travel time. The standard deviation of transit increased by 11 seconds (or 10%), which meant that transit arrivals were more unpredictable because it provided less green time on transit streets. Cross road travel times also improved by 6.2 seconds (or 9%). The simulation results indicated that the conditional provision of priority was very effective in reducing delays on cross roads without negatively affecting the current transit signal priority system.

Conditional TSP on the transit route without traffic produced very minor improvements, that were less than 1%, in transit cycle time, travel distance, travel speed, average transit headway, and service frequency and overall traffic speed. Transit headway standard deviation, however, was significantly improved by 14 seconds (or 14%). It should be noted
that standard deviations were seriously increased on the base network, while it was improved by 14% on the network banning traffic on King Street. Banning traffic on King Street contributed 40 seconds of difference in headway standard deviation. Finally, conditional TSP improved cross road travel time by 12.8 seconds (or 29%), which is much more significant compared to an increase in 9% on the base network with traffic.

The current signal priority was beneficial in improving transit mobility, transit headway variance, service frequency, overall vehicle speed, and cross road travel time. Additional implementation of left turn ban on the transit route yielded further improvements in transit performance. Banning all traffic on King Street produced significant improvements except for transit vehicle bunching, which is possibly caused by the removal of vehicles that acted as ‘cushion’ between streetcars.

Conditional transit signal priority produced improvements in reducing cross road travel times without significant harmful effects to transit vehicles and other vehicles on transit streets. Transit headway variance, however, showed opposite simulation results from two scenarios. Without traffic on King Street, conditional TSP turned out to be very effective in reducing transit headway spread, while the effect would be adverse if heavy traffic was applied the transit route. Thus, the tested conditional TSP algorithm could be said to fail to improve transit headway regularity on the network with near saturated condition.

As mentioned earlier, only King streetcar route and the side streets were modeled in this study. However some scenarios banned turning movements or all traffic from King street.
The banned traffic would actually divert to parallel routes causing travel time increase on such routes, and some of which could potentially appear as cross traffic on King street intersections causing some delays to streetcars. The only way to capture the true effect on traffic, therefore, seems to be via network expansion to include several parallel routes north and south of King street.

Further studies are also recommended to enhance conditional transit signal priority in ways that considering passenger delay in calculating signal timing or in providing conditional signal priority as a criterion and that providing various level of signal priority strategies depend on current transit and passenger conditions.
REFERENCES


APPENDIX A

Turning movements counts
<table>
<thead>
<tr>
<th></th>
<th>Real network</th>
<th>Simulation network</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Danforth / Broadview</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>209</td>
<td>133</td>
<td>32</td>
</tr>
<tr>
<td>93</td>
<td>181</td>
<td>166</td>
</tr>
<tr>
<td><strong>Broadview / Queen</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>65</td>
<td>104</td>
<td>48</td>
</tr>
<tr>
<td>59</td>
<td>67</td>
<td>52</td>
</tr>
<tr>
<td><strong>King / parliament</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>63</td>
<td>273</td>
<td>54</td>
</tr>
<tr>
<td>48</td>
<td>235</td>
<td>31</td>
</tr>
<tr>
<td><strong>King / Yonge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>0</td>
<td>537</td>
<td>54</td>
</tr>
<tr>
<td>0</td>
<td>577</td>
<td>56</td>
</tr>
<tr>
<td><strong>King / University</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>31</td>
<td>836</td>
<td>14</td>
</tr>
<tr>
<td>39</td>
<td>946</td>
<td>14</td>
</tr>
<tr>
<td><strong>King / Bathurst</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>24</td>
<td>254</td>
<td>38</td>
</tr>
<tr>
<td>4</td>
<td>284</td>
<td>43</td>
</tr>
<tr>
<td><strong>King / Dufferin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>25</td>
<td>225</td>
<td>84</td>
</tr>
<tr>
<td>23</td>
<td>245</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>EB</td>
</tr>
<tr>
<td>----------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td><strong>Jameson / King</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>43</td>
<td>111</td>
<td>26</td>
</tr>
<tr>
<td>69</td>
<td>120</td>
<td>68</td>
</tr>
<tr>
<td><strong>HighPark / Roncesvalles</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>48</td>
<td>253</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>253</td>
<td>0</td>
</tr>
<tr>
<td><strong>Dundas / Roncesvalles</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>55</td>
<td>739</td>
<td>6</td>
</tr>
<tr>
<td>0</td>
<td>409</td>
<td>0</td>
</tr>
<tr>
<td><strong>Bloor / Dundas</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>TH</td>
<td>RT</td>
</tr>
<tr>
<td>6</td>
<td>361</td>
<td>69</td>
</tr>
<tr>
<td>0</td>
<td>307</td>
<td>45</td>
</tr>
</tbody>
</table>
APPENDIX B

Headway Variance Graphs
Headway Distribution (2)

- Base case
- Base case + conditional TSP
APPENDIX C

Simulation Results Summary
## Scenario 1 - Base case

### Simulation Summary

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Avg. Hw. Distance (sec)</th>
<th>HWY 1-30sec</th>
<th>HWY 1-5min</th>
<th># of finished trips</th>
<th>Overall Speed</th>
<th>Transl. Speed</th>
<th>Avg. Travel time</th>
<th>Cross St. Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>134.30</td>
<td>38</td>
<td>43</td>
<td>46</td>
<td>5.03</td>
<td>0.5924</td>
<td>18685.63</td>
<td>13.60</td>
</tr>
<tr>
<td>2</td>
<td>140.44</td>
<td>39</td>
<td>43</td>
<td>46</td>
<td>5.75</td>
<td>0.5291</td>
<td>18865.03</td>
<td>13.60</td>
</tr>
<tr>
<td>3</td>
<td>136.14</td>
<td>38</td>
<td>43</td>
<td>46</td>
<td>6.83</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>4</td>
<td>136.42</td>
<td>39</td>
<td>43</td>
<td>46</td>
<td>7.79</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>5</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>6.08</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>6</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>7</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>8</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>9</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>10</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>11</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>12</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>13</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>14</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>15</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>16</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>17</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>18</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>19</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
<tr>
<td>20</td>
<td>136.42</td>
<td>40</td>
<td>43</td>
<td>46</td>
<td>5.54</td>
<td>0.5291</td>
<td>18956.24</td>
<td>12.90</td>
</tr>
</tbody>
</table>

| Avg               | 133.87                  | 39.10       | 42.90      | 0.5285             | 0.5232        | 18940.184       | 13.12             | 6.54                |
Simulation Summary

