A Method for Evaluating and Prioritizing Candidate Intersections for Transit Signal Priority Implementation

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Transit agencies seeking to improve transit service delivery are increasingly considering the deployment of transit signal priority (TSP). However, the impact of TSP on transit service and on the general traffic stream is a function of many factors, including intersection geometry, signal timings, traffic demands, TSP strategies and parameters, transit vehicle headways, timing when transit vehicles arrive at the intersection, etc. Previous studies have shown that depending on these factors, the net impact of TSP in terms of vehicle or person delay can be positive or negative. Furthermore, due to financial constraints, transit agencies are often able to deploy TSP at only a portion of all of the candidate intersections. Consequently, there is a need to estimate the impact of TSP prior to implementation in order to assist in determining at which intersections TSP should be deployed.

Currently, the impacts of TSP are often estimated using microscopic simulation models. However, the application of these models is resource intensive and requires specialized expertise that is often not available in-house to transit agencies.

In this thesis, an analytical model was proposed for estimating the delay impacts of green extension and early green (red truncation) TSP strategies. The proposed model is validated with analytical model reported in the literature and microscopic simulation model. This is followed by model sensitivity analysis. A software module is developed using the proposed model. The usefulness of the model is illustrated through its application to estimate the TSP performance. Finally, a prioritization is conducted on sixteen intersections with different geometric and operational traffic strategies.

The overall results indicate that the proposed model is suitable for both estimating the pre-deployment and post-deployment TSP performance. The proposed model is suitable for implementation within a spreadsheet and requires considerably less effort, and less technical expertise, to apply than a typical micro-simulation model and therefore is a more suitable tool for transit agencies to use for prioritising TSP deployment.

Acknowledgements

Dedication

This work is dedicated to my family. My father Prof. *Badrul Hasan Abdy*, my mother *Rehana Abdy*, my beloved *Zainab Abdy* and my brother *Kamran Abdy*. It is all due to their love, constant support, and sacrifice.

Table of Contents

List of Figures

List of Tables

Nomenclature

α	=	Regression parameter [56]
β	=	Slope of the regression [56]
Δd	=	Average increased delay per vehicle (s) [23, 56]
ΔD	=	Total additional delay (s) [23, 23, 65]
$\Delta d_{NoTSP,pers}$	=	Intersection Person delay with No TSP control (sec/pers) [113]
Δd_{pers}	=	Delta Intersection Person delay (sec/pers) [113]
$\Delta d_{TSP,pers}$	=	Intersection Person delay with TSP control (sec/pers) [113]
$\Delta E'$	=	Additional GHG Emissions due to TSP implementation [58]
$\Delta F'$	=	Additional Fuel consumed due to TSP implementation (liters per vehicle) [57, 58]
ΔF	=	Additional Fuel used per vehicle due to the signal operation based on the additional total delay per vehicle that resulted from the signal (versus no signal at all), (litres per vehicle) [56]
$\Delta F_{No\,TSP}$	=	Fuel consumed due to No TSP control (liters per vehicle) [57]
ΔF_{TSP}	=	Fuel consumed due to TSP implementation (liters per vehicle) [57]
γ	=	Tonnes of CO2 equivalents per million liters of fuel consumed [58]
λ	=	average arrival rate over analysis period [17, 18, 19, 19, 23, 23, 51, 63, 63, 65, 74, 75,75, 75, 76, 77]
λ_g	=	Vehicle Arrival rate during the green interval [76]
λ_{np}	=	Vehicle Arrival rate at the non-prioritized approach [38,48, 49, 50, 50, 51, 51, 51, 52, 53, 53, 53, 54]
λ_p	=	Vehicle Arrival rate at the prioritized approach [38, 46, 47, 47, 48, 96]
λ_r	=	Vehicle Arrival rate during the red interval [77]
μ	=	average service rate over analysis period [19,23, 51, 63, 63, 93]
μ_{np}	=	Vehicle Service rate at the non-prioritized approach [38, 50, 50, 51, 51, 51, 53, 53, 53, 54]
μ_p	=	Vehicle Service rate at the prioritized approach [38,23, 47]
ρ	=	Traffic Intensity, Flow ratio [18, 19, 19, 23, 65]
ρ_{np}	=	Traffic Intensity at the non-prioritized approach [38, 48, 49, 51, 52, 53, 54]
ρ_p	=	Traffic Intensity at the prioritized approach [38, 46, 47, 47, 48, 96]
A_{np}	=	Amber interval duration for non prioritized approach (seconds) [39, 39, 42]
A_p	=	Amber interval duration for prioritized approach (seconds) [39, 39, 42]
AR_{np}	=	All red interval duration for non prioritized approach (seconds) [39,39, 42]
AR_P	=	All red interval duration for prioritized approach (seconds) [39,39, 42]
c	=	capacity of intersection approach (veh/h) [19, 21]
C_B	=	Number of bus arrival cycles per hour [22, 22]
C_N	=	Number of cycles per hour [22]
C_{NB}	=	Number of non-bus arrival cycles per hour [22, 22]
d	=	average delay per vehicle (s/veh) [19, 19, 20, 21, 63, 63]
d_1	=	average overall uniform delay (s/veh) [20]
d_2	=	incremental delay accounting for randomness of vehicle arrivals and over-saturation delay (s/veh) [20, 21]

d_3	=	residual delay for over-saturation queues that may have existed before the analysis period (s/veh) [20]
$D_{(1B-NP)}$	=	Average person delay with one bus and no priority (sec/cycle) [22]
$D_{(1B-P)}$	=	Average person delay with one bus and no priority (sec/cycle) [22]
D_{GETSP}^{np}	=	Total Delay on the Non Prioritized approach with Green Extension TSP control [52, 53]
D_{GETSP}^{p}	=	Total Delay on the Prioritized approach with Green Extension TSP control [48]
$d_{i,transit}$	=	Bus delay for i^{th} bus time of arrival (sec/veh) [113]
$d_{i,veh}$	=	Intersection Auto delay for i^{th} bus time of arrival (sec/veh) [113]
$D_{(NB-OS)}$	=	Average person delay with no bus for original green splits (sec/cycle) [22]
$D_{No\ TSP}^{np}$	=	Total Delay on the Non Prioritized approach with No TSP control [48]
$D_{No\ TSP}^{p}$	=	Total Delay on the Prioritized approach with No TSP control [46, 96]
d_{pers}	=	Intersection Person delay (sec/pers) [113]
D_{RTTSP}^{np}	=	Total Delay on the Non Prioritized approach with Red Truncation TSP control [49, 50, 50]
D_{RTTSP}^{p}	=	Total Delay on the Prioritized approach with Red Truncation TSP control [47]
D_t	=	total delay (s/veh) [17, 19]
$d_{transit}$	=	Bus delay (sec/veh) [113, 113]
d_{veh}	=	Intersection Auto delay (sec/veh) [113, 113]
f_P	=	adjustment factor for situations in which the platoon arrives during the green interval (0.9–1.2) [21]
f_{PF}	=	adjustment factor accounting for the quality of progression in coordinated systems [20, 21]
f_T	=	adjustment factor for residual delay component [20]
$F_{transit}$	=	Transit Frequency (vph) [113]
g	=	green duration interval (s) [17,51, 63, 63, 76, 111]
g_e	=	duration of effective green interval (s) [19, 21, 21]
g_{ext}	=	Green extension time on the prioritized approach (seconds) [39,39, 42, 48, 52, 52, 53, 53, 53, 53, 54, 54]
g_{min}	=	Minimum green times for non-prioritized approach (seconds) [39, 39, 42]
g_{np}	=	Green interval on the non-prioritized approach (seconds) [39,39, 42, 50, 50, 50, 51, 51, 51, 51, 51, 53, 53, 53, 53, 54, 54]
g_p	=	Green interval on the prioritized approach (seconds) [39,39, 42]
g_{tr}	=	Reduced green time on the non prioritized approach (s) [23, 47, 47, 47, 51, 51, 51, 39, 39, 48, 49, 49, 50,50, 50, 51, 51, 51]
h	=	Analysis time period (minutes) [75, 75, 77]
k	=	incremental delay factor accounting for pre-timed or actuated signal controller settings [21]
l	=	adjustment factor for upstream filtering/metering [21,21]
$L_{transit}$	=	Transit Occupancy [113]
m	=	capacity guide model parameters [21]
n	=	Number of cycles required to dissipate the queue on non-prioritized approach [39, 51, 51, 53, 54, 54, 75]
N	=	Number of vehicles arriving during the analysis period [75]

N_g	=	number of vehicles arriving during green interval during entire analysis period [75, 75]
N_r	=	number of vehicles arriving during red interval during entire analysis period [75, 75]
O_a	=	Auto Occupancy rate [113]
P	=	proportion of all vehicles in movement or lane group arriving during green interval [111]
P_e	=	proportion of vehicles arriving during effective green interval [21]
P_g	=	proportion of vehicles arriving during the green interval [75, 76]
P_r	=	proportion of vehicles arriving during the red interval [75, 77]
$P[T \geq t_a]$	=	Probability of time headway T being greater than or equal to time t_a [74, 75]
r	=	red duration interval (s) [17, 23, 65, 77]
r_{np}	=	Red interval on the non prioritized approach (seconds) [39, 48, 49, 49, 50, 50, 51, 51, 51, 51, 51, 52, 52, 53, 53, 54, 54, 54]
r_p	=	Red interval on the prioritized approach (seconds) [39, 46, 46, 47, 47, 47, 48, 48, 96]
R_p	=	platoon ratio [111]
$\bar{t}$	=	Average time headway of traffic stream [75, 75, 75]
t	=	Time call for priority is received by controller (seconds) measured from the start of A_p [39, 42, 65]
T	=	evaluation period (h) [21]
t_a	=	average arrival rate over analysis period [74,75, 75]
t_c	=	time of dissipation (s) [17]
t_d	=	Bus travel time [42]
t_i	=	time of the ith vehicle [77]
t'_{npi}	=	Non-prioritized approach Green time in Cycle i at which queue is dissipated with TSP [39, 49, 49, 50, 50, 51, 51, 51, 52, 52, 53, 53, 54]
t_{npi}	=	Non-prioritized approach Green time in Cycle i at which queue is dissipated with No TSP [17, 39]
t'_{pi}	=	Prioritized approach Green time in Cycle i at which queue is dissipated with TSP [39, 47, 47, 47, 48, 48]
t_{pi}	=	Prioritized approach Green time in Cycle i at which queue is dissipated with No TSP [39, 46, 46]
t_r	=	Time when existing phase is terminated as a result of TSP (seconds) [39, 42]
t_q	=	Bus Time spent in queue [42]
t_T	=	Bus travel time minus inter green time and time required to serve queue $$t_T = t_d - AR_{np} - t_q \text{ (Seconds) [39, 42]}$$
U_N	=	Independent uniform random variables between 0 and 1.0 [75]
V_{int}	=	Intersection Vehicular Volume (vph) [113]
WD_{NP}	=	Weighted delay with no priority provided to transit vehicle (person sec/cycle) [22]
WD_P	=	Weighted delay with priority provided to transit vehicle (person sec/cycle) [22, 22]
X	=	volume-to-capacity ratio [19, 21, 21]

X_o = volume-to-capacity ratio below which the overflow delay is negligible in capacity guide models [21]

y = capacity guide model parameters [21]

Chapter 1

Introduction

1.1 Study Background

Transportation planners and traffic engineers are increasingly faced with the challenge of selecting appropriate strategies for enhancing public transit service without adversely impacting auto traffic. Transit Signal Priority (TSP) has emerged as an enhanced operational strategy that facilitates the movement of transit vehicles through traffic-signal controlled intersections.

Figure 1.1 shows a simplified representation of TSP at a traffic signal. Typically, the following steps are conducted:

- Transit vehicle is detected at the check in point upstream of the intersection;

- A request is sent to the signal controller and a decision is made whether or not to grant priority;

- If a priority is granted, then the passage of the transit vehicle through the intersection is detected at the checkout point downstream of the intersection;

- After the priority treatment, the signal controller restores the normal signal timing

Signal

check in   Intersection   check out
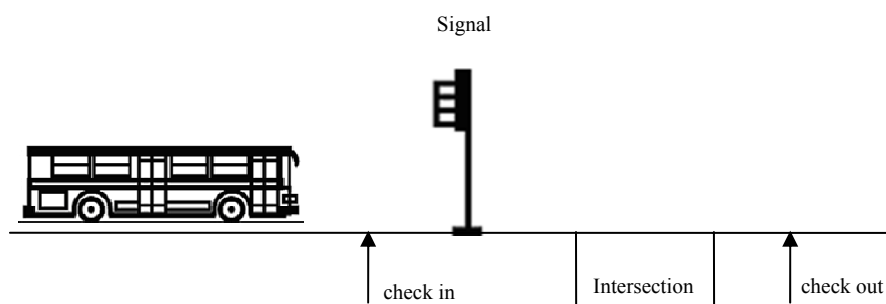
Figure 1.1: A simplified representation of transit signal priority [27]

TSP strategies can be classified into passive, active, and adaptive strategies. Passive strategies are offline strategies that provide priority to transit vehicles without transit vehicle detection. Active and adaptive strategies are online techniques that provide priority to a transit vehicle upon detection.

There are generally two methods used to provide priority; (1) an *unconditional priority* that provides TSP to all transit vehicles; and (2) *conditional priority* that grants TSP only to those transit vehicles that meet predefined criteria (e.g. bus running more than *n* minutes late). Though giving priority to the transit vehicle maximizes the transit vehicle's speed and reduces operating cost and transit passenger travel time, giving unconditional priority to transit vehicles that are ahead of schedule may negatively impact service reliability. In addition, various strategies can be combined with conditional or unconditional priority:

- Green extension,

- Early green (also called red truncation),

- Phase insertion (special transit phase),

- Phase rotation.

The most widely applied TSP strategies by North American transit agencies are green extension and red truncation [27]. Figure 1.2 illustrates the green extension strategy. If the bus time of arrival at the check in detector is during the green on the prioritized approach and bus requires additional time to clear the intersection, the green time on the prioritized approach is extended to permit the bus to pass through the intersection prior to the end of the green phase.

Figure 1.3 shows the early green strategy that can be applied when the signal is red for the prioritized approach when the bus arrives. If the bus time of arrival is during the non-prioritized green phase, the green phase on the non-prioritized approach is terminated early. The time reduced from the non-prioritized green is then awarded to the prioritized approach green to begin the cycle earlier then it would normally.
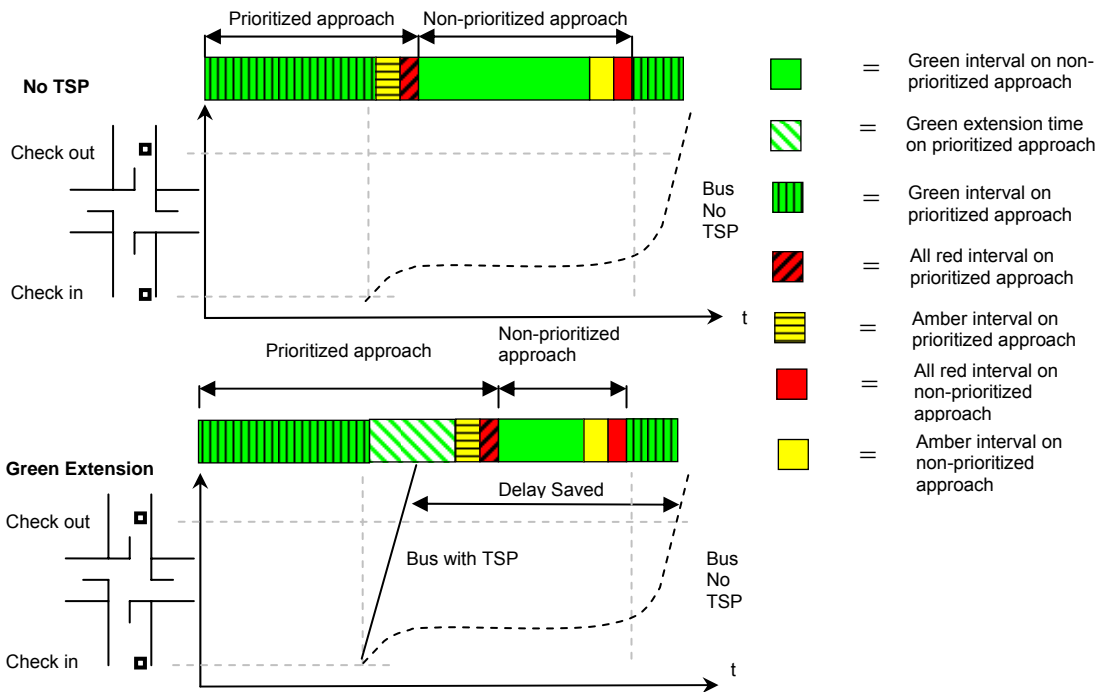
Figure 1.2: Space – Time diagram illustrating green extension TSP
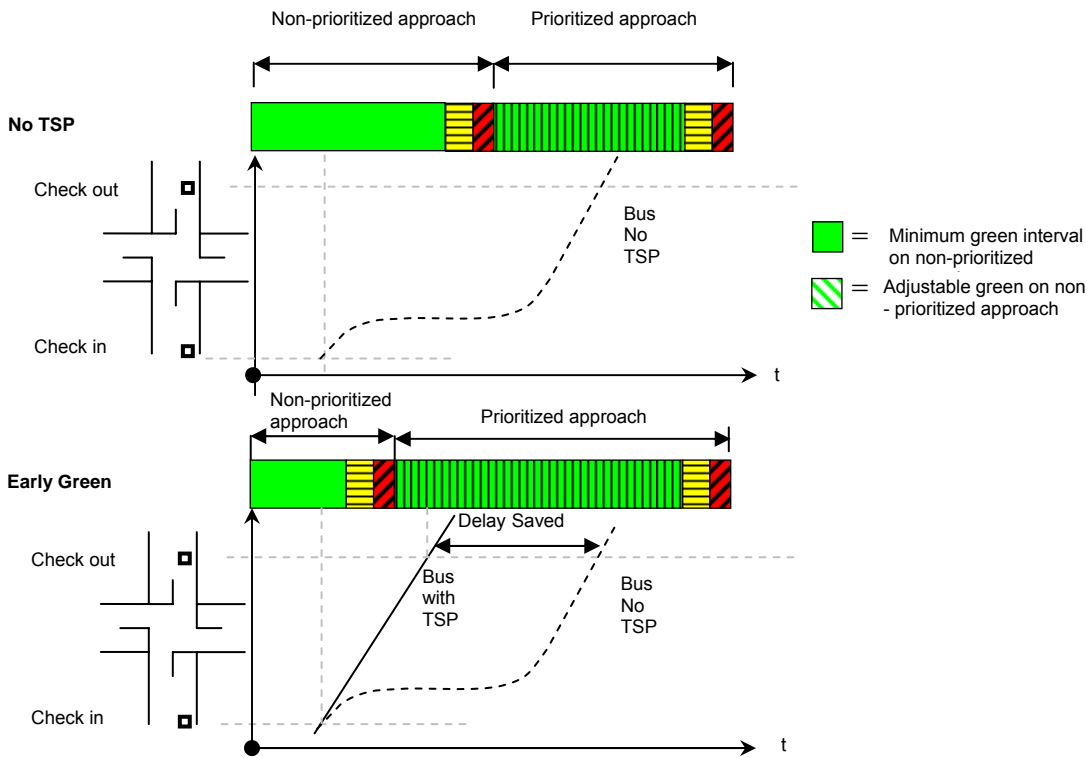
Figure 1.3: Space – Time diagram illustrating early green TSP

3

The collective goal of TSP is to improve transit service from the perspective of both transit users and transit service operators. TSP has the potential to reduce delays to transit vehicles at signalized intersections, thereby making transit more competitive with auto from a transportation mode choice perspective and reducing transit agency operating cost (and potentially reducing fleet size requirements if travel time savings accumulated over a route are sufficiently large to result in the need for fewer buses). TSP also has the potential to reduce the variability of delays to transit vehicles at signalized intersections, thereby increasing the reliability of transit travel times.