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Avg. Hwy (sec)</th>
<th>Hwy. STDEV (sec)</th>
<th>HWAY LT 30sec</th>
<th>HWAY MT 5min</th>
<th># of finished trips</th>
<th>Avg. Travel time</th>
<th>Transits travel Distance</th>
<th>Transit Speed</th>
<th>Overall Speed</th>
<th>Cross St. Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140.04</td>
<td>151.50</td>
<td>9.99%</td>
<td>11.49%</td>
<td>31</td>
<td>1:11:04</td>
<td>0:59:55</td>
<td>1752622</td>
<td>11.00</td>
<td>6.00</td>
</tr>
<tr>
<td>2</td>
<td>135.28</td>
<td>145.29</td>
<td>11.66%</td>
<td>11.95%</td>
<td>36</td>
<td>1:12:27</td>
<td>1:02:50</td>
<td>1672540</td>
<td>10.00</td>
<td>5.40</td>
</tr>
<tr>
<td>3</td>
<td>140.85</td>
<td>159.56</td>
<td>10.56%</td>
<td>11.40%</td>
<td>38</td>
<td>1:15:14</td>
<td>1:01:11</td>
<td>1593600</td>
<td>9.60</td>
<td>5.40</td>
</tr>
<tr>
<td>4</td>
<td>134.98</td>
<td>116.72</td>
<td>9.69%</td>
<td>11.36%</td>
<td>36</td>
<td>1:08:53</td>
<td>1:01:13</td>
<td>1838695</td>
<td>11.30</td>
<td>6.10</td>
</tr>
<tr>
<td>5</td>
<td>143.51</td>
<td>151.23</td>
<td>8.62%</td>
<td>12.68%</td>
<td>28</td>
<td>1:04:06</td>
<td>1:05:15</td>
<td>1757094</td>
<td>11.20</td>
<td>6.60</td>
</tr>
<tr>
<td>6</td>
<td>142.59</td>
<td>149.57</td>
<td>9.49%</td>
<td>11.87%</td>
<td>27</td>
<td>1:10:16</td>
<td>1:01:43</td>
<td>1833722</td>
<td>12.00</td>
<td>6.70</td>
</tr>
<tr>
<td>7</td>
<td>143.14</td>
<td>138.15</td>
<td>8.12%</td>
<td>12.95%</td>
<td>35</td>
<td>1:11:23</td>
<td>1:04:07</td>
<td>1825931</td>
<td>12.30</td>
<td>6.90</td>
</tr>
<tr>
<td>8</td>
<td>143.93</td>
<td>151.25</td>
<td>9.65%</td>
<td>13.41%</td>
<td>23</td>
<td>1:02:03</td>
<td>1:07:22</td>
<td>1683521</td>
<td>10.70</td>
<td>5.70</td>
</tr>
<tr>
<td>9</td>
<td>133.07</td>
<td>106.53</td>
<td>8.16%</td>
<td>10.83%</td>
<td>39</td>
<td>1:00:35</td>
<td>1:00:28</td>
<td>1728152</td>
<td>10.80</td>
<td>5.80</td>
</tr>
<tr>
<td>10</td>
<td>143.75</td>
<td>175.62</td>
<td>10.99%</td>
<td>13.51%</td>
<td>34</td>
<td>1:11:40</td>
<td>1:10:47</td>
<td>1741672</td>
<td>11.10</td>
<td>6.10</td>
</tr>
<tr>
<td>11</td>
<td>150.44</td>
<td>199.90</td>
<td>10.46%</td>
<td>12.90%</td>
<td>31</td>
<td>1:17:36</td>
<td>1:07:55</td>
<td>1663350</td>
<td>10.20</td>
<td>5.50</td>
</tr>
<tr>
<td>12</td>
<td>132.48</td>
<td>116.89</td>
<td>10.28%</td>
<td>12.20%</td>
<td>39</td>
<td>1:01:41</td>
<td>1:03:52</td>
<td>1765610</td>
<td>11.30</td>
<td>6.00</td>
</tr>
<tr>
<td>13</td>
<td>139.81</td>
<td>141.16</td>
<td>8.53%</td>
<td>11.75%</td>
<td>35</td>
<td>1:16:56</td>
<td>0:58:17</td>
<td>1846644</td>
<td>12.70</td>
<td>7.00</td>
</tr>
<tr>
<td>14</td>
<td>135.33</td>
<td>140.54</td>
<td>8.55%</td>
<td>9.65%</td>
<td>41</td>
<td>1:06:50</td>
<td>0:58:45</td>
<td>1713596</td>
<td>10.50</td>
<td>6.10</td>
</tr>
<tr>
<td>15</td>
<td>143.64</td>
<td>205.78</td>
<td>9.72%</td>
<td>12.48%</td>
<td>31</td>
<td>1:20:54</td>
<td>1:05:57</td>
<td>1629279</td>
<td>9.70</td>
<td>5.30</td>
</tr>
<tr>
<td>16</td>
<td>136.71</td>
<td>130.93</td>
<td>9.48%</td>
<td>11.72%</td>
<td>29</td>
<td>1:04:19</td>
<td>0:56:31</td>
<td>1867233</td>
<td>12.40</td>
<td>6.50</td>
</tr>
<tr>
<td>17</td>
<td>137.84</td>
<td>125.78</td>
<td>9.66%</td>
<td>11.84%</td>
<td>35</td>
<td>1:03:41</td>
<td>1:05:54</td>
<td>1786705</td>
<td>11.40</td>
<td>6.40</td>
</tr>
<tr>
<td>18</td>
<td>134.78</td>
<td>137.24</td>
<td>10.26%</td>
<td>11.75%</td>
<td>39</td>
<td>1:12:15</td>
<td>1:03:25</td>
<td>1822394</td>
<td>12.10</td>
<td>6.40</td>
</tr>
<tr>
<td>19</td>
<td>137.71</td>
<td>142.01</td>
<td>9.98%</td>
<td>11.85%</td>
<td>29</td>
<td>1:19:46</td>
<td>0:53:50</td>
<td>1763580</td>
<td>11.40</td>
<td>6.30</td>
</tr>
<tr>
<td>20</td>
<td>148.29</td>
<td>149.72</td>
<td>9.20%</td>
<td>13.84%</td>
<td>20</td>
<td>1:02:46</td>
<td>1:09:35</td>
<td>1828349</td>
<td>11.70</td>
<td>6.50</td>
</tr>
<tr>
<td>Avg.</td>
<td>139.91</td>
<td>146.77</td>
<td>9.65%</td>
<td>12.07%</td>
<td>32.80</td>
<td>1:09:43</td>
<td>1:02:57</td>
<td>1755714</td>
<td>11.17</td>
<td>6.14</td>
</tr>
</tbody>
</table>
### Simulation Summary - Scenario 3 - Ban left turns

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Avg. Hwy (sec)</th>
<th>HwY. STDEV (sec)</th>
<th>HWY LT 30sec</th>
<th>HWY MT 5min</th>
<th># of finished trips</th>
<th>Avg. Travel time</th>
<th>Transit travel Distance</th>
<th>Transit Speed</th>
<th>Overall Speed</th>
<th>Cross St. Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>139.92</td>
<td>108.90</td>
<td>4.80%</td>
<td>10.85%</td>
<td>37</td>
<td>0:56:30</td>
<td>1800700</td>
<td>13.20</td>
<td>6.20</td>
<td>64.74</td>
</tr>
<tr>
<td>2</td>
<td>139.55</td>
<td>115.92</td>
<td>4.59%</td>
<td>10.72%</td>
<td>37</td>
<td>0:57:30</td>
<td>1766959</td>
<td>12.70</td>
<td>5.70</td>
<td>68.78</td>
</tr>
<tr>
<td>3</td>
<td>130.98</td>
<td>103.16</td>
<td>5.25%</td>
<td>8.78%</td>
<td>46</td>
<td>0:55:25</td>
<td>1915037</td>
<td>14.30</td>
<td>7.40</td>
<td>66.69</td>
</tr>
<tr>
<td>4</td>
<td>131.98</td>
<td>103.06</td>
<td>6.39%</td>
<td>8.70%</td>
<td>42</td>
<td>0:58:30</td>
<td>1906789</td>
<td>14.10</td>
<td>7.30</td>
<td>55.68</td>
</tr>
<tr>
<td>5</td>
<td>137.89</td>
<td>102.59</td>
<td>5.12%</td>
<td>12.55%</td>
<td>41</td>
<td>0:57:28</td>
<td>1831733</td>
<td>12.90</td>
<td>5.80</td>
<td>83.75</td>
</tr>
<tr>
<td>6</td>
<td>133.85</td>
<td>101.03</td>
<td>5.36%</td>
<td>10.22%</td>
<td>39</td>
<td>0:57:21</td>
<td>1890608</td>
<td>13.70</td>
<td>6.40</td>
<td>82.16</td>
</tr>
<tr>
<td>7</td>
<td>130.53</td>
<td>102.22</td>
<td>6.15%</td>
<td>10.74%</td>
<td>43</td>
<td>0:55:54</td>
<td>1936428</td>
<td>14.10</td>
<td>6.70</td>
<td>80.21</td>
</tr>
<tr>
<td>8</td>
<td>133.64</td>
<td>99.00</td>
<td>5.03%</td>
<td>10.12%</td>
<td>40</td>
<td>0:52:50</td>
<td>1887758</td>
<td>14.70</td>
<td>6.80</td>
<td>68.93</td>
</tr>
<tr>
<td>9</td>
<td>136.44</td>
<td>112.24</td>
<td>5.97%</td>
<td>11.70%</td>
<td>40</td>
<td>0:57:57</td>
<td>1846443</td>
<td>12.80</td>
<td>6.00</td>
<td>88.45</td>
</tr>
<tr>
<td>10</td>
<td>135.42</td>
<td>124.88</td>
<td>7.09%</td>
<td>10.39%</td>
<td>39</td>
<td>0:58:46</td>
<td>1858635</td>
<td>13.20</td>
<td>6.30</td>
<td>85.93</td>
</tr>
<tr>
<td>11</td>
<td>135.78</td>
<td>99.90</td>
<td>5.43%</td>
<td>11.26%</td>
<td>39</td>
<td>0:59:06</td>
<td>1859091</td>
<td>13.80</td>
<td>6.70</td>
<td>81.06</td>
</tr>
<tr>
<td>12</td>
<td>136.87</td>
<td>115.35</td>
<td>7.10%</td>
<td>11.59%</td>
<td>41</td>
<td>0:57:56</td>
<td>1805904</td>
<td>12.70</td>
<td>6.10</td>
<td>72.17</td>
</tr>
<tr>
<td>13</td>
<td>134.48</td>
<td>107.15</td>
<td>5.12%</td>
<td>11.95%</td>
<td>42</td>
<td>0:53:12</td>
<td>1862562</td>
<td>14.00</td>
<td>6.70</td>
<td>66.27</td>
</tr>
<tr>
<td>14</td>
<td>141.57</td>
<td>143.45</td>
<td>6.02%</td>
<td>11.89%</td>
<td>42</td>
<td>1:00:33</td>
<td>1759008</td>
<td>12.20</td>
<td>5.90</td>
<td>70.45</td>
</tr>
<tr>
<td>15</td>
<td>141.84</td>
<td>108.37</td>
<td>4.49%</td>
<td>12.82%</td>
<td>39</td>
<td>0:56:31</td>
<td>1754498</td>
<td>12.50</td>
<td>5.60</td>
<td>70.68</td>
</tr>
<tr>
<td>16</td>
<td>130.89</td>
<td>97.15</td>
<td>5.80%</td>
<td>9.27%</td>
<td>43</td>
<td>0:55:56</td>
<td>1923295</td>
<td>14.00</td>
<td>6.30</td>
<td>65.63</td>
</tr>
<tr>
<td>17</td>
<td>133.63</td>
<td>96.77</td>
<td>4.87%</td>
<td>10.31%</td>
<td>41</td>
<td>0:57:25</td>
<td>1864122</td>
<td>13.10</td>
<td>6.20</td>
<td>68.41</td>
</tr>
<tr>
<td>18</td>
<td>138.79</td>
<td>112.60</td>
<td>5.08%</td>
<td>11.29%</td>
<td>39</td>
<td>0:55:20</td>
<td>1893796</td>
<td>14.00</td>
<td>6.80</td>
<td>72.09</td>
</tr>
<tr>
<td>19</td>
<td>131.37</td>
<td>93.85</td>
<td>5.60%</td>
<td>9.64%</td>
<td>40</td>
<td>0:56:37</td>
<td>1810204</td>
<td>12.90</td>
<td>6.70</td>
<td>60.57</td>
</tr>
<tr>
<td>20</td>
<td>139.70</td>
<td>111.24</td>
<td>5.68%</td>
<td>11.10%</td>
<td>45</td>
<td>0:55:08</td>
<td>1915303</td>
<td>14.20</td>
<td>7.30</td>
<td>61.43</td>
</tr>
<tr>
<td>Avg.</td>
<td>135.76</td>
<td>107.94</td>
<td>5.55%</td>
<td>10.79%</td>
<td>40.75</td>
<td>0:56:48</td>
<td>1854448</td>
<td>13.46</td>
<td>6.45</td>
<td>72.07</td>
</tr>
</tbody>
</table>
### Simulation Summary