Numerous studies and experiments have been conducted in order to find more efficient ways to achieve these goals by adjusting traffic signal timings in response to prevailing traffic conditions in real-time (active) and in off-line (passive) modes. TSP has shown its relative efficiency and effectiveness over pre-timed signal control in a number of installations in North America [2, 3].

However, drawbacks to the implementation of TSP have also been revealed, particularly for intersections at which approaches not receiving priority are operating at or near capacity. From a general traffic control perspective, in mixed traffic flow, transit vehicles often become the source of traffic flow disruption due to comparatively slower driving speeds with frequent and regular stops for boarding and alighting of passengers.

Numerous field studies and simulation studies have demonstrated the potential for TSP to provide benefits to transit vehicles. However, TSP also has the potential to have negative impacts including:

- increase in delay to vehicles on the non-prioritized approach due to decreased green times

- disruption to traffic progression (platooned arrivals) at downstream signalized intersections

- recovery from TSP operation modified traffic signal timings requires several signal cycles. Typically, the non-prioritized approach is not compensated for reduced green times and therefore traffic signals on the non-prioritized approach operate at non-optimal timing plans during the TSP grant

Studies [38, 40, 41, 53, 63, 64] have shown the TSP impacts are a function of many factors including:

- Intersection geometry

- Signal timing plan

4

- Traffic demands

- TSP strategy

- TSP parameters

- Frequency of buses

- Bus time of arrival during signal cycle

- Level of progression

Furthermore, studies have shown that the net impacts of TSP may be positive or may be negative. Therefore, an estimate of TSP performance is required before implementation to ensure TSP is deployed at intersections at which net benefits can be achieved.

1.2 Limitations of Current Practices

Given that TSP can have net positive or negative impacts, and that performance is a function of many factors, transit agencies require the ability to: (1) determine whether TSP should be deployed at a particular intersection, and (2) rank candidate intersections to prioritize resource allocation. Carrying out these tasks in an objective manner requires an ability to answer the following questions for each intersection.

- What performance benefits are achieved in terms of vehicular delay on prioritized and non-prioritized approaches?

- What is the expected impact of TSP on average bus delay?

- How much improvement is expected in bus delay variability with TSP implementation?

- What is the impact of TSP implementation on fuel consumption and emissions?

- How does TSP performance changes as a function of changes in:

  o Day-to-day variability in Mean peak hour volumes?

  o Progression levels?

  o Roadway capacity?

  o TSP parameter values?

The answers to these questions can be obtained via three main methods namely; (1) field measurements (2) microscopic simulation and (3) analytical expressions for quantifying delay.

There are several challenges with conducting an empirical field study including, the difficulty of measuring delays to transit and non-transit vehicles and to do so for an appropriate range of conditions.

Microscopic simulation models overcome several of the challenges associated with empirical studies. Namely, simulation models can directly estimate delays to transit and general-purpose vehicles and can do so for TSP and No TSP signal control. However, microscopic simulation modeling requires specialized expertise that typically may not be available within transit agencies and is resource intensive. Moreover, the microscopic simulation results vary significantly from project to project [8, 9, 10, 11, 12].

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

1.3 Study Scope and Objectives

The primary objective of this thesis is to develop analytical model(s) based on commonly used TSP control strategies. This research has the following seven specific objectives:

1. Quantify, based on empirical data, the impact of day-to-day variation in peak hour volume on intersection performance

2. Develop multiphase analytical model(s) for estimating TSP performance with green extension and red truncation strategies. The model must be able to provide an objective and verifiable means of evaluating the impact of TSP performance for a wide range of conditions

3. Validate the developed model(s) with microscopic simulation model and analytical model. Select model(s) based on one of proposed queue systems for TSP implementation

4. Develop a relationship between TSP performance measured in terms of delays and emission impacts. This relationship will help in assessing TSP impacts from an environmental perspective

5. Determine based on sensitivity analysis, the influence on TSP performance to progression levels, TSP parameters values, bus headway and bus delay variability

6. Demonstrate the application of the proposed model using selected intersections in Waterloo Region

The scope of this research is limited to following:

1. TSP performance impacts are for roadway based transit system.

2. TSP performance is evaluated when the traffic signal is under saturated for the No TSP case.

3. Only fixed time control strategies are considered. Actuated signals must be modeled as operating under a fixed time plan.

4. In development of the proposed models the modal shift impact of TSP is not considered (i.e. vehicle demands do not change between the performance estimated using No Transit Signal Priority and with Transit Signal Priority).

This dissertation consists of 10 chapters. Chapter 2 provides a review of the existing TSP evaluation methods. Chapter 3 investigates the impact of day-to-day variability on the performance of intersection. In Chapter 4, a D/D/1 model is proposed, followed by validation in Chapter 5. In Chapter 6, a Poisson arrival model is considered and validation is conducted. Chapter 7 shows detailed application of proposed model to a candidate signalized intersection. Chapter 8 conducts sensitivity analysis of the proposed model followed by aggregated results for candidate-signalized intersections in Chapter 9. The Chapter 10 concludes this study, summarizes the work, highlighting both successes and limitations, and provides recommendations for future research.

Chapter 2

Literature Review

TSP can be an effective method for improving transit service, efficiency, and reliability in spite of increasing congestion; however, TSP does not always provide net benefits. Consequently, it is important to evaluate the impact of TSP for demonstrating the benefit of a TSP system, to assess its impact on non-prioritized approach, and to determine the specific conditions under which TSP is most effective.

This chapter presents a review of literature with particular focus on five topic areas, namely: (1) measures used to evaluate TSP performance, (2) impact of day-to-day variability of peak hour volume, (3) factors influencing TSP performance (4) methods for TSP prioritization and (5) methods used to estimate TSP performance evaluation.

2.1 Measure of performance for evaluating TSP

Average auto delay is one of the most common performance measures used to quantify the interruption of vehicular traffic flow due to the operation of signal control [10, 11, 51, 55, 58, 61, 62]. This delay is experienced by both general-purpose vehicles and transit vehicles. Implementation of TSP has an impact on general-purpose vehicle and transit delay.

Auto delay at signalized intersections is estimated as the difference between the ideal vehicle trajectory and observed vehicle trajectory. At signalized intersections, the vehicles have to decelerate, stop, and accelerate to clear the intersection. In this process the deceleration delay, stopped delay and acceleration delay is incurred to the vehicles.

There are various auto delay terms used by transportation professionals depending on the components of delay. For example, *Stopped Delay* is the delay incurred when a vehicle is fully stopped i.e. not accelerating or decelerating [32]. If the delay when vehicles are reducing speed upstream of an intersection is added to the stopped delay and is compared with uncontrolled condition (no signal) condition, it is referred to as *Control Delay* [13]. The sum of all components of delay, including control delay is referred to as *Total Delay*.

Person delay is often used as a measure of performance (MOP) for comparing the impact of TSP implementation [12, 41, 53]. The use of person delay as the MOP implies the assumption that the value of time for a bus passenger is the same as that for a non-transit vehicle occupant. This assumption allows use

of the same scale to evaluate the impact of TSP to both auto and transit users and provides flexibility to practitioners by allowing variable auto occupancy and bus occupancy rates.

The total overall person delay is determined as the sum of all person delays, calculated as the delay to individual vehicle categories weighted by their average occupancy during the evaluation time [30]. This measure considers the delay experienced to the people in vehicles rather than the delay experienced by vehicles.

Consider a two-phase operation for which the average delay is 10 seconds per vehicle in each phase. In the first phase, there are four buses with 45 persons per vehicle. In the second phase, there are four cars with average car occupancy of 1.2 persons per vehicle. The total person delay for the first phase is 10 x 4 x 45 = 1800 seconds. For the second phase, the delay is only 10 x 4 x 1.2 = 48 seconds. Therefore, based on minimizing person delay the first phase deserves a more favourable green allocation However, based on average vehicle delay there is no need for a more favourable allocation.

Ova et al. [41] found that TSP with green extension strategy resulted in 8.5% decrease in person delay during midday but has an increase of 13.5 % in afternoon. The Red truncation strategy resulted in 8% decrease in person delay during midday but has an increase of 6.5% in afternoon.

Changes to average bus delay are also commonly used to quantify the TSP performance. It is expected that TSP implementation results in reduction in bus delay as the TSP signal timing favours the bus movement. There are reported reduction in bus delays of up to 29% [10], 4.1% [11], 28% [41], 34% [50], 28.7% [53], 14% [54], 80% [55], 46% [57], 25% [59] and 39% [60]. With implementation of TSP, a reduction is expected in bus delay variability. The reduction is measured as the difference in standard deviation of bus delay with and without TSP control. Studies have shown that the TSP improves bus schedule adherence as the average bus delay is decreased [10, 11, 12].

Reducing the intersection delays by TSP implementation does not always results in reducing the fuel consumption and emission. Dion et al. indicated that implementation of TSP can either result in increase or reduction in GHG emissions. No conclusive impacts on vehicle emission were observed in the study. The study [11] indicated that implementation of TSP resulted in reduction in fuel consumption.

2.2 Impact of day-to-day variability on performance measures

The problems of estimating delays at signalized intersections have been extensively studied in the literature. The vast majority of the work has focused on developing models for estimating the mean delay

- a point estimate of stochastic delays. Detailed discussions of these average delay prediction models have been provided by [15, 16, 17].

Some work has been done to investigate the variability of delay at signalized intersections. Several studies have developed analytical expressions for the variance of delay. Cronje [18] and Olszewski [19, 20] developed a Markov-chain model to calculate the average delay and time-dependant distribution of average cyclic delay. Fu and Hellinga [21] developed an analytical model of the variance of control delay based on simulated data. Engelbrecht et al. [22] developed a generalized model for mean control delay and investigated the variability of delay using simulation. In all of these studies, the variability in delay is solely a result of the variability in the time headways of vehicles arriving at the stop line. The mean arrival rate, saturation flow rate, and signal timings are all assumed deterministic and constant.

Several studies have also examined the variability of delay based on field data. Teply and Evans [23] analyzed the delay distribution at a signalized approach for evaluating signal progression quality. They observed that most of the delay distributions are bimodal and a point estimator is not adequate to describe these distributions. Details pertaining to the field data collection effort (i.e. the number of days and time of day over which field data were collected) are not provided in the paper so it is difficult to ascertain the cause for the observed variability. However, given that the study was conducted to evaluate signal progression, it seems likely that the majority of the observed variability in delay was a result of the time of vehicle arrivals.

More recently, Colyar and Rouphail [24] examined the variability in control delay on a signalized arterial corridor. They observed that when the mean control delay was relatively small - in the level of service (LOS) A-B range, the distribution of control delay had a single peak. However, for larger mean delays, the distribution was increasingly bi-modal. Data were collected during the AM peak (7-9 AM) and PM peak (4-6 PM) periods over a number of different days. The authors consider the possibility that traffic volumes vary by time of day (though they do not consider the possibility that traffic volumes vary from one day to the next) but conclude that these changes in volume (within the two hour peak period) are small and therefore the observed variability in control delay is predominantly due to the stochastic nature of vehicle arrivals on a cycle-by-cycle basis.

A recent study conducted by Sullivan et al., [25] specifically examined the impact of day-to-day variations in peak hour traffic volumes on intersection service levels. Using weekday data from 22 directional continuous traffic counting stations in the city of Milwaukee, the authors computed the

coefficient of variation (COV = standard deviation divided by the mean), of peak hour traffic volume. They found that the COV ranged from 0.048 to 0.155 with a mean of 0.089.

Using this COV in peak hour volumes, they examined the impact on a hypothetical intersection approach controlled by a fixed time signal with a 90-second cycle length and an assumed saturation flow rate of 1900 vph. The approach delay was estimated using the Highway Capacity Manual (HCM) method for mean peak hour volumes, the 85th percentile volume (i.e. mean plus one standard deviation) and the 97.5 percentile volume (i.e. mean plus two standard deviations).

The authors found that the use of average volume to capacity ratio tends to understate level of service (LOS) at busy intersections and concluded that for intersections operating at LOS D, a 10 % increase in traffic volumes would cause deterioration to LOS E or LOS F, about 15% of the time.

The authors also concluded, "It is desirable to base intersection service level computations on several days' peak hour volumes" [25]. This conclusion suggests the importance of the day-to-day variability. However, no recommendation has been made regarding number of days or computation method.

An earlier study by Kamarajugadda and Park [26] proposed an analytical method to compute the impact of day-to-day variability of peak hour volume on variance of delay. Two separate estimation methods were developed – one for under-saturated intersections and the other for over-saturated intersections. The under-saturation model uses the concept of expectation functions to relate analytically the mean, variance, and distribution of peak hour volume to the mean and variance of delay. In this model, the HCM delay expression is approximated using the Taylor Series expansion technique. This approach is not applicable to over-saturated conditions as the HCM [13] delay expression is discontinuous at degree of saturation equal to 1.0. Consequently, the method of expectation functions cannot be used for degree of saturation $\geq$ 1.0. Kamarajugadda and Park [26] define an under-saturated critical lane group as one for which the 99.99th percentile degree of saturation is less than 1.0. The over-saturated model numerically integrates the expectation function over the range of degree of saturation from zero to three.

Kamarajugadda and Park [26] validated their proposed models using Monte Carlo Simulation (MCS) for a hypothetical intersection. The validation consisted of comparing the mean and variance of delay estimated by the proposed models with the mean and variance of delay resulting from the MCS. The validation was conducted assuming that delay follows a normal distribution.

11

Though Kamarajugadda and Park [26] do not provide any statistical measures of validity, they conclude that their proposed models well represent the MCS results. However, they also note that the accuracy of their proposed models for estimating the mean delay decreases when degree of saturation exceeds 0.6. Furthermore, they conclude that the variance of delay is substantially influenced by the distribution of peak hour volume that is assumed but they do not provide any recommendation on which distribution is most appropriate.

Given the available literature, it appears that the following questions remain to be addressed:

1. What is the magnitude and distribution of day-to-day variability in peak hour intersection approach volumes?

2. To what extent does the variability in peak hour approach volumes impact the mean and distribution of intersection delay?

3. Should the variability of peak hour volumes be considered when estimating the impact of TSP?

In next section, the factors influencing TSP performance are presented.

2.3 Factors influencing TSP

Many factors affect the performance of TSP. The following sections identify some of these factors, as they relate to 1) the roadway geometry and traffic signal system, and 2) the transit system [63].

Intersection geometry is one of the most important factors for the operation of any transportation system since it directly dictates transportation system capacity and types of possible operations [63]. Surrounding development, among other factors, influences the location and number of intersections, generates traffic in the area, and dictates transit stop locations. Roadway geometry is usually the limiting factor in TSP implementation [63].

The TSP system wide performance is influenced by the traffic demand [66]. There are periods, *peak hours*, during the day when the intersections are operating with the greatest volume of regular traffic as well as transit vehicles [63]. Typically, peak hour volume is one of the key components in determining the signal timing plans. A high demand on non-prioritized approach may signify fewer opportunities to allocate green time to prioritized approach, hence result in limiting the TSP performance. The Transit vehicle arrivals on heavily congested approaches may result in system wide benefits if the conflicting

approaches are not congested. Alternatively, transit vehicle arrivals on lightly congested approaches may produce significant system wide disbenefits if the conflicting approaches are heavily congested [66].