**Scenario 4 - Ban all traffic on King St.**

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Avg. Hwy (sec)</th>
<th>Hwy. STDEV (sec)</th>
<th>HWY LT 30sec</th>
<th>HWY MT 5min</th>
<th># of finished trips</th>
<th>Avg. Travel time</th>
<th>Transit travel</th>
<th>Transit Speed</th>
<th>Overall Speed</th>
<th>Cross St. Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120.67</td>
<td>105.22</td>
<td>10.25%</td>
<td>5.53%</td>
<td>57</td>
<td>0:42:09</td>
<td>2108990</td>
<td>19.80</td>
<td>20.90</td>
<td>32.55</td>
</tr>
<tr>
<td>2</td>
<td>120.74</td>
<td>93.91</td>
<td>11.29%</td>
<td>10.25%</td>
<td>56</td>
<td>0:41:36</td>
<td>2109780</td>
<td>19.80</td>
<td>20.00</td>
<td>34.18</td>
</tr>
<tr>
<td>3</td>
<td>121.13</td>
<td>93.66</td>
<td>11.67%</td>
<td>10.73%</td>
<td>54</td>
<td>0:40:48</td>
<td>2102421</td>
<td>20.00</td>
<td>17.50</td>
<td>32.73</td>
</tr>
<tr>
<td>4</td>
<td>121.36</td>
<td>99.88</td>
<td>11.25%</td>
<td>9.69%</td>
<td>55</td>
<td>0:41:36</td>
<td>2096438</td>
<td>19.80</td>
<td>21.60</td>
<td>30.99</td>
</tr>
<tr>
<td>5</td>
<td>121.60</td>
<td>100.13</td>
<td>12.11%</td>
<td>11.03%</td>
<td>53</td>
<td>0:41:27</td>
<td>2090027</td>
<td>19.70</td>
<td>16.30</td>
<td>38.20</td>
</tr>
<tr>
<td>6</td>
<td>121.86</td>
<td>103.76</td>
<td>10.80%</td>
<td>8.16%</td>
<td>53</td>
<td>0:41:40</td>
<td>2085601</td>
<td>19.50</td>
<td>21.00</td>
<td>31.54</td>
</tr>
<tr>
<td>7</td>
<td>121.43</td>
<td>99.11</td>
<td>12.17%</td>
<td>8.63%</td>
<td>55</td>
<td>0:42:32</td>
<td>2098117</td>
<td>19.60</td>
<td>20.70</td>
<td>31.26</td>
</tr>
<tr>
<td>8</td>
<td>121.31</td>
<td>93.26</td>
<td>11.45%</td>
<td>9.28%</td>
<td>54</td>
<td>0:40:42</td>
<td>2102324</td>
<td>20.00</td>
<td>20.90</td>
<td>31.81</td>
</tr>
<tr>
<td>9</td>
<td>122.63</td>
<td>112.95</td>
<td>12.66%</td>
<td>9.78%</td>
<td>49</td>
<td>0:41:34</td>
<td>2084203</td>
<td>19.40</td>
<td>20.00</td>
<td>33.03</td>
</tr>
<tr>
<td>10</td>
<td>121.76</td>
<td>104.83</td>
<td>13.16%</td>
<td>11.00%</td>
<td>54</td>
<td>0:42:01</td>
<td>2094225</td>
<td>19.70</td>
<td>19.30</td>
<td>32.06</td>
</tr>
<tr>
<td>11</td>
<td>121.08</td>
<td>98.01</td>
<td>11.81%</td>
<td>9.51%</td>
<td>56</td>
<td>0:42:09</td>
<td>2102999</td>
<td>19.80</td>
<td>19.90</td>
<td>44.46</td>
</tr>
<tr>
<td>12</td>
<td>121.45</td>
<td>102.89</td>
<td>12.61%</td>
<td>11.69%</td>
<td>53</td>
<td>0:41:21</td>
<td>2097200</td>
<td>19.70</td>
<td>21.40</td>
<td>29.52</td>
</tr>
<tr>
<td>13</td>
<td>120.56</td>
<td>97.40</td>
<td>10.91%</td>
<td>10.36%</td>
<td>55</td>
<td>0:40:55</td>
<td>2115609</td>
<td>20.00</td>
<td>18.70</td>
<td>35.72</td>
</tr>
<tr>
<td>14</td>
<td>120.70</td>
<td>90.83</td>
<td>11.35%</td>
<td>9.22%</td>
<td>57</td>
<td>0:41:01</td>
<td>2115755</td>
<td>19.90</td>
<td>20.60</td>
<td>35.38</td>
</tr>
<tr>
<td>15</td>
<td>121.21</td>
<td>103.82</td>
<td>13.29%</td>
<td>9.96%</td>
<td>51</td>
<td>0:42:57</td>
<td>2103691</td>
<td>19.60</td>
<td>20.40</td>
<td>58.39</td>
</tr>
<tr>
<td>16</td>
<td>122.44</td>
<td>117.13</td>
<td>13.61%</td>
<td>9.36%</td>
<td>46</td>
<td>0:44:15</td>
<td>2087245</td>
<td>19.00</td>
<td>18.00</td>
<td>46.49</td>
</tr>
<tr>
<td>17</td>
<td>120.84</td>
<td>97.61</td>
<td>12.40%</td>
<td>10.09%</td>
<td>54</td>
<td>0:42:03</td>
<td>2108277</td>
<td>19.80</td>
<td>18.20</td>
<td>69.48</td>
</tr>
<tr>
<td>18</td>
<td>120.73</td>
<td>97.22</td>
<td>11.91%</td>
<td>8.39%</td>
<td>54</td>
<td>0:41:08</td>
<td>2112110</td>
<td>19.50</td>
<td>19.90</td>
<td>77.42</td>
</tr>
<tr>
<td>19</td>
<td>121.14</td>
<td>109.35</td>
<td>13.41%</td>
<td>9.95%</td>
<td>56</td>
<td>0:40:10</td>
<td>2101585</td>
<td>19.40</td>
<td>21.80</td>
<td>59.88</td>
</tr>
<tr>
<td>20</td>
<td>121.20</td>
<td>102.36</td>
<td>12.70%</td>
<td>10.66%</td>
<td>55</td>
<td>0:41:35</td>
<td>2107054</td>
<td>19.70</td>
<td>19.60</td>
<td>69.09</td>
</tr>
<tr>
<td>Avg</td>
<td>121.29</td>
<td>101.17</td>
<td>12.04%</td>
<td>9.66%</td>
<td>53.85</td>
<td>0:41:41</td>
<td>2101498</td>
<td>19.69</td>
<td>19.84</td>
<td>44.21</td>
</tr>
</tbody>
</table>
## Simulation Summary