Another influencing factor is traffic signal operation. There are several components to traffic signal operation that include cycle length, number of phase, phase sequence, green time allocation and required pedestrian clearance. There is an impact on TSP performance if there is less green time that can be extracted from non-prioritized approach. A TSP strategy is configured for a control operation. A selected TSP strategy consists of parameters such as the amount of green time that can be reduced from the non-prioritized approach. An inappropriate selection of TSP parameters may result in increased intersection delays [63]. Therefore, these parameters must be selected with caution.

The TSP system wide performance is influenced by the transit vehicle frequency [66]. As bus frequency increases, the likelihood of conflicting TSP requests is also increased [63]. Consequently, we expect the effectiveness of TSP (in terms of reducing bus delays) to diminish as bus frequency increases. This may result in large overflow queues because the cross street signal cannot restore the background cycle in two consecutive priority requests. *Conditional Priority* is one of the techniques to limit the number of TSP grants on intersections with high transit frequency.

If a bus is expected to arrive on green interval on the prioritized approach, the green interval is extended after fulfilling the pedestrian and other applicable constraints. However, if the bus arrives on the cross street green then the bus has to wait until the minimum green time on the cross street is served. Rakha et al. [49] suggested that TSP benefits are highly dependent on the bus time of arrival within the signal cycle and therefore, the bus time of arrival is important for determination of TSP performance.

Another factor that influences TSP performance is level of progression. An overall net benefit is expected if the signal timings altered due to TSP control favours the traffic progression. On the contrary, if the TSP altered signal timing results in interruption to the traffic progression a negative impact is expected.

2.4 Methods for Prioritizing TSP Implementation

One of the issues that must be addressed by transit agencies is the selection of the intersections at which TSP should be implemented. Due to fiscal constraints, there is a need to identify and prioritize signalized intersections for TSP implementation. Currently, most intersection prioritization consists of adhoc

methods that employ "rule of thumb". Table 2.1 lists the prioritization criterion used in four TSP implementation studies in Canada and the USA.

Table 2.1: Intersection Prioritization Methods

Location	Prioritization Criteria
King County Metro, Seattle, WA [50]	Forecast of potential average bus time savings.
Pierce Transit, Tacoma, WA [51]	Measure benefits using Synchro and VISSIM
Trimet, Portland, OR [53]	Bus Driver Survey: Eliminated intersections that are close together, in downtown, or complicated to implement.
iXpress, Waterloo, ON [31]	Signal control type, Movement and Intersection LOS

King County Metro [50] is one of the leading agencies that implement TSP. They developed a Transit Signal Priority Interactive Model (TIM) that inputs cost assumptions, signal phase splits, and TSP settings and provides expected benefits (potential average bus timesavings) of one transit trip. The forecasted potential average bus timesaving was used for intersection prioritization.

Pierce Transit, Tacoma, WA [51] used Synchro in general and VISSIM for selected intersections. A simulation evaluation study is conducted on the corridor and the benefits in terms of general-purpose vehicle delay, bus delays, and person delays are compared to baseline scenario. The intersections providing highest benefit were selected for TSP implementation.

Trimet, Portland, OR [53] conducted a bus driver survey asking which signals bother them most. The driver responses were analyzed using the AVL data and TriMet took the top 30 intersections. Intersections that were too close together, downtown, or just too complicated were eliminated from the prioritization list.

Region of Waterloo [31] prioritized intersections based on type of signal control, intersection level of service and movement level of service. The prioritization was conducted based on a composite score. The composite score was calculated using information of overall level of service (LOS), transit movement LOS and mode of control. The higher the composite score the higher the priority of the intersection to be selected. A higher score was given to intersections operating at LOS E or F with the

premise that TSP implementation is important on heavily congested intersections. A higher score was also given to intersections with full and semi-actuated signal control operations. Using this prioritization scheme, 13 intersections in the Region of Waterloo were selected for TSP implementation.

2.5 Methods for Evaluating TSP

2.5.1 Field Evaluations

Typically, field studies conducted for evaluating the impact of TSP consist of collecting data before and after TSP deployment. Data may consist of travel times collected from "floating car" studies [43], and/or turning movement volume counts and direct observation of intersection approach delays [44,45, 46]. The advantage of field studies is that they are able to measure directly the in-use performance of TSP. However, obtaining reliable measures of the impact of TSP is complicated by:

- The need to control for the influence of external factors that may change due to data collection periods.

- The challenge of collecting sufficient number of floating car runs to meet sample size requirements for statistically reliable conclusions.

- The ability to compute TSP impacts for only the conditions (e.g. geometry, signal timings, v/c ratios, bus arrival frequency, TSP parameter values) that are contained within the field study. Consequently, there is usually limited ability to transfer the observed impacts to other locations or even the same location but with different traffic, transit, or signal operating conditions.

In addition to these challenges, a significant constraint of field studies is that they can only be used to quantify the impact of TSP after TSP has already been implemented. Consequently, this method is not applicable for studies in which the objective is to determine the most appropriate locations at which TSP should be deployed.

2.5.2 Simulation Evaluations

Microscopic traffic simulation models have the ability to track individual vehicle movements. Vehicle tracking is usually done using the car following, lane changing and gap acceptance logic. This allows such models to consider virtually any traffic conditions, ranging from highly under-saturated to highly over saturated conditions.

Microscopic simulation models have the ability to track the movements of individual vehicles. As such, they can determine the delay incurred by an individual vehicle while traveling a network of links with different characteristics by comparing simulated and ideal travel times. No specific formulas are therefore required to evaluate uniform and overflow delay, or delays in under-saturated traffic conditions, thus allowing for the evaluation of complex traffic situations. In addition, the ability to record vehicle speed and position on a second-by-second basis further allows the recording of speed profiles and the direct estimation of deceleration, stopped and acceleration delays.

The use of microscopic traffic simulation models appears to be the most common TSP evaluation method. Models, such as VISSIM [39, 40, 41], PARAMICS, AIMSUN, INTEGRATION, and NETSIM [37, 38], provide the ability to model individual vehicles as they travel through a virtual road network. Vehicle movements and traffic controls (such as signals) are updated on a time scale typically about 0.1 seconds. The most significant advantages of using simulation models are:

- The ability to estimate the impact of TSP without implementing TSP in the field.

- The ability to consider a wide range of conditions that are encountered in the field (e.g. signal timings, vehicle arrival patterns, intersection geometries, transit vehicle arrival times, and TSP strategies).

The application of these microscopic simulation models requires considerable effort and expertise. The user must code the roadway and intersection geometry, traffic signal timing plans and control logic, traffic demands, transit routes, transit vehicle arrival frequency, transit signal priority operations, bus checkout and check-in detector locations, etc. The microscopic simulation requires calibration and validation that requires the collection of field data. There are many simulation-based TSP evaluation studies reported in the literature. However, given the variety of study objectives, simulation models used, conditions tested, and methods employed, the results vary significantly across the studies [8, 9, 10, 11, 12].

For this study, the VISSIM [39] microscopic traffic simulation software was selected to validate the proposed analytical model. VISSIM [39] was selected due to its ability to model complex interaction between the vehicular, pedestrian and environment interface. The following summarizes the abilities of the VISSIM model,

- Capability to simulate traffic operations in urban streets, especially handling public transportation issues such as Transit Signal Priority.

- Can analyze impacts of different signal operations such as fixed time, actuated, and adaptive TSP. In particular, users can define signal control logic through VISSIM's VAP language logic. It has the capability to model phase signal operations with traffic or transit detector actuations.

- Uses psychophysical driver behaviour model [42].

- Utilizes link-connector structure for network construction as opposed to typical simulation models based on link-node schematics.

- Generates vehicles using a Poisson distribution.

- Provides a comprehensive set of output files that can be customized by user.

These features make VISSIM well suited for evaluating TSP strategies.

2.6 Analytical Methods for Evaluation of TSP Delay for Signalized intersections

2.6.1 Deterministic Queuing Model

Deterministic queuing models view traffic as a uniform stream of arriving vehicles seeking service from the traffic signal controller. Time headways in arrival traffic stream and service times at the intersection are uniform and constant. The queues build vertically not horizontally. Vehicles follow the "first in – first out" queue displace implying vehicles have the queue in the same order in which they join the queue. The deterministic queuing process for under saturated conditions at signalized intersection is depicted in Figure 2.1. The building and dissipation process of the queue works in the following way: at the beginning of the red signal phase, the queue starts to grow. When the signal changes from red to green, the queue starts dissipating.

The area between the arrival and departure curve is the total uniform delay incurred by all vehicles attempting to cross an intersection within a signal cycle. Using the concept of the area of a triangle, the total delay can be computed as:

$$D_t = 0.5r\lambda\left(r + t_{np}\right)$$

(1)

where:

D_t =   total delay (s),
r =   red duration interval (s),

g =   green duration interval (s),

t_{np} =   time of dissipation (s).

λ =   vehicle arrival flow rate (veh/h),
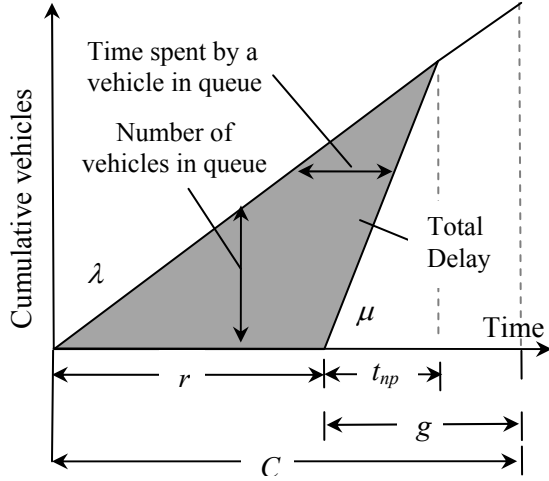
Figure 2.1: Deterministic queuing process for under-saturated condition

The time when the queue is dissipated can be computed by equating total arrivals $\lambda(r + t_{no})$ with total departures μt_{np} during the cycle resulting in

$$t_{np} = \frac{\rho r}{(1-\rho)} \qquad (2)$$

where:

ρ =   Traffic Intensity $= \dfrac{\lambda}{\mu}$,

μ =   service rate (veh/second)

Substituting equation 2 into equation 1 provides an estimate of total delay in the cycle.

$$D_t = 0.5r\lambda\left(r + \frac{\rho r}{(1-\rho)}\right)$$

$$= 0.5r^2\lambda + \frac{0.5r^2\lambda\rho}{(1-\rho)}$$

18

$$= \frac{(1-\rho)r^2\lambda + r^2\lambda\rho}{2(1-\rho)}$$

$$= \frac{r^2\lambda - r^2\lambda\rho + r^2\lambda\rho}{2(1-\rho)}$$

$$D_t = \frac{r^2\lambda}{2(1-\rho)} \tag{3}$$

Average delay is obtained by dividing D_t by λC to obtain

$$d = \frac{r^2}{2C(1-\rho)} \tag{4}$$

where:

C	=	traffic signal cycle time (s),
d	=	average delay per vehicle (s/veh)

2.6.2 Capacity Guide Delay Models

In 1958, Webster [14] proposed one of the fundamental and most often quoted signalized intersections delay estimation models:

$$d = \frac{C\left(1 - \frac{g_e}{C}\right)^2}{2\left(1 - X\frac{g_e}{C}\right)} + \frac{X^2}{2\lambda(1-X)} - 0.65\left(\frac{C}{\lambda^2}\right)^{1/3} X^{2+\frac{g_e}{C}} \tag{5}$$

where:

X	=	volume-to-capacity ratio; $\left(X = \frac{\lambda}{c}\right)$,
c	=	capacity of intersection approach (veh/h),
g_e	=	duration of effective green interval (s),

There are three components of Webster's [14] expression. The first term is the average delay assuming deterministic uniform arrivals and service and can be shown to be same as equation 4. The second term accounts for the delay due to randomness of arrivals (i.e. Poisson distribution). The last term is an empirical correction factor that reduces the estimated delay by 5–15%. The term was calibrated by

Webster with field observation and with simulation results. Webster's formulation (equation 5) is valid only for $X < 1.0$. To permit application to oversaturated conditions researchers [33, 34] employed the coordinate transformation technique to develop expressions for delay that are applicable even for $X >$ 1.0. Figure 2.2 shows Webster's curve and the transformed curve. It can be observed that the Webster's equation is asymptotic to $X = 1.0$, while the transformed curve is asymptotic to the over-saturation delay line. Although there is no rigorous theoretical basis for this approach [35], empirical evidence indicates that these models yield reasonable results [32].
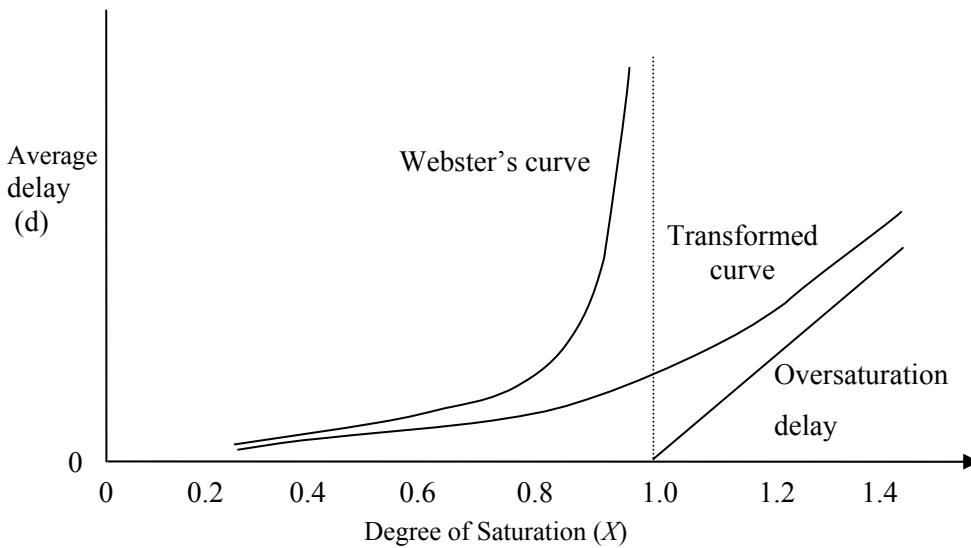
Figure 2.2: Illustration of coordinate transformation process

The methods in the HCM [13] and Canadian Capacity Guide (CCG) [36] are based on the work of Webster [14]. These models are all similar with specific values assigned to parameters in each model [32]. The general form of these models can be expressed by equations (6) – (9), with Table 2.2 indicating specific values [32]:

Table 2.2: Capacity guide delay model parameters

Model	Parameters						
	f_T	y	m	k	l	T	X_o
CCG [36]	0	0	4	n/a	n/a	variable	0
HCM [13]	1	0	8	Pre timed 0.5, Actuated 0.04-0.05	1.0	variable	0

$$d = d_1 f_{PF} + d_2 + d_3 f_T \qquad (6)$$

20

$$d_1 = \frac{C\left(1 - \frac{g_e}{C}\right)^2}{2\left[\left(1 - \frac{g_e}{C}\right)(\min\ (X\,,1.0))\right]} \tag{7}$$

$$d_2 = 900X^y T\left[(X-1) + \sqrt{(X-1)^2 + \frac{mkl}{cT}(X - X_o)}\right] \tag{8}$$

$$d_3 = \frac{1800Q_b(1+u)t}{cT} \tag{9}$$

$$f_{PF} = \frac{(1 - P_e)f_P}{1 - \frac{g_e}{C}} \tag{10}$$

where:

c	=	capacity of intersection approach (veh/h),
d_1	=	average overall uniform delay (s/veh),
d_2	=	incremental delay accounting for randomness of vehicle arrivals and over-saturation delay (s/veh),
d_3	=	residual delay for over-saturation queues that may have existed before the analysis period (s/veh),
f_{PF}	=	adjustment factor accounting for the quality of progression in coordinated systems,
f_T	=	adjustment factor for residual delay component,
f_P	=	adjustment factor for situations in which the platoon arrives during the green interval $(0.7 \le f_P \le 1.2)$,
k	=	incremental delay factor accounting for pre-timed or actuated signal controller settings,
l	=	adjustment factor for upstream filtering/metering,
y, m	=	capacity guide model parameters,
t	=	duration of unmet demand in T (h),
T	=	evaluation period (h),
Q_b	=	initial queue at the start of period T (veh),
u	=	delay parameter,
X_o	=	volume-to-capacity ratio below which the overflow delay is negligible in capacity guide models,
P_e	=	proportion of vehicles arriving during effective green interval.

The vehicle arrivals in these models are assumed to follow a Poisson distribution [32].

2.6.3 Analytical TSP models

The delay models presented in the previous section are applicable when signal timings do not change over the analysis period. Under TSP control, signal timing change in the cycle that priority is granted and in the subsequent cycle.

Sunkari et al. [4] proposed a technique for evaluating TSP control that utilized equation 6. The authors applied the equation to the no TSP signal timings and to signal timing plans associated with four TSP cases namely; maximum green extension, minimum green extension, maximum early green, and minimum early green. The proposed model utilized person delay to evaluate non-priority and priority strategies. The delay expression is given as:

$$WD_{NP} = \frac{\left(D_{(1B-NP)}\right) + \left(D_{(NB-OS)}\right)}{C_N} \tag{11}$$

$$WD_P = \frac{\left(D_{(1B-P)} C_B\right) + \left(D_{(NB-OS)} C_{NB}\right)}{C_N} \tag{12}$$

where:

WD_{NP} = weighted delay with no priority provided to transit vehicle (person sec/cycle),

WD_P = weighted delay with priority provided to transit vehicle (person sec/cycle),

$D_{(NB-OS)}$ = average person delay with no bus for original green splits (sec/cycle),

$D_{(1B-NP)}$ = average person delay with one bus and no priority (sec/cycle),

$D_{(1B-P)}$ = average person delay with one bus and with priority (sec/cycle),

C_B = number of cycles per hour in which a bus arrives and receives priority treatment,

C_{NB} = number of cycles per hour in which no priority is provided,

C_N = number of cycles per hour.

Average vehicle stopped delay is computed using the HCM delay equation (equation 6). The HCM delay value is then converted to average person delay (i.e. $D_{(NB-OS)}$, $D_{(1B-P)}$ and $D_{(1B-NP)}$) knowing the number of vehicles per cycle, and the average person occupancy per car and per bus. Field data was collected for southbound approach of Texas Avenue in College Station, Texas. Field data and model results were compared and it was indicated that the model overestimates the delay values as v/c ratio increases. After removing the data for high v/c ratios > 0.85, the regression analysis indicates a strong linear relationship between the field data and model results. However, it was also found that the

WD_{NP} and WD_P equations over estimate delay by as much as 41 percent. Furthermore, this approach does not explicitly consider the impact of the variation in signal timings over time that occurs because of the granting of TSP. Rather, these changes are approximated by considering average signal timings. Consequently, it is not clear that this approach is able to correctly capture the impact of TSP for a wide range of traffic and signal control conditions, especially when the granting of TSP causes over saturation on the non-prioritized approach.

Liu et al. [5] recently proposed one of the few analytical models applicable for estimating the impact of TSP in terms of the expected change in average vehicle delay. In the development of their model, Liu et al. assume that the implementation of TSP does not significantly change the randomness of traffic stream arrivals to the intersection and consequently the impact of TSP on the change in average vehicle delay can be captured by assuming deterministic arrivals and deterministic service. They construct the cumulative vehicle diagram over two consecutive signal cycles – the cycle in which the green extension or early green TSP occurs and the subsequent cycle (Figure 2.3).

The additional delay experienced by vehicles on the non-prioritized approach over the two cycles is simply the difference between the delay experienced with TSP control and delay experienced with no TSP control (shaded area in Figure 2.3, labelled as ΔD).

According to Liu et al. [5] the additional delay ΔD on the non-prioritized approach resulting from the granting of red truncation is calculated by

$$\Delta D = \frac{\lambda g_{tr}(2r + g_{tr})}{2\lambda(1-\rho)} + \mu\left[\frac{r}{1-\rho} - (C - g_{tr})\right](r + g_{tr}) \tag{13}$$

The increased delay per vehicle is then computed as

$$\Delta d = \frac{\Delta D}{\lambda C} \tag{14}$$

23
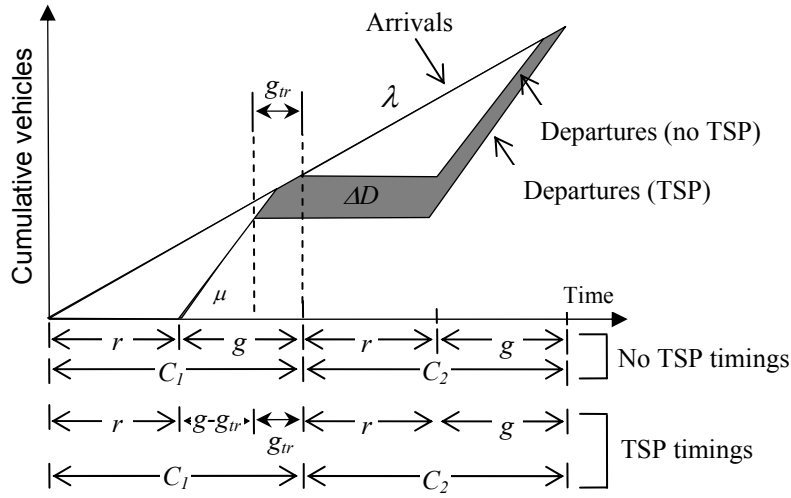
Figure 2.3: Impact of Red Truncation TSP on non-prioritized approach (Liu et al. [5])

where:

ρ = flow ratio, $\rho = \dfrac{\lambda}{\mu}$.

μ = saturation flow rate (vehicle/second),

λ = arrival rate (vehicle/second),

Δd = average increased delay per vehicle (s),

ΔD = total additional delay (s),

C = cycle length (seconds),

C_1, C_2 = first and second Cycle (s),

g_{tr} = reduced green time on the non prioritized approach (s),

r = duration of red interval (seconds),

t = the amount of green time "borrowed" from non prioritized green interval,

There are four issues with this model formulation:

First, the calculation of average vehicle delay using Equation 13 divides the additional delay caused by the TSP by the number of vehicles arriving at the intersection in a single cycle. If, as depicted in Figure 2.3, the impacts of TSP to the non-prioritized approach are limited to the two cycles (the cycle in which TSP is granted and the following cycle), then the additional delay should be averaged over the number of vehicles arriving over the two cycles (i.e. $2\lambda C$).

Second, the formulation ignores TSP impacts that may extend beyond the first cycle following the green extension or early green TSP. This leads to an underestimation of the increase in delay to the

24

traffic on the non-prioritized approach, especially at high v/c ratios when there is less spare green time in the cycle.

Third, when the granting of TSP causes the non-prioritized approach to become temporarily over-saturated (i.e. the impacts extend for more the one cycle following the cycle in which TSP is granted), then the change in average vehicle delay needs to be computed as the increase in total delay, divided by $n\lambda C$, where n is the number of cycles required for the over-saturation queue to be served.

Fourth, the evaluation of the impact of TSP should be done as a function of the frequency at which TSP is requested, which is a function of bus headway. The evaluation of TSP in terms of the impact on average vehicle (or person) delay should consider the impact on total delay divided by the number of vehicles (persons) arriving at the intersection approach over a period equal to the bus headway.

2.7 Chapter Conclusions

It is clear that transit signal priority can be a cost-effective approach for enhancing the attractiveness of transit and for increasing the capacity of the urban road infrastructure. However, TSP does not provide benefits under all conditions and may have net disbenefits. This chapter presented a set of MOEs for evaluating the performance of a TSP system. These MOEs are used to stratify the impact of the TSP system on different components of a transportation system, including transit vehicles and general traffic. Following conclusions are deduced from this chapter:

- There is impact of variability in the day-to-day peak hour volume on mean and distribution of MOE (intersection delay) used for TSP evaluation. However, no work has been done that has quantified this impact.

- TSP performance is influenced by several factors that include intersection geometry, traffic demands, signal timing plan, TSP strategy, bus frequency, bus time of arrival during the cycle and level of progression.

- Very little literature exists on method to prioritize the intersection for TSP implementation. Most of intersection prioritization schemes are based on engineering judgement or rule of thumbs.

- There are significant challenges to conduct a field and microscopic TSP studies.

- Studies have been conducted in order to bridge the gap in TSP analytical models. However, the reported TSP analytical models do not correctly capture the TSP performance. Therefore, there is a need for developing an analytical model that captures the TSP performance.

In Chapter 3, the impact of variability in day-to-day peak hour volume on mean and distribution of intersection delay is quantified.

Later chapters develop and validate an analytical model that bridges the need for an analytical model.

Chapter 3

Impact of Day-to-Day Variability on Performance Measures

Intersection performance as measured by delay is a function of many factors including, signal timing plan, turning movement traffic demands, traffic stream composition, pedestrian volumes, intersection geometry, temporal variation in traffic demands, the headway distribution of each traffic stream, driver characteristics, weather and road surface conditions and visibility. Some of these factors are invariant for a given intersection operating under a defined signal control strategy (e.g. geometry and signal timing plan) while others vary (e.g. weather, traffic demands, etc.).

Some of this variability is captured by (or controlled for) the intersection analysis methodology. For example, when using HCM [13] or CCG [36] methodologies (i.e. equation 6) traffic demand variations by time of day are controlled for by applying the analysis method for the peak hour volume and utilizing the peak hour factor (*PHF*) [1]. Weather conditions are controlled for by assuming ideal weather conditions. Variability of vehicle arrivals (i.e. headway distribution of the approach traffic steams) is considered by assuming arrivals follow a Poisson process and then the influence of nearby upstream-signalized intersections in terms of creating platoons is considered.

However, variability of other factors is not considered including the day-to-day variability in the peak hour traffic volumes, *PHF*, and saturation flow rates. This variability is important with respect to evaluating TSP and prioritizing intersections for TSP implementation.

3.1 Variation in Peak Hour Volume

Waterloo and Kitchener are adjacent cities located in south western Ontario, Canada approximately 120 km west of Toronto. The combined population of these two cities is 300,000. The regional government, which is responsible for traffic signal operations within these two cites, operates 16 continuous volume counting loop detector stations located mid-block on major arterial roadways. Vehicle counts are obtained for each lane in both directions and aggregated at 15-minute intervals. Data from these vehicle count stations were obtained for the 2005 calendar year.

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[1] PHF = peak hour volume / (maximum 15 minutes volume x 4)

It is assumed that the volume counts from these stations can be interpreted as the approach volumes at the signalized intersections immediately downstream of the detector stations. This assumption implies that:

1. Any oversaturated conditions that may occur at the downstream-signalized intersections do not cause queues to spill over the vehicle count stations for any significant portion of the 15-minute interval.

2. There are no significant mid-block flows (entering or leaving) between the vehicle count station and the downstream-signalized intersection.

Local knowledge of the intersections near the volume counting stations suggests that this assumption is reasonable.

The individual lane data were aggregated to provide vehicle counts by direction (resulting in 26 directional volume count stations) and were filtered to remove data associated with weekends (i.e. Saturdays and Sunday) and all local and national holidays. This resulted in a maximum of 20,736 fifteen-minute volume observations for each volume count station. However, because of hardware and communication system failures, some stations provided only a portion of these data. Stations with less than 70% data availability (i.e. fewer than 14,515 fifteen-minute volume counts) were eliminated from the analysis. The remaining 13 stations exhibited an average annual daily traffic volume ranging from a low of 8,000 vehicles to 30,000 vehicles per non-holiday weekday.

Typically, traffic engineers consider the PM peak period to be the highest demand period of the day and therefore, only data from 3:45 PM to 6:30 PM were considered for further analysis.

Table 3.1 provides descriptive statistics for the peak hour volumes determined for the remaining ten volume count stations. The mean peak hour volume varies significantly from one station to the next (i.e. ranging from 594 vph to 1375 vph), however, this variation is attributable to different traffic patterns on different roads, and is not of interest with respect to random day-to-day variations.

Table 3.1: Peak hour volume descriptive statistics

Volume Count Detector Station	Mean (vph)	Standard Deviation (vph)	Coefficient of Variation	No. of obs.	max. (vph)	min. (vph)	No. of lanes
62 (North Bound)	1287	69.6	0.054	209	1448	1042	3
182 (West Bound)	1375	97.6	0.071	213	1671	811	2
184 (West Bound)	658	61.5	0.094	213	1047	454	2
184 (East Bound)	594	54.9	0.093	213	788	277	2
290 (West Bound)	1282	111.5	0.087	213	1750	996	2
312 (North Bound)	971	62.6	0.065	214	1160	746	2
313 (North Bound)	822	52.7	0.064	214	987	640	2
313 (South Bound)	855	112.3	0.131	214	1033	564	2
484 (North Bound)	720	69.4	0.096	204	1134	558	2
484 (South Bound)	961	106.6	0.111	171	1193	490	2
Overall Average	952	79.9	0.084	208	1750	277	

What is of interest, however, is the day-to-day variation in the peak hour volume that occurs at each site. This variation can be quantified by the coefficient of variation (*COV*) which is computed as the ratio of the standard deviation over the mean. The *COV* varies from a minimum of 5.4% to a maximum of 13.1% and on average is equal to 8.7%.

Sullivan et al., [25] conducted a similar analysis using data from the City of Milwaukee and found that the *COV* varied between approximately 5% and 16%. They suggested that the *COV* decreases with increasing mean volume but they did not fit a statistical model to confirm this. Figure 3.1 presents the standard deviation of peak hour volume as a function of mean peak hour volume for Waterloo.
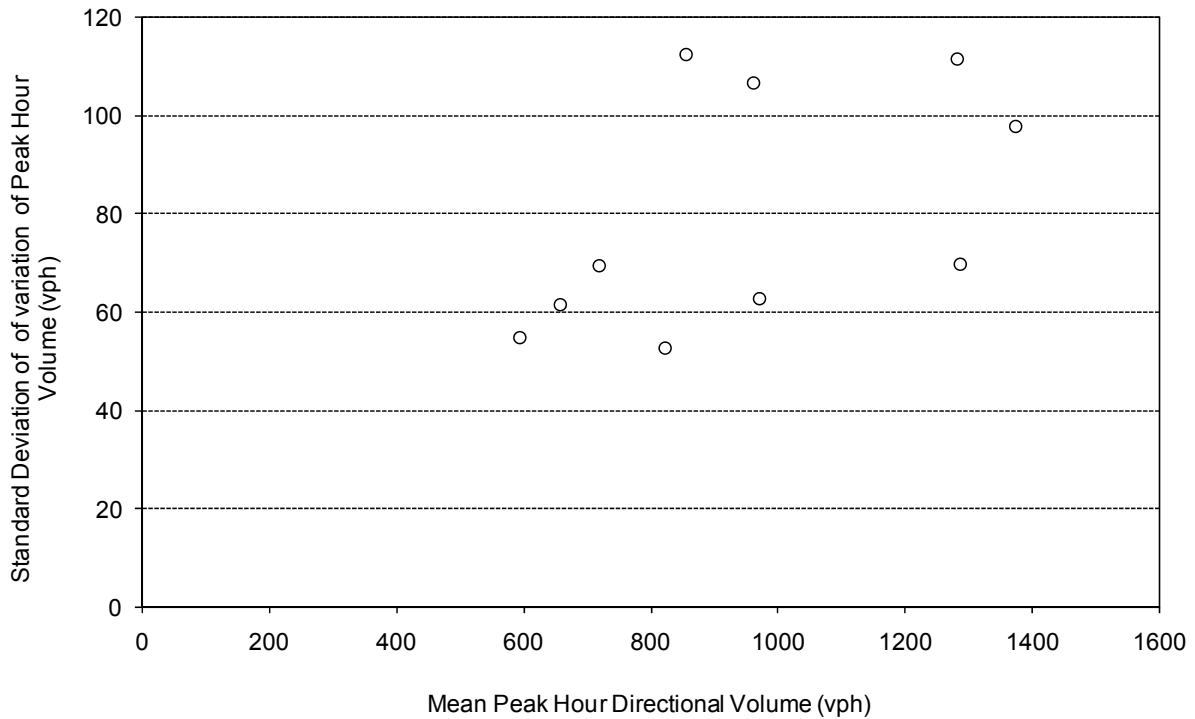
Figure 3.1: Standard Deviation of peak hour volume as a function of peak hour volume (Waterloo Data)

A least squares linear regression was calibrated to the data in Figure 3.1 to develop a relationship between the standard deviation of mean peak hour volume and mean peak hour volume.

Regression intercept and coefficient are statistically significant at the 95% level. The coefficient of intercept is 36.62 and the coefficient of Peak hour volume was 0.0865.

We also were interested in determining the shape of the distribution of peak hour volumes. This was accomplished by normalizing each peak hour volume observation by dividing it by the mean peak hour volume for that volume count station. Consequently, it was possible to create distributions of normalized peak hour volumes and to compare these distributions for each of the 8 volume count stations (Figure 3.2).

The Kolmogorov-Smirnov (K-S) test was used to determine if each distribution could be adequately described by the Normal, Gamma, and Lognormal distribution at the 99% level of confidence.

It was found that the 6 of 8 distributions of day-to-day normalized peak hour volume are best described by the Normal distribution with a mean of 1.0 and a standard deviation of 0.087.

3.2 Impact of Variability of Day-to-Day Peak Hour Volume on Intersection Delay and LOS

The objective of this section is to explore the impact that the day-to-day variability of peak hour volumes has on the operating characteristics of a typical 4-leg intersection operating under a fixed time traffic signal control strategy. Intersection delay is difficult to measure accurately in the field and it is cost prohibitive to do so for a number of intersections over a large number of days. Consequently, in this study, (and as is typically done in practice) intersection delay was estimated using the Highway Capacity Manual [13] methodology. The following sections describe the hypothetical intersection developed for this study, the Monte Carlo Simulation (MCS) used to evaluate the intersection performance, present and discuss the results.