### Scenario 5 - Base case + Conditional TSP

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Avg. HW (sec)</th>
<th>HW. STDEV (sec)</th>
<th>HWY LT 30sec</th>
<th>HWY MT 5min</th>
<th># of finished trips</th>
<th>Avg. Travel time</th>
<th>Transit travel Distance</th>
<th>Transit Speed</th>
<th>Overall Speed</th>
<th>Cross St. Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>133.32</td>
<td>109.77</td>
<td>7.34%</td>
<td>10.03%</td>
<td>42 44</td>
<td>1:00:23</td>
<td>0:58:26</td>
<td>1915846</td>
<td>13.50</td>
<td>7.10</td>
</tr>
<tr>
<td>2</td>
<td>138.58</td>
<td>111.70</td>
<td>5.55%</td>
<td>11.01%</td>
<td>39 39</td>
<td>1:02:50</td>
<td>1:00:04</td>
<td>1839005</td>
<td>12.60</td>
<td>6.20</td>
</tr>
<tr>
<td>3</td>
<td>138.58</td>
<td>118.97</td>
<td>9.04%</td>
<td>8.86%</td>
<td>40 35</td>
<td>1:11:44</td>
<td>1:04:27</td>
<td>1837330</td>
<td>11.40</td>
<td>6.60</td>
</tr>
<tr>
<td>4</td>
<td>138.14</td>
<td>138.61</td>
<td>6.69%</td>
<td>9.33%</td>
<td>38 42</td>
<td>1:07:43</td>
<td>0:56:12</td>
<td>1853621</td>
<td>12.50</td>
<td>6.70</td>
</tr>
<tr>
<td>5</td>
<td>136.68</td>
<td>128.35</td>
<td>10.10%</td>
<td>10.90%</td>
<td>44 42</td>
<td>1:10:38</td>
<td>0:59:54</td>
<td>1862725</td>
<td>12.30</td>
<td>7.00</td>
</tr>
<tr>
<td>6</td>
<td>133.13</td>
<td>121.26</td>
<td>7.71%</td>
<td>9.17%</td>
<td>35 46</td>
<td>1:07:26</td>
<td>0:55:59</td>
<td>1873431</td>
<td>12.50</td>
<td>6.30</td>
</tr>
<tr>
<td>7</td>
<td>131.66</td>
<td>131.78</td>
<td>9.19%</td>
<td>8.58%</td>
<td>40 47</td>
<td>1:01:25</td>
<td>0:53:11</td>
<td>1914742</td>
<td>13.70</td>
<td>6.70</td>
</tr>
<tr>
<td>8</td>
<td>133.81</td>
<td>126.34</td>
<td>7.60%</td>
<td>9.25%</td>
<td>41 40</td>
<td>1:06:27</td>
<td>1:02:04</td>
<td>1866218</td>
<td>12.70</td>
<td>7.10</td>
</tr>
<tr>
<td>9</td>
<td>130.89</td>
<td>116.05</td>
<td>8.71%</td>
<td>10.72%</td>
<td>44 46</td>
<td>1:00:56</td>
<td>0:57:46</td>
<td>1942200</td>
<td>13.60</td>
<td>7.50</td>
</tr>
<tr>
<td>10</td>
<td>135.07</td>
<td>106.14</td>
<td>5.87%</td>
<td>10.06%</td>
<td>39 42</td>
<td>0:58:01</td>
<td>0:56:29</td>
<td>1879287</td>
<td>13.50</td>
<td>7.80</td>
</tr>
<tr>
<td>11</td>
<td>141.01</td>
<td>118.14</td>
<td>4.76%</td>
<td>759/7168</td>
<td>33 40</td>
<td>0:59:16</td>
<td>0:58:58</td>
<td>1773741</td>
<td>12.20</td>
<td>6.20</td>
</tr>
<tr>
<td>12</td>
<td>133.11</td>
<td>101.01</td>
<td>7.36%</td>
<td>10.14%</td>
<td>34 45</td>
<td>1:06:06</td>
<td>0:55:45</td>
<td>1892574</td>
<td>13.00</td>
<td>7.00</td>
</tr>
<tr>
<td>13</td>
<td>133.94</td>
<td>106.04</td>
<td>6.34%</td>
<td>9.22%</td>
<td>41 43</td>
<td>0:53:01</td>
<td>0:56:31</td>
<td>1906238</td>
<td>14.10</td>
<td>7.20</td>
</tr>
<tr>
<td>14</td>
<td>140.51</td>
<td>124.17</td>
<td>8.41%</td>
<td>11.90%</td>
<td>42 45</td>
<td>1:00:38</td>
<td>1:01:52</td>
<td>1806248</td>
<td>11.50</td>
<td>6.20</td>
</tr>
<tr>
<td>15</td>
<td>140.83</td>
<td>124.29</td>
<td>7.18%</td>
<td>11.07%</td>
<td>38 36</td>
<td>1:06:42</td>
<td>1:01:18</td>
<td>1797164</td>
<td>11.90</td>
<td>6.40</td>
</tr>
<tr>
<td>16</td>
<td>136.88</td>
<td>121.43</td>
<td>6.15%</td>
<td>9.34%</td>
<td>37 41</td>
<td>0:59:56</td>
<td>0:56:57</td>
<td>1843820</td>
<td>13.00</td>
<td>7.40</td>
</tr>
<tr>
<td>17</td>
<td>132.31</td>
<td>122.17</td>
<td>7.40%</td>
<td>8.48%</td>
<td>44 42</td>
<td>1:00:55</td>
<td>0:58:09</td>
<td>1942541</td>
<td>13.50</td>
<td>7.20</td>
</tr>
<tr>
<td>18</td>
<td>135.18</td>
<td>105.29</td>
<td>5.78%</td>
<td>8.00%</td>
<td>41 41</td>
<td>1:06:19</td>
<td>0:57:51</td>
<td>1881139</td>
<td>12.80</td>
<td>6.40</td>
</tr>
<tr>
<td>19</td>
<td>134.32</td>
<td>118.35</td>
<td>8.67%</td>
<td>10.80%</td>
<td>41 40</td>
<td>1:09:16</td>
<td>1:04:17</td>
<td>1884688</td>
<td>12.10</td>
<td>6.60</td>
</tr>
<tr>
<td>20</td>
<td>135.60</td>
<td>113.29</td>
<td>6.57%</td>
<td>9.55%</td>
<td>46 49</td>
<td>0:55:46</td>
<td>0:51:58</td>
<td>1899478</td>
<td>13.40</td>
<td>6.80</td>
</tr>
</tbody>
</table>