3.2.1 Hypothetical Intersection

A hypothetical four-leg intersection was assumed. Each approach consisted of an exclusive left turn lane, an exclusive through lane, and a shared through and right turn lane. All lane widths, grade, curb radii, etc. were considered to be ideal with no on-street parking, no transit vehicles, and adequate storage and discharge space. The base saturation flow rate was assumed 1900 passenger cars per hour per lane (pcphpl). The intersection was controlled by a two-phase signal timing plan with a cycle length of 80s; 38s effective green for phase 1; 34s effective green for phase 2; and 4 seconds of inter green between each phase. Right-turn on red was not permitted.
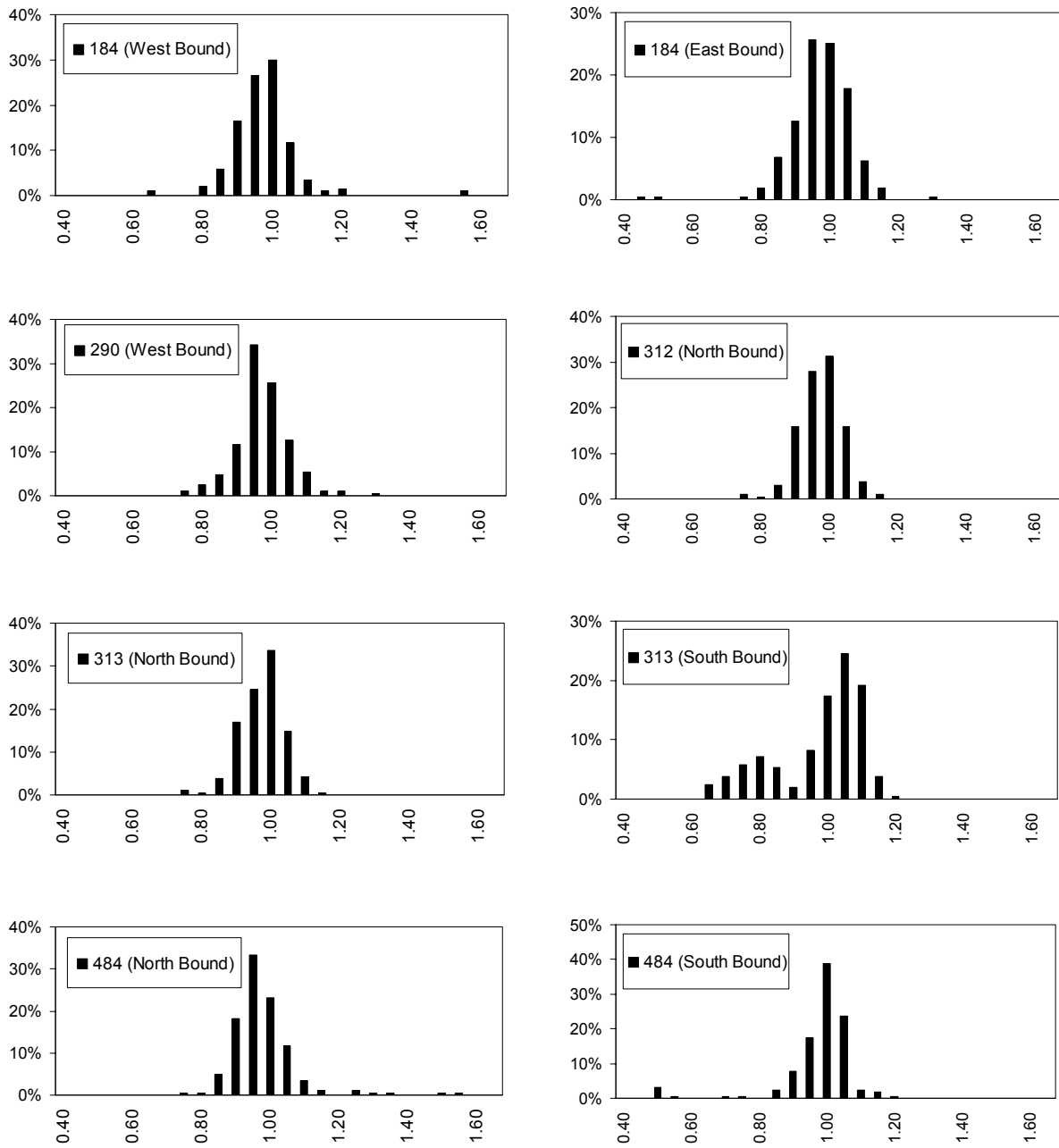
Figure 3.2: Distributions of normalized peak hour volume

Eleven traffic demand scenarios were developed encompassing intersection volume to capacity (v/c) ratios ranging from 0.6 to 1.10. For each scenario, the turning movement proportions remained constant (1% left turn, 79% through, and 20% right turn) but the total approach demands varied (Table 3.2). For all cases, the traffic stream was assumed to consist of only passenger cars.

Table 3.2: Evaluation Scenarios

Scenario	Intersection performance		Average approach peak hour traffic demand (pcph)			
	Delay[1] (s/veh)	Volume to capacity Ratio	East bound	West bound	North bound	South bound
1	15.6	0.600	942	936	840	849
2	17.4	0.700	1099	1092	980	990
3	20.3	0.800	1256	1249	1120	1132
4	22.6	0.850	1335	1327	1190	1202
5	26.2	0.900	1413	1405	1260	1273
6	28.9	0.925	1453	1444	1295	1308
7	32.5	0.950	1492	1483	1330	1344
8	37.1	0.975	1531	1522	1365	1379
9	43.1	1.000	1571	1561	1400	1414
10	58.5	1.050	1649	1639	1470	1485
11	77.2	1.100	1728	1717	1540	1556
[1] Delay computing using HCM method and average approach peak hour demands						

3.2.2 Monte Carlo Simulation

The performance of the hypothetical intersection, in terms of average vehicle delay, was evaluated using the HCM methodology (equations 6 – 9). The following parameter values required within the HCM methodology were assumed:

- Evaluation time period, $T = 0.25$ hours,

- PHF = 0.923,

- Area type = 1 (Central Business District, CBD),

- Arrival type = 4.

For each of the eleven demand scenarios, 1000 Monte Carlo trials were evaluated. For each Monte Carlo trial, peak hour approach volumes were generated randomly using a Normal distribution with a COV = 0.087 and the mean peak hour volume from Table 3.2. The volumes on each approach

were generated to be correlated with $\rho = 0.3$. For all simulations, the signal-timing plan, saturation flow rate, PHF, turning movement proportions and all other inputs except the approach volumes remained unchanged. For each Monte Carlo trial, the HCM [13] methodology was used to estimate the average delay during the peak hour. All simulation runs were conducted using Crystal Ball[TM] version 7.2.2 combined with the HCM [13] methodology implemented within Excel.

3.2.3 Results

Figure 3.3 illustrates the cumulative distribution of average intersection delay associated with each of the eleven traffic demand scenarios. Figure 3.4 illustrates the associated standard deviation of peak hour average delay as a function of the mean delay for each of the eleven demand scenarios. The standard deviation increases dramatically as the mean delay increases.
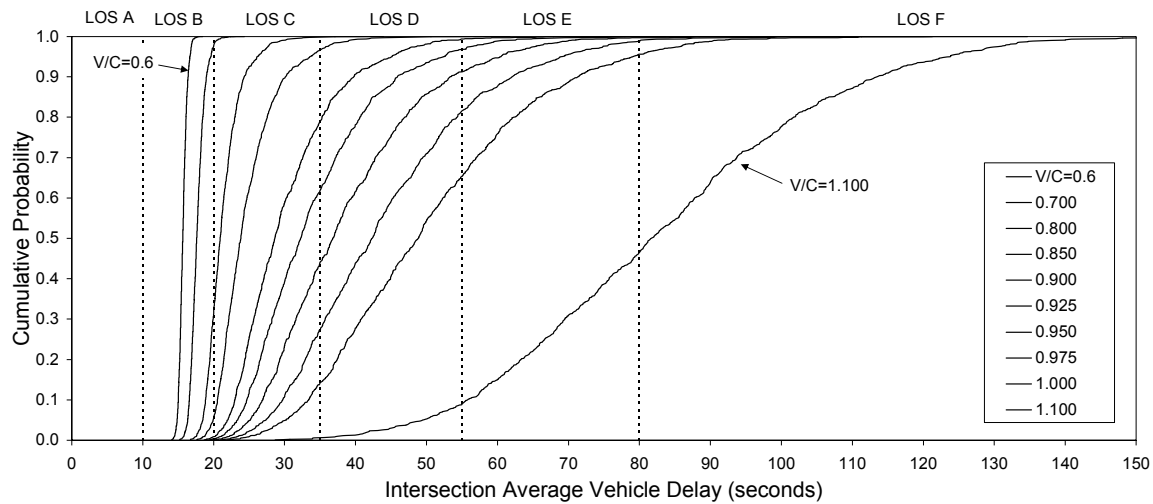
Figure 3.3: Distribution of intersection delay as a function of v/c ratio
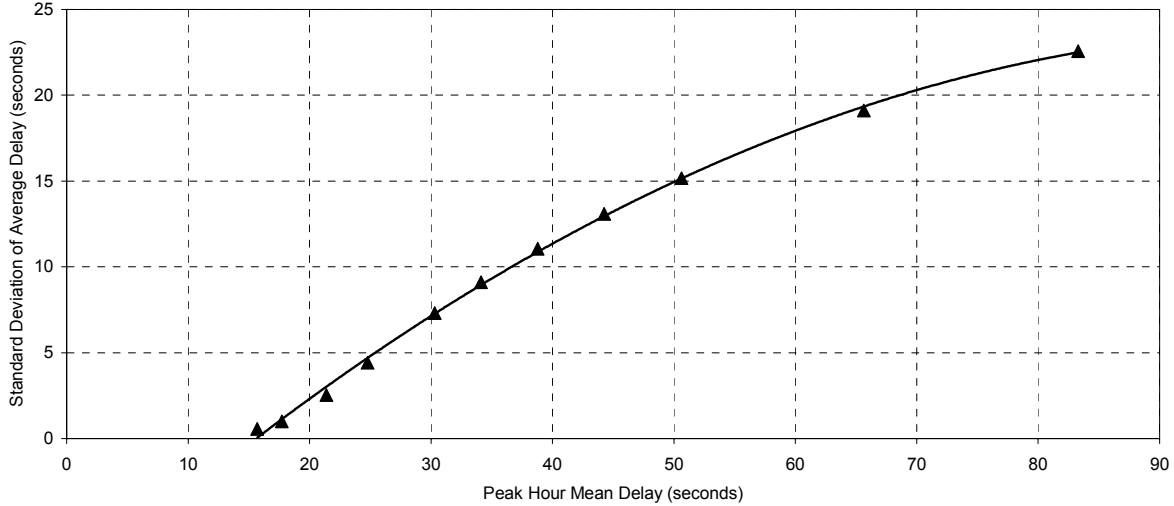
Figure 3.4: Standard deviations of average delay as a function of peak hour mean delay

The effect of this is illustrated in Figure 3.5 which depicts the mean, 95% and 99% confidence limits (i.e. 2.5, 97.5 percentile and 0.5, 99.5 percentile of the Monte Carlo simulation results) associated with the intersection delay. Several observations can be made based on these results.

First, as expected, the variation in the intersection delay increases dramatically as the intersection v/c ratio increases. For example, consider the 95% confidence limits of the intersection delay when v/c=0.6. It is expected that 95% of the time, the peak hour intersection delay will be between 14.8 and 17.1 seconds/vehicle (LOS B). However, for v/c=0.9, the 95% confidence limit is from 21.6 to 51.9 seconds / vehicle (LOS C and D).

Second, the distribution of intersection delay appears to be generally log-Normally distributed. This was confirmed by the K-S test that showed that 9 of the 11 scenarios could be described by a lognormal distribution at the 99% level of confidence.

35
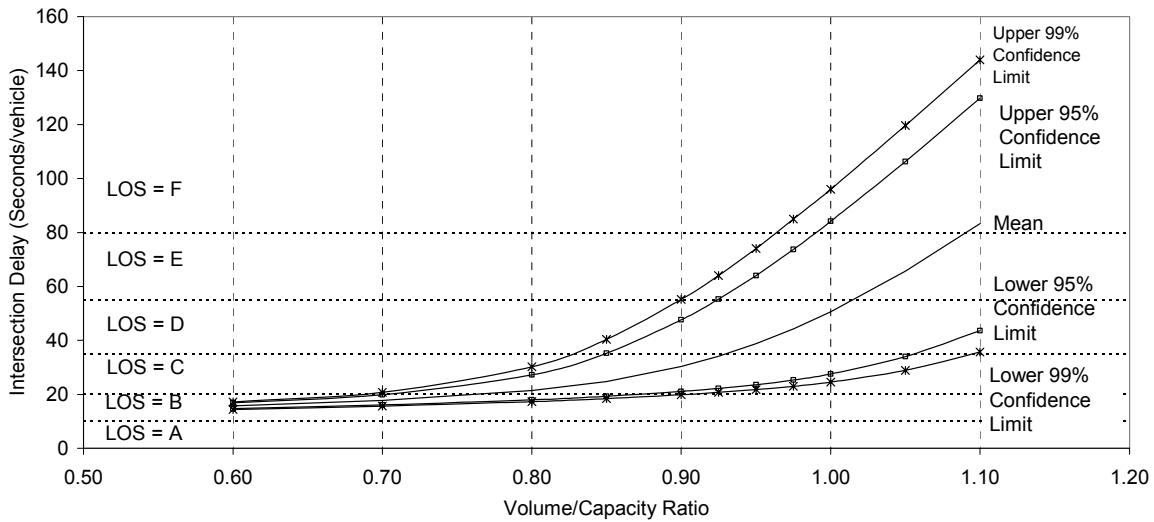
Figure 3.5: Mean and confidence limits of intersection peak hour delay

Figure 3.6 illustrates the impact that the non-linear relationship between volume and delay has on estimating the mean intersection delay. The x-axis is the volume to capacity ratio as specified in Table 3.2. The left-hand y-axis is the estimated intersection delay and the right-hand y-axis is the estimation error computed as; $100\% \times (d - d')/d$; Where, d' = mean intersection delay computed using the average approach volumes, d= mean intersection delay computed as the average of the delays obtained from the 1000 Monte Carlo simulation trials.

When the estimation error is equal to zero, both methods provide the same estimate of average intersection delay. The estimation error is small (but positive) for low v/c ratios and increases as v/c approaches 1.0 to a maximum value of approximately 20% and then begins to decrease as v/c continues to increase. For all the v/c scenarios examined, the estimation error is positive indicating that that computing the intersection delay based on the average volumes, and ignoring the variability of these volumes, under-estimates the true average intersection delay by as much as 20%.

36
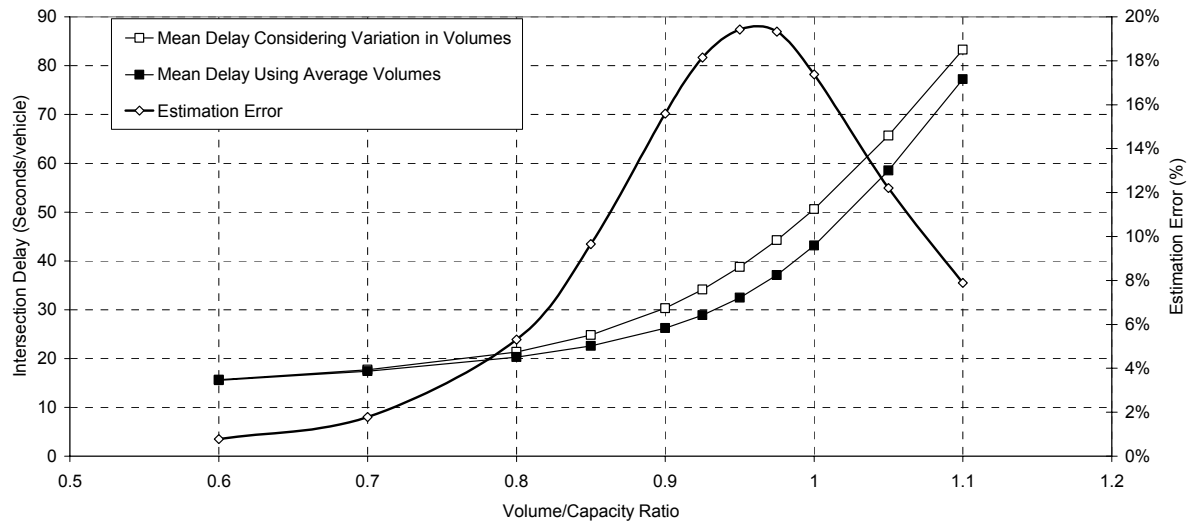
Figure 3.6: Error in intersection delay estimation when using mean approach volumes instead of considering the variation of peak hour volume

3.3 Chapter Conclusions

In current practice, signal timings are typically developed and evaluated based on average volumes (turning movement counts) obtained from a single day. However, if peak hour volumes vary from day-to-day, then so will the performance of the intersection. In this chapter, we showed that computing the intersection delay based on the average volumes, and ignoring the variability of these volumes, under-estimates the true average intersection delay by as much as 20%.

Therefore, the day-to-day variability of peak hour volume should be considered when estimating average intersection delays for TSP performance.

In the next chapter, an analytical TSP model is developed to bridge the research need indicated in chapter 2.

Chapter 4
Analytical Transit Signal Priority Modeling

The proposed TSP model is developed based on queuing theory. In the development of the proposed model, analytical expressions are developed for the assumption that the intersection can be modeled as a $D/D/1^2$ or $M/D/1^2$ queuing system.

In the following sections, a series of equations are derived that quantify average delay associated with and without TSP. TSP consists of green extension and early green (red truncation) strategies.

4.1 Terminology

Figure 4.1 shows TSP green extension strategy. The strategy extends the green phase for the prioritized approach for the transit vehicle. It does not require additional clearance intervals and allows the transit vehicle to be served in the current green phase.

Figure 4.2 shows the red truncation strategy. The strategy truncates the current prioritized approach red phase to serve the transit vehicle earlier than it would with a no TSP. The reduced green time from the non-prioritized approach is allocated to prioritized approach.

Where:

λ_p, λ_{np}	=	vehicle arrival rate at the prioritized approach and non-prioritized approach respectively
μ_p, μ_{np}	=	vehicle service rate at the prioritized approach and non-prioritized approach respectively
ρ_p, ρ_{np}	=	traffic intensity at the prioritized approach and non-prioritized approach respectively
A_p, AR_p	=	amber and all red interval duration for prioritized approach (seconds)
A_{np}, AR_{np}	=	amber and all red interval duration for non-prioritized approach (seconds)
g_{ext}	=	green extension time on the prioritized approach (seconds)
g_{min}	=	minimum green times for non-prioritized approach (seconds)
g_p, g_{np}	=	green interval on the prioritized and non-prioritized approach respectively (seconds)

---

[2] $D/D/1$ = deterministic arrivals (λ); deterministic service rate (μ); single server; vertical queues located at stop line; $M/D/1$ = Poisson arrivals (rate = λ); deterministic service rate (μ); single server; vertical queues located at stop line
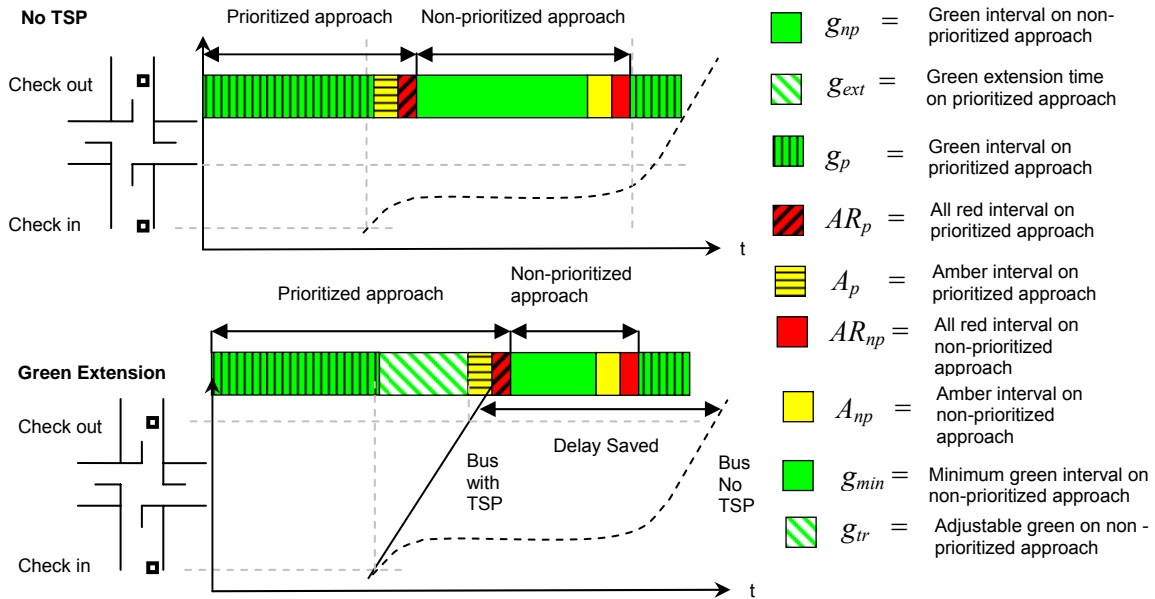
Figure 4.1: Space – Time diagram illustrating green extension TSP
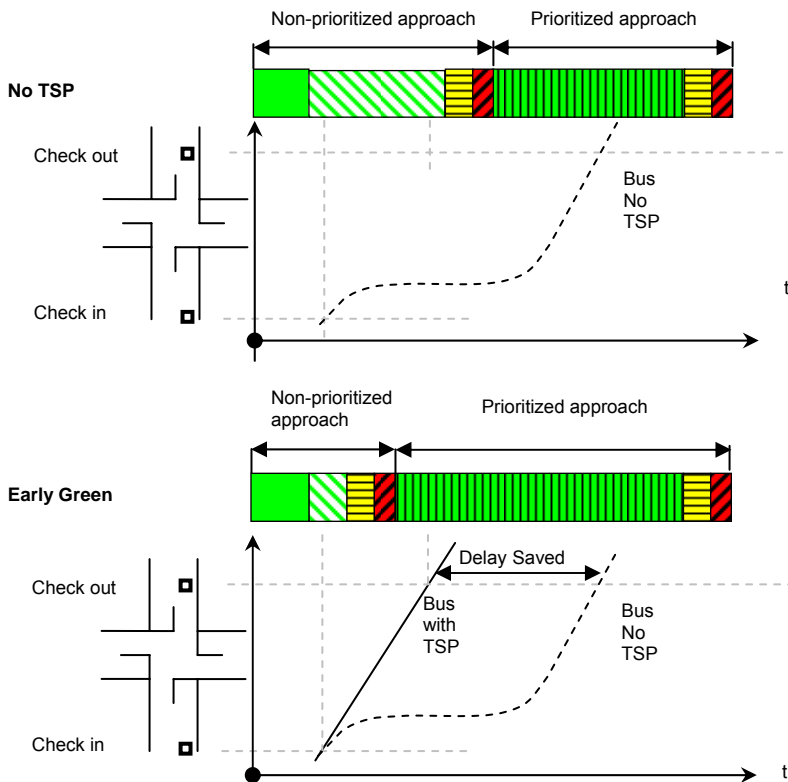
Figure 4.2: Space – Time diagram illustrating early green TSP

g_{tr}	=	Red truncation time on the non-prioritized approach (seconds)
n	=	Number of cycles required to dissipate the queue on non-prioritized approach
r_p , r_{np}	=	Red interval on the prioritized and non-prioritized approach respectively (seconds);
t	=	Time call for priority is received by controller (seconds) measured from the start of A_p
t'_{npi} , t_{npi}	=	Non-prioritized approach Green time in Cycle i at which queue is dissipated with TSP and No TSP respectively
t'_{pi} , t_{pi}	=	Prioritized approach Green time in Cycle i at which queue is dissipated with TSP and No TSP respectively
t_r	=	Time when existing phase is terminated as a result of TSP (Table 4.1) (seconds)
t_T	=	Bus travel time minus inter green time and time required to serve queue; $t_T = t_d - A_{np} - AR_{np} - t_q$ (seconds)

4.2 Transit Vehicle Detection and Traffic Signal Response

Within a given signal cycle, TSP response is a function of the time (t) when a transit vehicle is detected and the call for priority is received at the check in detector and the time required to transition from the existing phase to the prioritized phase. Table 4.1 defines mathematically the different TSP cases that can arise for green extension and red truncation TSP strategies.

As indicated in Table 4.1, under TSP control, signal timings and, therefore, delays are a function of the bus detection time. The derivation of analytical delay expressions is complicated by the fact that when TSP is granted, the green time on the non-prioritized approach is reduced and the non-prioritized approach may become temporarily oversaturated. The number of cycles required to serve the oversaturated queue and restore the non-prioritized approach to an under-saturated condition depends on the v/c ratio for the approach, the normal signal timing parameters (i.e. cycle length and non-prioritized approach green interval duration) and the amount of time by which the non-prioritized approach green is reduced during the red truncation. The implementation of TSP always increases delay for the non-prioritized approach and must be computed over all the cycles for which the influence of the TSP remains (i.e. until the non-prioritized approach becomes under-saturated). Consequently, it is possible to identify different cases for which delay expressions can be derived. The derivation assumes that:

1. The intersection is controlled by a traffic signal operating with a fixed time signal timing plan with a cycle length of C seconds.

2. TSP operates with a no compensation recovery algorithm[3].

3. Each approach is under-saturated (i.e. $\lambda C < \mu g$) when operating under no TSP.

When a detector upstream of the intersection signals the presence of a TSP bus to the traffic controller, red truncation TSP response cases can be identified and differentiated on the basis of when the call for the priority is received (t) and the time required to transition from the current non-prioritized phase or the prioritized phase (t_T). These cases are illustrated in Figure 4.3 and defined mathematically in Table 4.1.

Case 1: Full Red Truncation

In this case, the call for priority is received early in the current green phase on the non prioritized approach and therefore the green can be reduced to its minimum (g_{min}) resulting in a full red truncation. For the bus trajectory in Figure 4.3, t_T may be positive (bus experiences no delay), or negative (bus experiences some delay) depending on the values of t_d, A_{np}, AR_{np} and t_q.

Case 2: Partial Red Truncation

In this case, the call for priority is received partway during the non-prioritized green interval such that the current green phase can be reduced only partially but the current green interval for the non-prioritized approach can be terminated immediately.

Case 3: No Action

In this case, the bus is detected at time t such that the projected time of arrival is after the initial queue is served or the bus detection time is during the inter-green at the stop line or during the main street green time of the bus. Therefore, there is no need for TSP operations.

The response cases for green extension are shown in Figure 4.4. The termination time (t_r) and the bus detection decision boundaries are defined mathematically in Table 4.1.

---

[3] A standard TSP operation that does not compensate green time reduced from the cross street in subsequent cycles.

Table 4.1: Signal Priority Response Case and Termination Times

TSP Strategy: Red Truncation		
Response	Bus Detection Time (t)	Non-Prioritized Phase Termination Time
Full RT	$0 < t \leq \left(g_{min} + A_p + AR_p\right)$	$t_r = \max\begin{cases} g_{min} + A_p + AR_p \\ t + t_T \end{cases}$
Partial RT	$t > \left(g_{min} + A_p + AR_p\right)$ and $t \leq \min\begin{cases} A_p + AR_p + g_{np} - t_T \\ g_I + A_{np} + AR_{np} \end{cases}$	$t_r = \max\begin{cases} t \\ t + t_T \end{cases}$
No Action	$t > \min\begin{cases} A_p + AR_p + g_{np} + A_{np} + AR_{np} - t_d + t_q \\ A_p + AR_p + g_{np} + A_{np} + AR_{np} \end{cases}$	$t_r = \left(g_{np} + A_p + AR_p\right)$

TSP Strategy: Green Extension		
Response	Bus Detection Time	Prioritized Phase Termination Time
Full GE	$(A_{np} + AR_{np} + g_p - t_d) \leq t \leq \left(A_{np} + AR_{np} + g_p\right)$ and $g_{ext} \geq t_d$	$t_r = \left(A_{np} + AR_{np} + g_p + g_{ext}\right)$
No Action	$0 \leq t \leq (A_{np} + AR_{np} + g_p - t_d)$	$t_r = (A_{np} + AR_{np} + g_p)$

Where:

g_p, g_{np} = green interval on the prioritized and non-prioritized approach respectively;

A_p, AR_p = amber and all red interval duration for prioritized approach (seconds);

A_{np}, AR_{np} = amber and all red interval duration for non-prioritized approach (seconds);

g_{min} = minimum green times for non-prioritized approach (seconds);

t = time call for priority is received by controller (seconds) measured from the start of A_p

t_r = time at existing phase is terminated as a result of TSP (seconds);

t_T = bus travel time minus inter green time and time required to serve queue;

$\quad\quad t_T = t_d - A_{np} - AR_{np} - t_q$;

g_{tr} = red truncation Time on the non-prioritized approach;

g_{ext} = green extension time on the prioritized approach.

Case 1: Full Red Truncation

$g_{min} + A_p + AR_p$

t_d

check-in detector

Bus

non-prioritized approach

prioritized apprach

bus detection time

bus check-out time

RT TSP

NO TSP

Time (t)

0

Case 2: Partial Red Truncation

g_{min}

RT TSP

No TSP

Time (t)

0

Case 3: No Action

$A_p + AR_p + g_{np} + A_{np} + AR_{np} + t_q$

$A_p + AR_p + g_{np}$

No TSP

Time (t)

0

t

t_d

$A_p + AR_p$

Figure 4.3: Red Truncation TSP Response Case

43
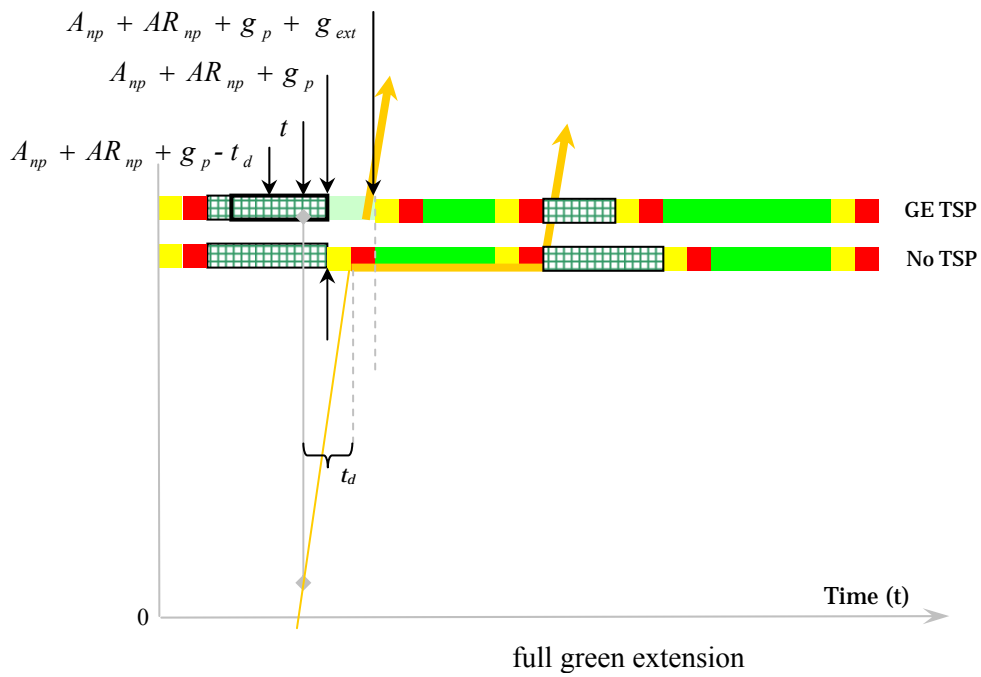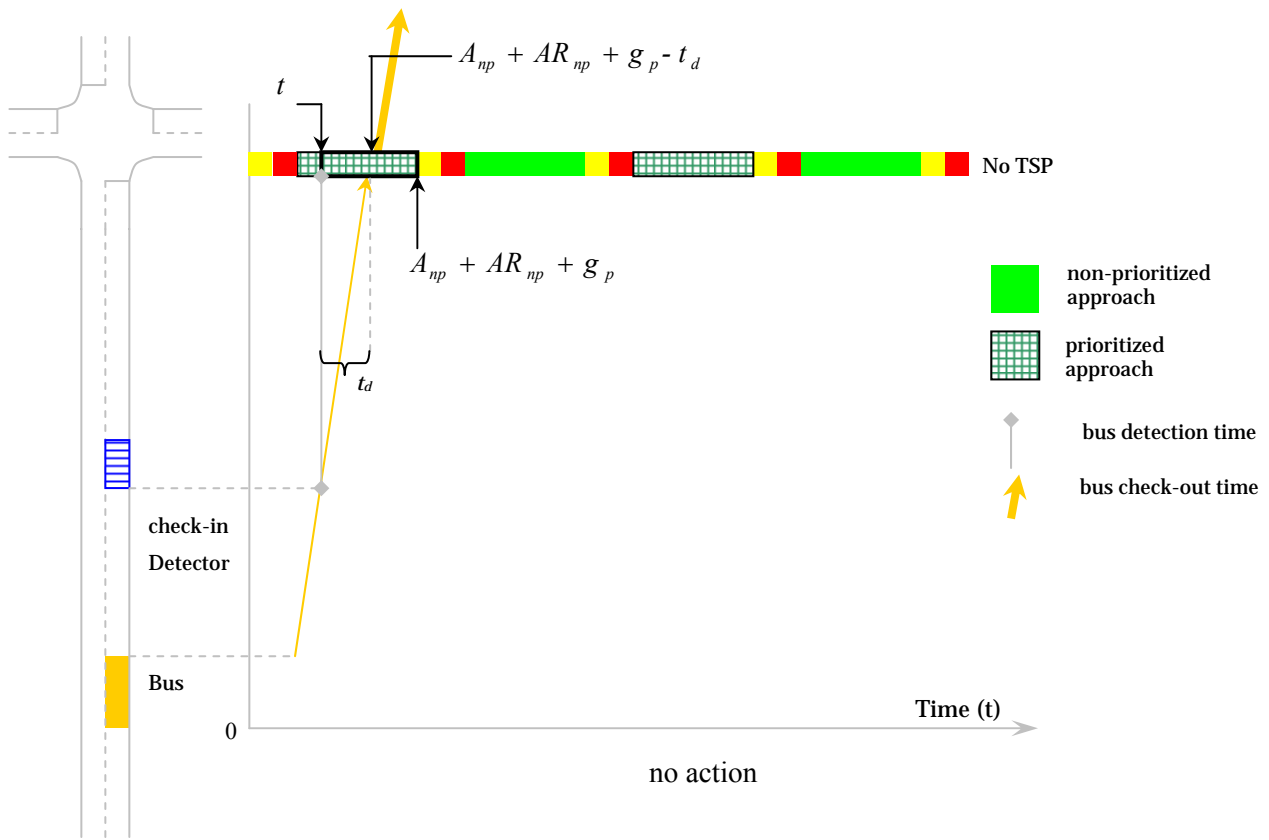
Figure 4.4: Case Definition for Green Extension

44

Case 1: No Action

In this case the projected bus time of arrival is during the green time of the prioritized approach. Therefore, the bus can clear the intersection during the green time and there is no need for GE TSP operation.

Case 2: Green Extension

In this case the projected bus time of arrival is after the green time of the prioritized approach is expected to end. This region is only valid when the bus can clear the intersection if a GE TSP extension is granted.

4.3 Calculating Vehicle Delays With and Without TSP

Depending on the arrival rate, departure rate and TSP parameters, and assuming a D/D/1 queuing system, the queue dissipation time can be estimated. Based on a queue dissipation time, the corresponding delay (i.e. area enclosed by the arrival and departure curve) can be computed.

Table 4.2 defines eleven cases depending on the queue dissipation time and signal control operation. Delay equations are derived for each of eleven cases. A unique case number is assigned if the queue is dissipating in the same number of cycles. For example, a letter Case No. B is assigned to both green extension and red truncation signifying that for both cases the queue is estimated to dissipate in Cycle 1.

In next section, delay equations are derived for prioritized and non-prioritized approach for all eleven cases defined in Table 4.2.