| Avg.             | 135.68        | 118.16          | 7.32%        | 9.81%       | 39.95 42.25        | 1:03:16          | 0:58:24               | 1871602       | 12.79         | 6.82                  | 63.84               |
Simulation Summary

Scenario 6 - Ban all traffic on King St. + conditional TSP

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Avg. Hvy (sec)</th>
<th>Hwy. STDEV (sec)</th>
<th>HWY LT 30sec</th>
<th>HWY MT 5min</th>
<th># of finished trips</th>
<th>Avg. Travel time</th>
<th>Transit travel Distance</th>
<th>Transit Speed</th>
<th>Overall Speed</th>
<th>Cross St. Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120.91</td>
<td>81.88</td>
<td>8.88%</td>
<td>6.97%</td>
<td>54</td>
<td>0:42:08</td>
<td>2129536</td>
<td>19.80</td>
<td>18.50</td>
<td>34.02</td>
</tr>
<tr>
<td>2</td>
<td>120.74</td>
<td>82.76</td>
<td>10.17%</td>
<td>7.83%</td>
<td>53</td>
<td>0:41:35</td>
<td>2127505</td>
<td>19.90</td>
<td>21.40</td>
<td>30.98</td>
</tr>
<tr>
<td>3</td>
<td>122.15</td>
<td>95.54</td>
<td>10.76%</td>
<td>8.81%</td>
<td>51</td>
<td>0:41:56</td>
<td>2108536</td>
<td>19.40</td>
<td>20.30</td>
<td>32.91</td>
</tr>
<tr>
<td>4</td>
<td>121.47</td>
<td>82.35</td>
<td>8.51%</td>
<td>8.47%</td>
<td>55</td>
<td>0:41:28</td>
<td>2123542</td>
<td>19.80</td>
<td>21.90</td>
<td>29.83</td>
</tr>
<tr>
<td>5</td>
<td>121.68</td>
<td>93.89</td>
<td>10.61%</td>
<td>8.45%</td>
<td>53</td>
<td>0:43:14</td>
<td>2122084</td>
<td>19.40</td>
<td>19.10</td>
<td>32.67</td>
</tr>
<tr>
<td>6</td>
<td>121.81</td>
<td>86.92</td>
<td>10.24%</td>
<td>8.20%</td>
<td>53</td>
<td>0:43:08</td>
<td>2121711</td>
<td>19.40</td>
<td>21.30</td>
<td>29.96</td>
</tr>
<tr>
<td>7</td>
<td>121.77</td>
<td>91.35</td>
<td>9.66%</td>
<td>8.12%</td>
<td>54</td>
<td>0:41:59</td>
<td>2133090</td>
<td>19.90</td>
<td>17.30</td>
<td>34.41</td>
</tr>
<tr>
<td>8</td>
<td>121.16</td>
<td>82.17</td>
<td>9.16%</td>
<td>7.96%</td>
<td>55</td>
<td>0:44:06</td>
<td>2127586</td>
<td>19.30</td>
<td>21.90</td>
<td>29.81</td>
</tr>
<tr>
<td>9</td>
<td>120.93</td>
<td>90.48</td>
<td>9.88%</td>
<td>8.01%</td>
<td>53</td>
<td>0:42:56</td>
<td>2136109</td>
<td>19.70</td>
<td>19.40</td>
<td>32.33</td>
</tr>
<tr>
<td>10</td>
<td>121.81</td>
<td>86.92</td>
<td>9.03%</td>
<td>7.74%</td>
<td>54</td>
<td>0:41:57</td>
<td>2122462</td>
<td>19.80</td>
<td>20.90</td>
<td>31.42</td>
</tr>
<tr>
<td>11</td>
<td>121.11</td>
<td>82.96</td>
<td>8.23%</td>
<td>7.86%</td>
<td>53</td>
<td>0:43:47</td>
<td>2127736</td>
<td>19.60</td>
<td>19.20</td>
<td>34.92</td>
</tr>
<tr>
<td>12</td>
<td>121.55</td>
<td>82.66</td>
<td>9.64%</td>
<td>7.57%</td>
<td>54</td>
<td>0:42:28</td>
<td>2125893</td>
<td>19.80</td>
<td>21.70</td>
<td>30.22</td>
</tr>
<tr>
<td>13</td>
<td>121.30</td>
<td>81.35</td>
<td>8.84%</td>
<td>7.80%</td>
<td>56</td>
<td>0:42:09</td>
<td>2126219</td>
<td>19.70</td>
<td>21.30</td>
<td>30.66</td>
</tr>
<tr>
<td>14</td>
<td>122.23</td>
<td>91.06</td>
<td>9.71%</td>
<td>8.20%</td>
<td>54</td>
<td>0:43:29</td>
<td>2119046</td>
<td>19.40</td>
<td>21.60</td>
<td>30.12</td>
</tr>
<tr>
<td>15</td>
<td>121.54</td>
<td>84.46</td>
<td>9.28%</td>
<td>7.36%</td>
<td>50</td>
<td>0:42:02</td>
<td>2115036</td>
<td>19.50</td>
<td>21.50</td>
<td>31.05</td>
</tr>
<tr>