Table 4.2: Definition of Queue Dissipation Cases

Approach	Control Type	Case No.	Description
Prioritized	RT	A	Increased green time on the prioritized approach, the queue dissipates earlier compared with under-saturated fixed time control
	GE	A	
Non-Prioritized	RT	B	The non-prioritized approach green is terminated after the queue in Cycle 1 has been served
		C	The queue is served before the end of the Cycle 2.
		D	Cycle 2 is oversaturated, but the queue is fully served before the end of cycle 3
		E	The non-prioritized approach is oversaturated until cycle n where $n > 3$
	GE	B	Non-prioritized approach queue dissipates in Cycle 1 (under saturated)
		C	Non-prioritized approach queue is oversaturated in Cycle 1, but dissipates in Cycle 2
		E	Non-prioritized approach queue is oversaturated in Cycle 1, 2, …but dissipates in Cycle n
Prioritized	No TSP	F	Assumption that approach is under-saturated and the queues dissipate before the end of green
Non-Prioritized		F	

4.3.1 Prioritized Approach

In this section, the delay equations for the prioritized approach are derived for no TSP, green extension, and red truncation control strategies. Note that all variables have been defined in section 2.6 and section 4.1..

Case F (no TSP):

Delay incurred for the time when no TSP is implemented is simply the expression for delay of an under-saturated pulse D/D/1 queuing system

$$D^{\,p}_{NoTSP} = 0.5\lambda_p r_p \left(r_p + t_{p2}\right) \tag{15}$$

Where, time of dissipation of the queue can be expressed as

$$t_{p2} = \frac{\rho_p r_p}{1-\rho_p} \tag{16}$$

Case A (red truncation):

Now consider the prioritized approach with red truncation as illustrated in Figure 4.5. The delay associated with TSP operation can be estimated by computing the area between the respective cumulative arrivals and cumulative departures curves.
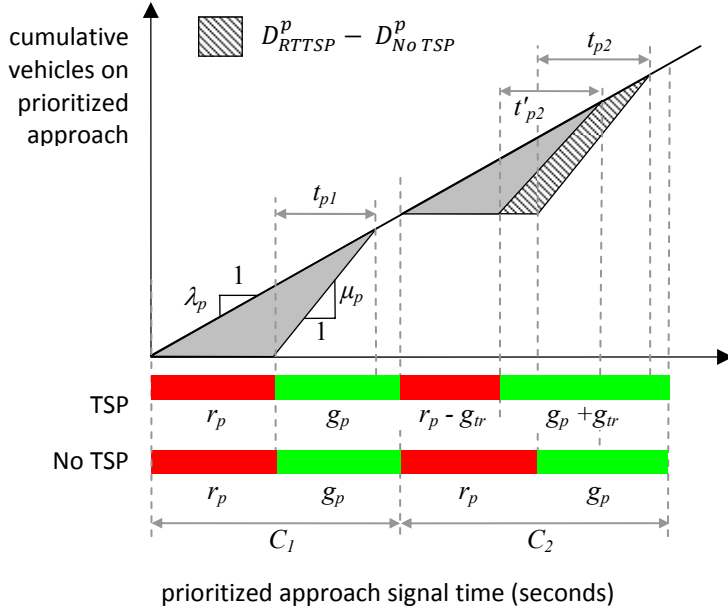
Figure 4.5: Prioritized Approach Case A (red truncation)

The delay incurred by traffic on the prioritized approach during the cycle in which priority is granted (i.e. C_2) is computed as:

$$D^p_{RTTSP} = 0.5\lambda_p\left(r_p - g_{tr}\right)\left(r_p - g_{tr} + t'_{p2}\right) \quad (17)$$

Where, time of dissipation of the queue (t'_{p2}) can be computed by equating the cumulative arrivals and departures

$$\lambda_p\left(r_p - g_{tr}\right) + \lambda_p t'_{p2} = \mu_p t'_{p2} \quad (18)$$

And, simplifying to obtain

$$t'_{p2} = \frac{\rho_p\left(r_p - g_{tr}\right)}{1 - \rho_p} \quad (19)$$

Case A (green extension):

Delay calculations for TSP with green extension control (Figure 4.6) can be computed as:

$$D^p_{GETSP} = 0.5\lambda_P\left(r_p - g_{ext}\right)\left(r_p - g_{ext} + t'_{p2}\right) \tag{20}$$

Where

$$t'_{p2} = \frac{\rho_p\left(r_p - g_{tr}\right)}{\left(1 - \rho_p\right)} \tag{21}$$
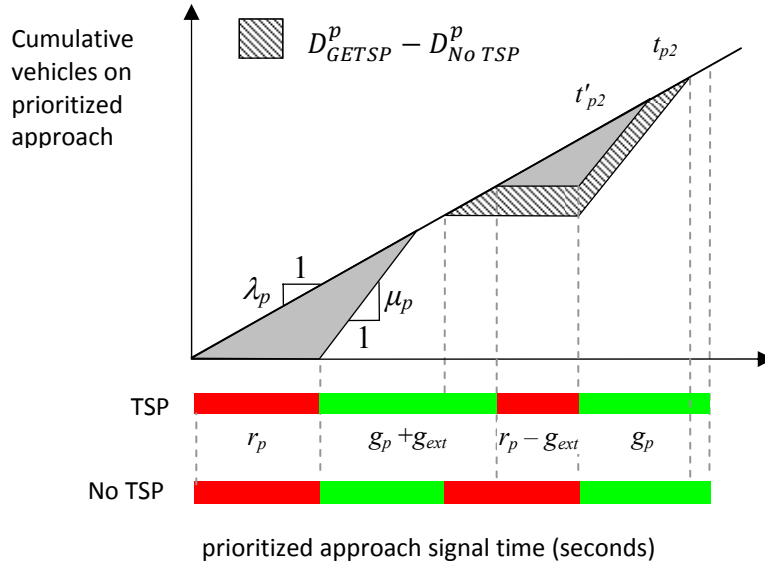
Figure 4.6: Prioritized Approach Case A (green extension)

4.3.2 Non-prioritized Approach

Case F (No TSP):

Similar to the calculations for No TSP on the prioritized approach the following expression can be derived by (Figure 4.7)

$$D^{np}_{No\,TSP} = \frac{\lambda_{np}r_{np}^2}{2\left(1 - \rho_{np}\right)} \tag{22}$$

48

cumulative
vehicles on
non-prioritized
approach

t_{np2}

t_{np1}

λ_{np}

μ_{np}

No TSP

r g_r r g

non-prioritized approach signal display time (seconds)
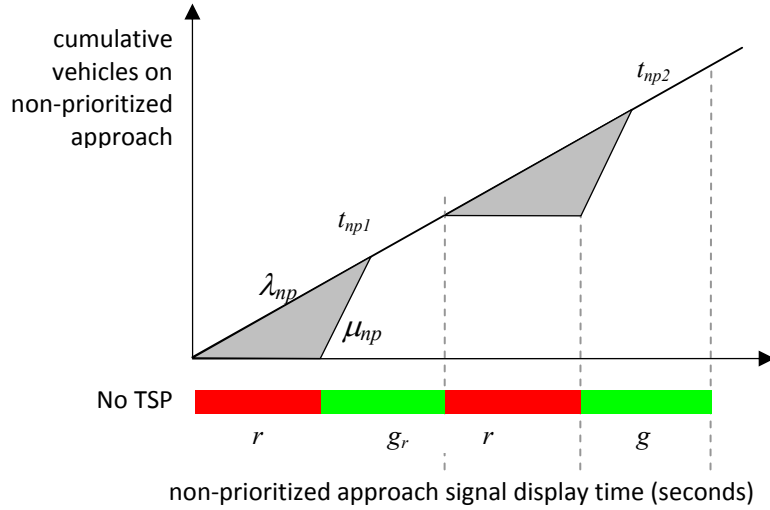
Figure 4.7: Non-Prioritized Approach Case F (no TSP)

Case B (red truncation):

The derivation of delay expressions for the non-prioritized approach is somewhat more complex because the green time on the non-prioritized approach is reduced when TSP is granted and this may lead to the non-prioritized approach being temporarily oversaturated. The number of cycles required to serve the oversaturated queue and restore the non-prioritized approach to an under-saturated condition depends on the v/c ratio for the approach, the normal signal timing parameters (i.e. cycle length and non-prioritized approach green interval duration) and the amount of time by which the non-prioritized approach green is reduced during the red truncation. The implementation of red truncation always increases delay for the non-prioritized approach and must be computed over all the cycles for which the influence of the TSP remains (i.e. until the non-prioritized approach becomes under-saturated). Case B under the Red Truncation control is illustrated in Figure 4.8 and the associated delay expression is:

$$D_{RTTSP}^{np} = 0.5\lambda_{np}\left(r_{np}^2 + g_{tr}\left(g_{tr} + 2r_{np}\right) + t'_{np2}\left(r_{np} + g_{tr}\right)\right) \tag{23}$$

Where

$$t'_{np2} = \frac{\rho_{np}\left(r_{np} + g_{tr}\right)}{\left(1 - \rho_{np}\right)} \tag{24}$$

49
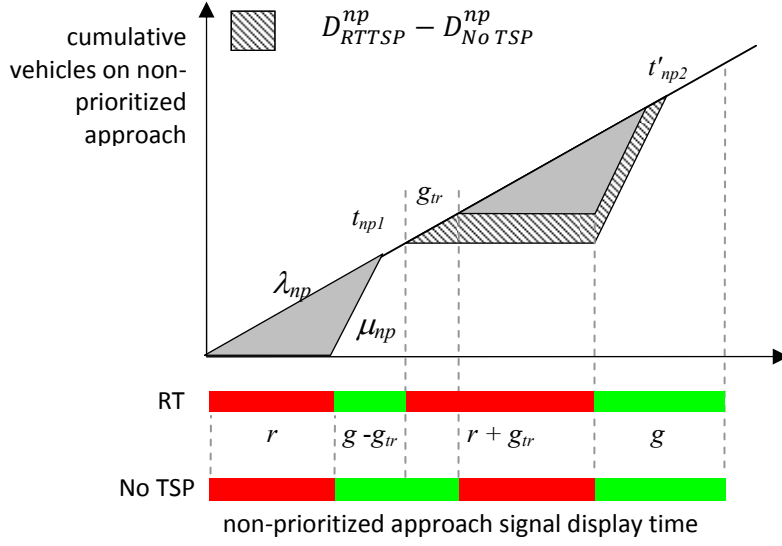
Figure 4.8: Non-Prioritized Approach Case B (red truncation)

Case C (red truncation):

In case, C the queue is served before the end of Cycle 2 (Figure 4.9). The delay expression for red truncation is expressed as:

$$D_{RTTSP}^{np} = \tfrac{1}{2}\left[\lambda_{np}(2C)^2 - \mu_{np}\left(g_{np} - g_{tr}\right)^2 - \mu_{np}\left(t'_{np2}\right)^2\right] - \left[\mu_{np}\left(g_{np} - g_{tr}\right)\left(C + g_{tr}\right)\right] \quad (25)$$

where

$$t'_{np2} = \frac{\rho_{np}\left(C + r_{np}\right) - \left(g_{np} - g_{tr}\right)}{1 - \rho_{np}} \quad (26)$$

Case D (red truncation):

The signal-timing plan in Cycle 3 is restored to fixed time operations. In case, D the queue is served before the end of Cycle 3 (Figure 4.9). The delay can be computed as:

$$D_{RTTSP}^{np} = \tfrac{1}{2}\left[\lambda_{np}\left(2C + r_{np} + t'_{np3}\right)^2 - \mu_{np}\left(g_{np} - g_{tr}\right) - \mu_{np}\left(t'_{np3}\right)^2 - \mu_{np}g_{np}^2\right] - \left[\mu_{np}\left(g_{np} - g_{tr}\right)\left(r_{np} + g_{tr} + C + g_{np}\right)\right] - \left[\mu_{np}g_{np}\left(r_{np} + t'_{np3}\right)\right] \quad (27)$$

where

$$t'_{np3} = \frac{2\rho_{np}C + \rho_{np}r_{np} - (g_{np} - g_{tr}) - g_{np}}{1 - \rho_{np}} \tag{28}$$

Case E (red truncation):

The delay expression for the case in which the queues does not dissipate until the nth cycle is estimated using equation 28 through equation 32. The series of expression for estimating the delay are:

$$D_{RTTSP,1}^{np} = 0.5\lambda_{np}(r_{np} + g_{np} - g_{tr})^2 - 0.5\mu_{np}(g_{np} - g_{tr})^2 \tag{29}$$

$$D_{RTTSP,2}^{np} = 0.5\lambda_{np}(C + g_{tr})^2 - 0.5\mu_{np}g_{np}^2 + [(C + g_{tr})(\lambda_{np}(r_{np} + g_{np} - g_{tr}) \\ - \mu_{np}(g_{np} - g_{tr}))] \tag{30}$$

$$D_{RTTSP,i}^{np} = \sum_{3}^{n-1}\{0.5\lambda C^2 - 0.5\mu g^2 + [C((n-2)\lambda C - \mu((g - g_{tr}) + (n-3)g))]\} \tag{31}$$

$$D_{RTTSP,n}^{np} = 0.5\lambda_{np}(r_{np} + t'_{npn})^2 - 0.5\mu_{np}(t'_{npn})^2 + [(r_{np} + t'_{npn})(\lambda_{np}(n-1)C \\ - \mu_{np}((g_{np} - g_{tr}) + (n-2)g_{np}] \tag{32}$$

$$D_{RTTSP}^{np} = D_{RTTSP,1}^{np} + D_{RTTSP,2}^{np} + D_{RTTSP,i}^{np} + D_{RTTSP,n}^{np} \tag{33}$$

Where:

D_{RTTSP}^{np} = total vehicle delay for Case E,

$D_{RTTSP,1}^{np}$ = vehicle delay in Cycle 1,

$D_{RTTSP,2}^{np}$ = vehicle delay in Cycle 2,

$D_{RTTSP,i}^{np}$ = sum of vehicle delay Cycle 3 through Cycle (n-1),

$D_{RTTSP,n}^{np}$ = vehicle delay in Cycle n.

The time of dissipation can be computed by:

$$t'_{npn} = \frac{(n-1)\rho_{np}C + \rho_{np}r_{np} - (g_{np} - g_{tr}) - (n-2)g_{np}}{1 - \rho_{np}} \tag{34}$$

51
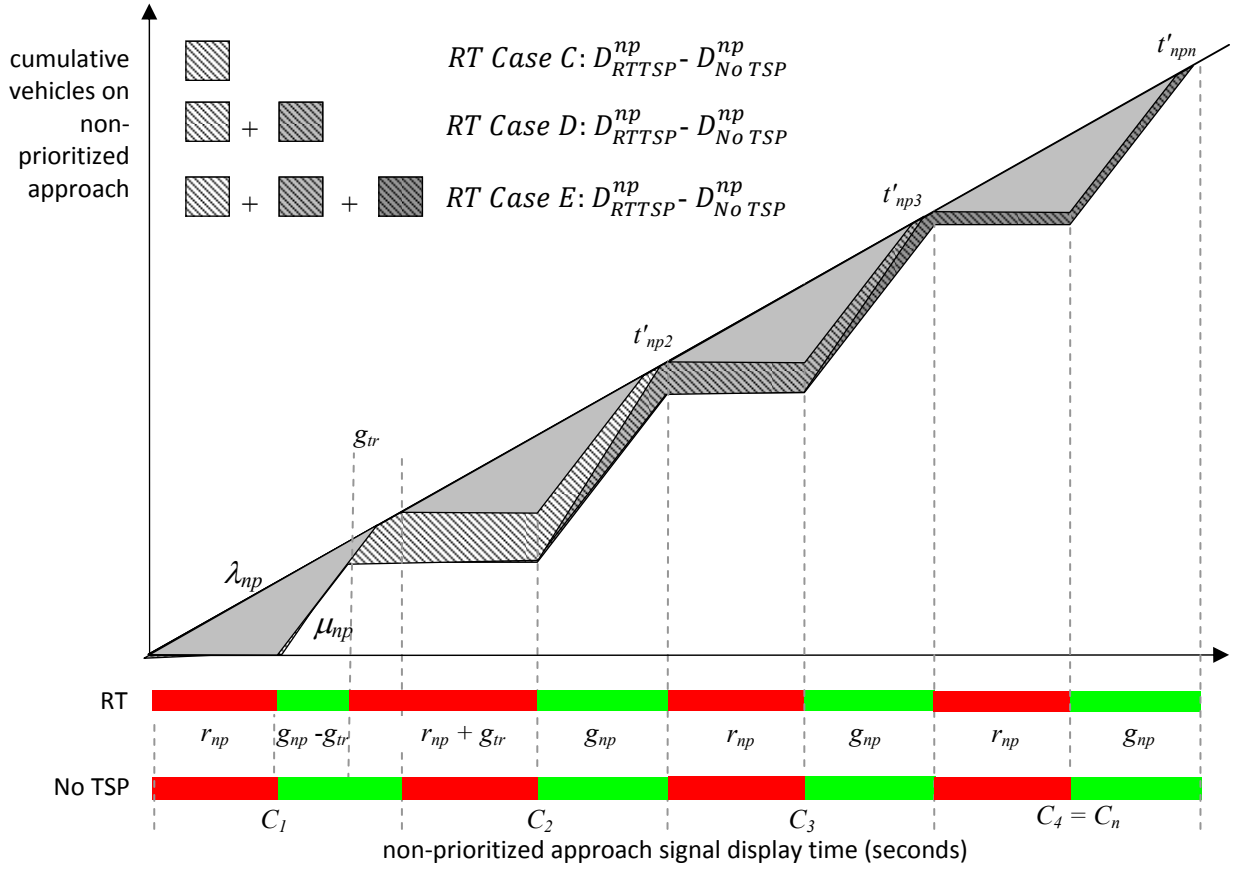
Figure 4.9: Non-Prioritized Approach Case C, D and E (red truncation)