<td>16</td>
<td>121.75</td>
<td>77.25</td>
<td>8.46%</td>
<td>7.04%</td>
<td>53</td>
<td>0:41:49</td>
<td>2111039</td>
<td>19.50</td>
<td>20.80</td>
<td>30.76</td>
</tr>
<tr>
<td>17</td>
<td>121.71</td>
<td>82.98</td>
<td>9.56%</td>
<td>9.36%</td>
<td>51</td>
<td>0:44:05</td>
<td>2118291</td>
<td>19.30</td>
<td>20.70</td>
<td>29.97</td>
</tr>
<tr>
<td>18</td>
<td>122.13</td>
<td>93.44</td>
<td>10.64%</td>
<td>7.08%</td>
<td>55</td>
<td>0:41:46</td>
<td>2129864</td>
<td>19.70</td>
<td>21.40</td>
<td>30.20</td>
</tr>
<tr>
<td>19</td>
<td>122.09</td>
<td>89.70</td>
<td>10.62%</td>
<td>8.69%</td>
<td>54</td>
<td>0:42:06</td>
<td>2119675</td>
<td>19.50</td>
<td>20.60</td>
<td>30.66</td>
</tr>
<tr>
<td>20</td>
<td>121.24</td>
<td>94.83</td>
<td>11.31%</td>
<td>8.75%</td>
<td>54</td>
<td>0:41:26</td>
<td>2107696</td>
<td>19.70</td>
<td>21.50</td>
<td>30.96</td>
</tr>
<tr>
<td><strong>Avg.</strong></td>
<td><strong>121.55</strong></td>
<td><strong>86.75</strong></td>
<td><strong>9.66%</strong></td>
<td><strong>8.01%</strong></td>
<td><strong>53.45</strong></td>
<td><strong>0:42:29</strong></td>
<td><strong>2122633</strong></td>
<td><strong>19.61</strong></td>
<td><strong>20.62</strong></td>
<td><strong>31.39</strong></td>
</tr>
</tbody>
</table>
APPENDIX D

Examples of the Signal Plans (Coded in Paramics Plan Language)

- Plans and Phases files -
## Plan for SAP mode Intersection with 4 loops

plan 2 definition
loops 4
parameters 3

if (init)
{
    variable,
    parameter[3] = 0,
}

if ((phase = 1) and (time[1] = 0))
{
    parameter[1] = 1,
    parameter[3] = 1,
}

if (parameter[3] = 1)
{
    if (parameter[1] = 1)
    {
        if (phase = 2)
        {
            if (time[2] = 0)
            {
                parameter[2] = (green1 - 0.2);
            }
            if (time[2] > parameter[2])
            {
                {
                    parameter[1] = 0.
                    else
                    {
                        green1 = 1.
                    }
                }
            }
        }
    }
}

## Detectors and Parameters in Phases file

use plan 2 on node 92 phase 2
with loop
ShawN lane 1
ShawN lane 2
ShawS lane 1
ShawS lane 2

with parameters
0
0
0
## Plan for SA2 Mode Intersection with loop

```plaintext
plan 6 definition
loops 1
parameters 1

if (init)
{
  variable.
  parameter[1] = 0;
}
if (phase = 1)
{
  if (time[1] = 0)
  {
    parameter[1] = 1;
  }
}
if (parameter[1] = 1)
{
  if (phase = 6)
  {
    if (time[6] = 0)
    {
      clear[1]:
    }
    if (count[1] > 0)
    {
      green[1] = 3;
      clear[1];
    }
  }
}

## Detectors and Parameters in Phases file

use plan 6 on node 90 phase 6
with loop
SudburySl lane 1

with parameters
0
```
plan 20 definition
loops 8
parameters 21

if (mtt)
    variable.
    parameter[18] = 0.

if (phase = 1)
    if (time[1] = 0)
        parameter[5] = 0.
        parameter[21] = 0.
    ;
    if (parameter[18] = i)

        if (count[1] type[16] > 0)


            if (parameter[6] = 0)
            ;
            clear[1].

        if (count[4] type[16] > 0)


            if (parameter[11] = 0)
            ;
            clear[4].

        if (count[2] type[16] > 0)


            clear[2].

        if (count[3] type[16] > 0)


            clear[3].

        if (parameter[7] = 1)

            parameter[7] = 0.
if (parameter[12] = 1)
{
    parameter[10] = parameter[8];
    parameter[12] = 0;
}
if (parameter[6] = 1)
{
    if (parameter[2] >= parameter[3])
    {
        parameter[6] = 0;
        parameter[3] = 0;
    }
}
if (parameter[11] = 1)
{
    if (parameter[9] >= parameter[10])
    {
        parameter[11] = 0;
        parameter[10] = 0;
    }
}

if ((phase = 2) and (time[2] = 0))
{
    parameter[4] = (green1 - 0.2);
    parameter[19] = (green2[6] - 0.2);
}
if (parameter[13] > 0)
{
    if (phase = 2)
    {
        if (time[2] > parameter[4])
        {
            if (parameter[5] = 0)
            {
                {
                }
                else
                {
                    parameter[15] = 0.
                }
                else if (parameter[5] > 0)
                {
                }
            }
        }
    }
}
if (parameter[5] = parameter[14])
{
    if (parameter[15] = 1)
    {
        if (parameter[13] > 0)
        {
            if (phase = 2)
            {
                if (time[2] > parameter[4])
            }
if (parameter[21] = 1)
{
    green1 = 1.
}
else if (parameter[21] = 0)
{
    green1 = 2.
}

if (parameter[20] = 1)
{
    if (phase = 6)
    {
        if (time[6] > parameter[19])
        {
            if (parameter[13] > 0)
            {
            }
        }
    }
    if (phase = 8)
    {
        if (time[8] > 3.8)
        {
            green[7] = green[7].
        }
    }
}

### Detectors and Parameters in Phases file ###

use plan 20 on node 90 phase 2
with loops
SudburyWBU lane 2
SudburyWBD lane 2
SudburyEBD lane 2
SudburyEBU lane 2
SudburyS1 lane 1
SudburyS1 lane 1
SudburyS1 lane 1
SudburyS1 lane 1

with parameters
(0.0.0.0.0.0.0.0.28,0.0.0.0.0.0.0)
### Offset Recovery Plan for the Intersection which has Red Truncation Plan

Plan 8 definition
loops 2
parameters 27

if (int)
  |
  variable.
  parameter[27] = 0.
|

if (phase = 1)
  |
  if (time[1] = 0)
  |
    parameter[27] = 1,
    parameter[7] = 0.
  |
|
if (parameter[27] = 1)
  |
  if (phase = 2)
  |
    if (parameter[1] = cycle)
      |
    |
  |
  if (phase = 8)
  |
    if (time[8] = 0)
      |
      parameter[20] = 0.
      |
      if (parameter[2] = parameter[6])
        |
        if (parameter[2] > parameter[6])
          |
          if (parameter[22] > cycle)
            |
            parameter[22] = (parameter[22] - cycle).
          |
          else if (parameter[2] < parameter[6])
            |
            parameter[22] = (cycle - parameter[22]).
          |
          else if (parameter[2] = parameter[6])
            |
            

102
parameter[22] = 0.

if (parameter[4] > cycle)

if (parameter[4] < 1)
  parameter[3] = 0.
else if ((parameter[4] > (cycle - 1)) and (parameter[4] < (cycle + 1))
  parameter[3] = 0.
else if (parameter[4] >= 1)

if (parameter[3] = 1)
  if (parameter[4] < ((1/4)*cycle))
  else if (parameter[4] >= ((1/4)*cycle))
if (parameter[7] = 1)
  if (parameter[13] >= parameter[15])
  else if (parameter[12] = 1)
    if (parameter[13] >= ((1/8)*cycle))
else if (parameter[7] = 2)
  parameter[23] = (cycle - parameter[4]).
  if (parameter[23] >= parameter[18])
    parameter[23] = parameter[18].
else if
parameter[24] = (parameter[23] * (1 - parameter[16]));
parameter[25] = (parameter[23] * parameter[16]);

if (parameter[7] > 0)
{
  if (parameter[24] > 16)
  {
    parameter[24] = (parameter[24] - 16);
    parameter[14] = (parameter[14] + 16);
  }
  if (parameter[24] > 8)
  {
    parameter[24] = (parameter[24] - 8);
    parameter[14] = (parameter[14] + 8);
  }
  if (parameter[24] > 4)
  {
    parameter[24] = (parameter[24] - 4);
    parameter[14] = (parameter[14] + 4);
  }
  if (parameter[24] > 2)
  {
    parameter[24] = (parameter[24] - 2);
    parameter[14] = (parameter[14] + 2);
  }
else if (((parameter[24] < 2) and (parameter[24] > 1))
{
  parameter[24] = 1;
  parameter[14] = 0;
}
else if (parameter[24] <= 1)
{
  parameter[24] = 0;
  parameter[14] = 0;
}
else if (parameter[24] = 2)
{
  parameter[14] = 0;
}

if (parameter[25] > 32)
{
  parameter[25] = (parameter[25] - 32);
  parameter[14] = (parameter[14] + 32);
}
if (parameter[25] > 16)
{
  parameter[25] = (parameter[25] - 16);
  parameter[14] = (parameter[14] + 16);
}
if (parameter[25] > 8)
{
  parameter[25] = (parameter[25] - 8);
  parameter[14] = (parameter[14] + 8);
}
if (parameter[25] > 4)
{
  parameter[25] = (parameter[25] - 4);

if (parameter[25] > 2)
{
}

if (parameter[25] > 1)
{
    parameter[14] = 0.
} else if (parameter[25] <= 1)
{
    parameter[14] = 0.
}

if (parameter[7] = 1)
{
    {
        if (green2[2] < parameter[10])
        {
        }
    }
    {
        if (green2[6] < parameter[11])
        {
        }
    }
    {
    }
    else
    {
    }
}
else if (parameter[7] = 2)
{
    if (parameter[12] = 1)
    {
    }
    else
    {
    }
}

105
```c
  green2[6] = green3[6].
```

### Detectors and Parameters in Phases file  ###

```
use plan 8 on node 8 phase 6
with loops
HowardparkNBD lane 1
HowardparkSBD lane 1

with parameters
(0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0)
```