Case B (green extension):

The delay expression for green extension on the non-prioritized approach when the queue dissipates in Cycle 1 (Figure 4.10) is given as:

$$D_{GETSP}^{np} = 0.5\lambda_{\text{np}}\left(r_{np} + g_{ext}\right)\left(r_{np} + g_{ext} + t'_{np1}\right) \tag{35}$$

where

$$t'_{np1} = \frac{\rho_{np}\left(r_{np} + g_{ext}\right)}{\left(1 - \rho_{np}\right)} \tag{36}$$
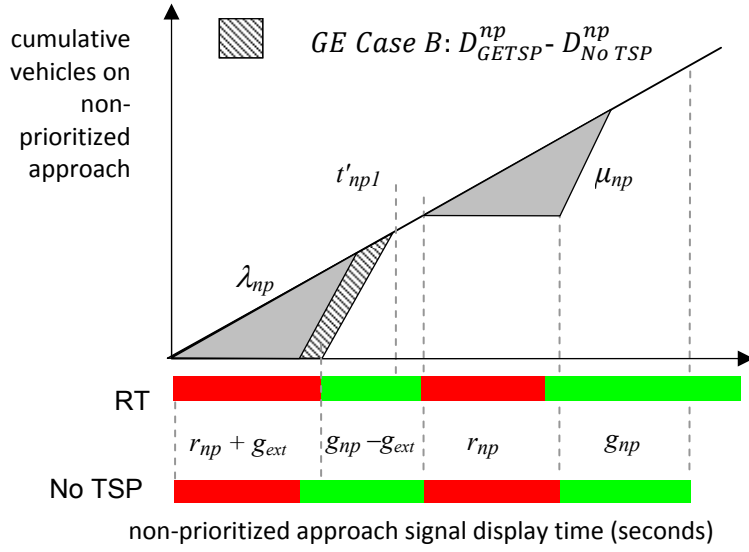
Figure 4.10: Non-Prioritized Approach Case B (green extension)

Case C (green extension):

If the queue is oversaturated in Cycle 1 and dissipates in Cycle 2 (Figure 4.11) the delay can be computed as:

$$D_{GETSP}^{np} = 0.5\lambda_{np}C^2 - 0.5\mu_{np}\left(g_{np} - g_{ext}\right)^2 + 0.5\lambda_{np}\left(r_{np} + t'_{np2}\right)^2 - 0.5\mu\left(t'_{np2}\right)^2$$
$$+ \left[\left(r_{np} + t'_{np2}\right)\left(\lambda_{np}C - \mu_{np}\left(g_{np} - g_{ext}\right)\right)\right] \tag{37}$$

where

$$t'_{np2} = \frac{2\rho_{np}r_{np} + \rho_{np}g_{np} - \left(g_{np} - g_{ext}\right)}{\left(1 - \rho_{np}\right)} \tag{38}$$

Case E (green extension):

The delay expressions for queue dissipating in the nth Cycle under the green extension strategy (Figure 4.12) can be computed as:

$$D_{GETSP,1}^{np} = 0.5\lambda_{np}C^2 - 0.5\mu_{np}\left(g_{np} - g_{ext}\right)^2 \tag{39}$$

$$D_{GETSP,i}^{np} = \sum_{3}^{n-1} 0.5\lambda_{np}C^2 - 0.5\mu_{np}g_{np}^2 + (C((n-2)\lambda_{np}C - \mu_{np}((g_{np} - g_{ext}) + (n-3)g_{np}))) \tag{40}$$

$$D_{GETSP,n}^{np} = 0.5\lambda_{np}\left(r_{np} + t'_{npn}\right)^2 - 0.5\mu_{np}\left(t'_{npn}\right)^2 + [(r_{np} + t'_{npn})\{(n-1)\lambda_{np}C$$
$$- \mu_{np}((g_{np} - g_{ext}) + (n-2)g_{np})\}] \tag{41}$$

$$D_{GETSP}^{np} = D_{GETSP,1}^{np} + D_{GETSP,i}^{np} + D_{GETSP,n}^{np} \tag{42}$$

where:

D_{GETSP}^{np} = Total vehicle delay for Case E,

$D_{GETSP,1}^{np}$ = vehicle delay in Cycle 1 and Cycle 2,

$D_{GETSP,i}^{np}$ = sum of vehicle delay Cycle 3 through Cycle (n-1),

$D_{GETSP,n}^{np}$ = vehicle delay in Cycle n.

The time of dissipation can be computed by:

$$t'_{npn} = \frac{n\rho_{np}r_{np} + (n-1)\rho_{np}g_{np} - (g_{np} - g_{ext}) - (n-2)g_{np}}{(1 - \rho_{np})} \tag{43}$$
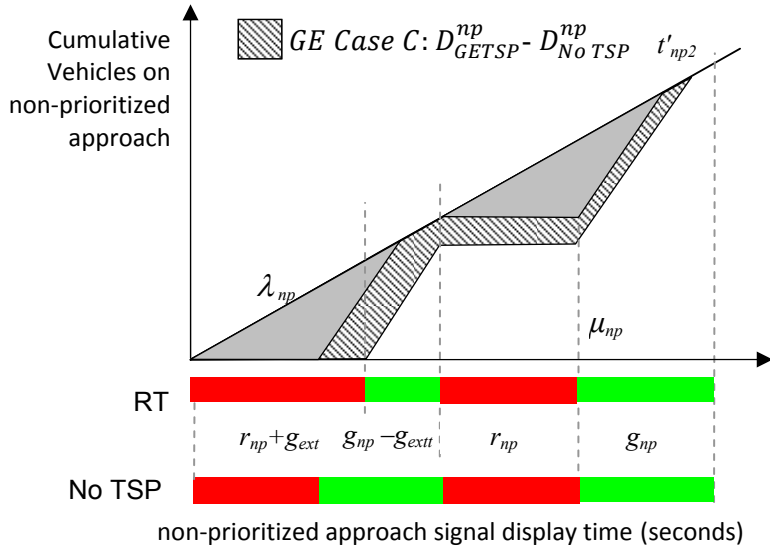
Figure 4.11: Non-Prioritized Approach Case C (green extension)
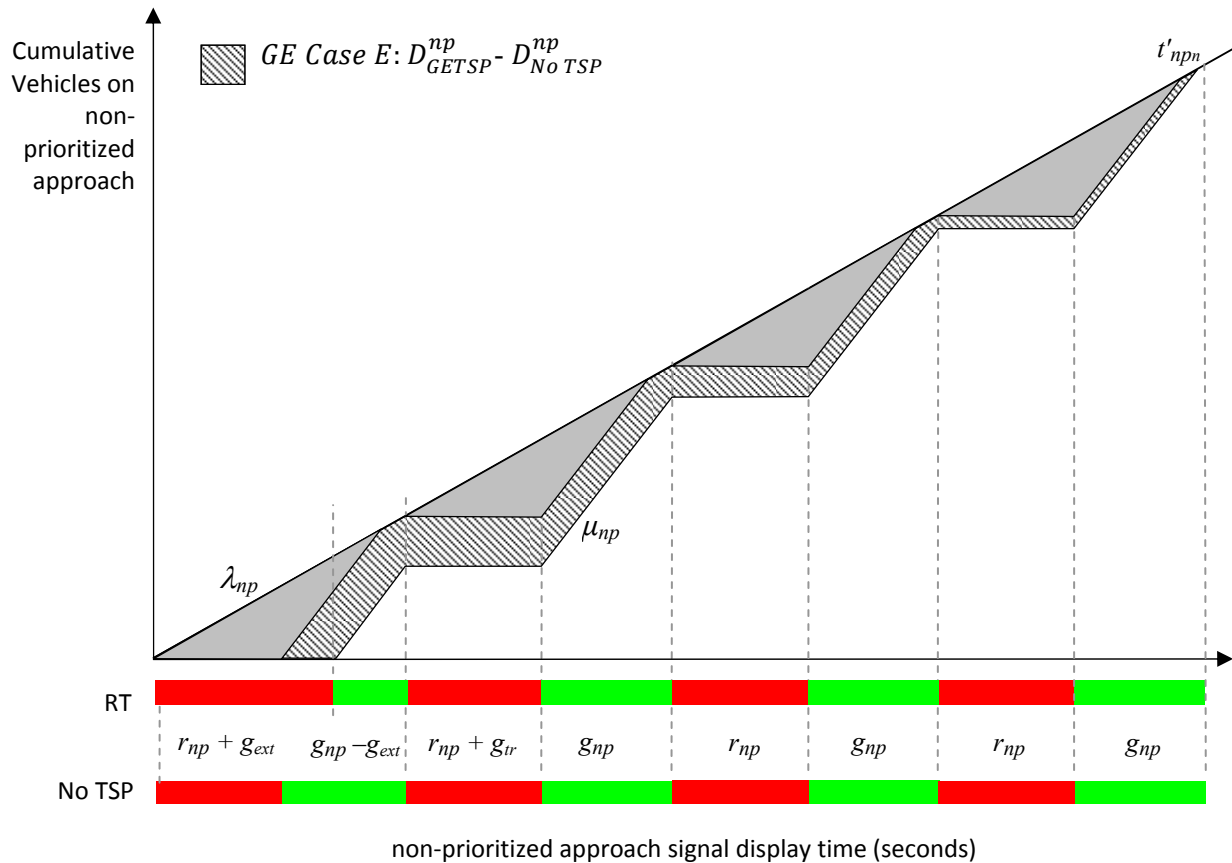
Figure 4.12: Non-Prioritized Approach Case E (green extension)

These equations permit estimation of delays occurring at a signalized intersection operating with or without TSP control, subject to the assumptions identified in section 4.2. The equations described above were implemented within a software tool to aid in their application.

4.4 Fuel Consumption and Emissions

For this research, a linear model calibrated from data obtained from the INTEGRATION traffic simulation model was used to estimate the fuel consumption and emissions. Hellinga et al. [48] used the INTEGRATION model to generate emission and fuel consumption data for a range of traffic and signal control conditions. A total of 8100 scenarios were simulated using the INTEGRATION model. In each case, the network consisted of a four-leg intersection with a single two-phase signal controlling exit privileges from each approach. Average fuel consumption was recorded for each scenario. The fuel consumption was obtained with and without a traffic signal.

The resulting fuel consumption data was compiled by subtracting the average vehicle fuel consumption associated with a non-signal scenario from the corresponding average vehicle fuel consumption associated with the traffic signal. This quantity represented the additional average fuel quantity that would be produced by each vehicle traversing a single approach because of the installation of a traffic signal.

A regression was performed on the change in fuel consumption (ΔF) and change in average delay (Δd) as:

$$\Delta F = \alpha + \beta \Delta d \tag{44}$$

where:

ΔF = additional fuel used per vehicle due to the signal operation based on the additional total delay per vehicle that resulted from the signal (versus no signal at all), (litres per vehicle),

Δd = additional total delay per vehicle that resulted from the signal (versus no signal at all), (seconds/veh)

α = regression parameter, $\alpha = 0.013$

β = slope of the regression; $\beta = 0.00053$ (automobiles) and $\beta = 0.0007$ (transit buses)

Table 4.3: Regression Statistics

Multiple R	0.9856
R Square	0.9715
Adjusted R Square	0.9715
Standard Error	0.0074
Observations	8100

Table 4.4: ANOVA Results

	df	SS	MS	F	Significance F
Regression	1	15.20	15.20	276229.36	0
Residual	8098	0.45	5.50E-05		
Total	8099	15.65			

The analytical equations developed in the previous section permit the estimation of average delay per vehicle resulting from traffic signal operation (without or with TSP).

Therefore, these equations can be used to estimate (Δd) in equation (44) for no TSP control (to provide (ΔF_{NoTSP}) and for TSP control (to provide ΔF_{TSP}). The impact of implementing TSP control (versus no TSP signal control) on fuel consumption is given by:

$$\Delta F' = \Delta F_{TSP} - \Delta F_{NoTSP} \qquad (45)$$

$\Delta F'$ = additional fuel consumed due to TSP implementation (litres per vehicle)

The additional fuel consumption due to TSP is multiplied by the number of vehicles (N) traversing the intersection per hour to determine the impact of TSP on fuel consumption in terms of litres per hour of operation.

There is no information available in the literature with which to verify directly the validity of equation 43 and it is not feasible to collect field data for verification. Consequently, an attempt was made to perform an indirect verification. Leung and Williams [29] conducted a regression on the idle fuel consumption rates reported in the literature for various sizes of light duty gasoline engines and suggested that a straight line with a slope of 8.5 mL/minute can be drawn through the data (Figure 4.13). Using their results the value of β for automobiles from equation 43 (β = 31.8 mL / min) is close to the idle fuel consumption rate for a 3.5 L engine suggesting that equation 44 is reasonable.
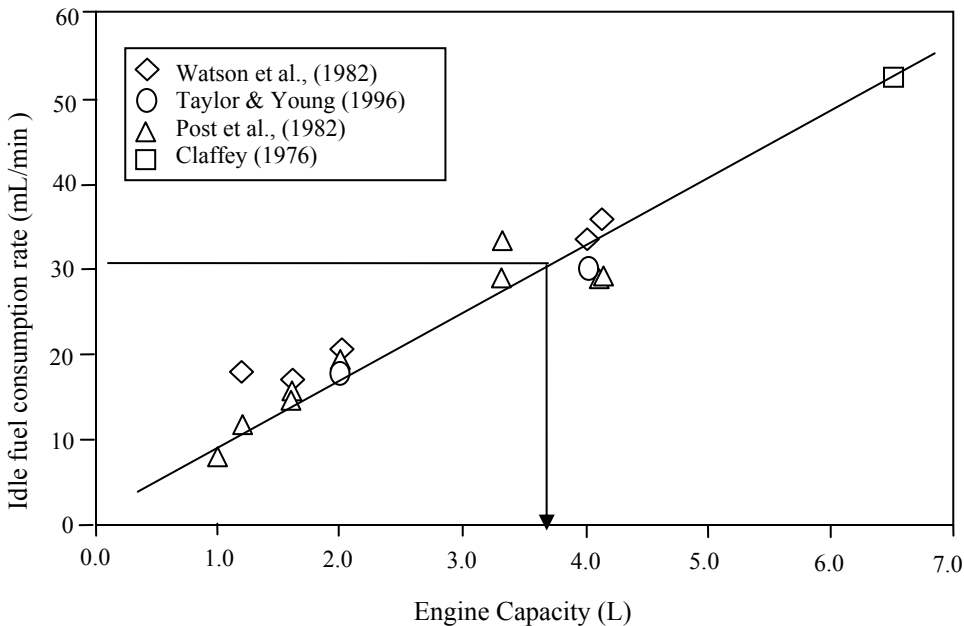
Figure 4.13: Idle fuel consumption rate for different sizes of light duty gasoline powered engines [29]

57

The impact in terms of GHG emissions can be computed using a constant conversion coefficient

$$\Delta E' = \gamma \Delta F' \tag{46}$$

where:

γ =   Tonnes of CO_2 equivalents per million litres of fuel consumed, Auto (Gasoline = 2503.86), Transit Buses (Heavy Duty Diesel = 2763.81).

4.5 Generalized Model

The TSP evaluation expressions developed earlier permit the estimation of delay for two-phase signal operation. These equations were embedded into a software module and further enhancements were made to permit analysis of fixed time signal timing plans with up to 8 phases. In this section, we describe the software implementation. The detailed VB code is attached in Appendix B. The model provides estimates of the incremental impact of implementing TSP in terms of:

- Transit vehicle and auto delays (seconds/vehicle and seconds/person) on the prioritized and non-prioritized intersection approaches

- Transit vehicles (diesel bus) and auto (light duty gasoline powered vehicles) fuel consumption

- GHG emissions

- Variability of bus delay

These estimates of the impact of TSP are a function of the following user specified inputs:

- Intersection geometry (number of approaches and lane configurations)

- Signal timing (number of phases; cycle length; green interval durations; saturation flow rate)

- TSP parameters (maximum green extension; maximum red truncation; time for transit vehicle to travel from detector to stop line; prioritized phases)

- Traffic demands (peak hour lane volumes; degree of progression; variability of peak hour volumes; arrival stream headway distribution)

- Transit characteristics (average bus passenger loads; transit vehicle headway; distribution of transit vehicle arrival within signal cycle)

The first step in the use of the evaluation tool is to provide the necessary input data. The tool requires input data in three categories, namely:

1. Intersection geometry and traffic conditions;

2. Traffic signal timing characteristics;

3. TSP operating parameters; and

4. Evaluation parameters.

Each of these inputs is described in the following sections.

4.5.1 Intersection Geometry and Traffic Conditions

As a first step, a user specifies intersection geometry and traffic condition data in the developed tool. Four types of input data must be specified:

1. The intersection geometry defined by lane groups. Three lane groups can be defined on each approach. Each lane group may consist of multiple lanes.

2. The movements that are permitted to discharge from each lane group need to be defined.

3. The average peak hour traffic volume in each lane is specified.

4. Finally, the adjusted saturation flow rate for each lane group is specified.

4.5.2 Traffic, Signal Control and TSP Parameters

The characteristics of the signal-timing plan operating during the period of interest are defined by the user in terms of:

1. Number of the phases that controls the discharge of traffic from each lane group;

2. Green, amber, and all red interval durations for each phase ; and

3. Lane group on which transit vehicles travel when requesting priority.

The user must specify the TSP operating parameters, including which phases permit green extension or red truncation. For each phase permitting green extension, the user must specify the

maximum green extension provided. For each phase permitting red truncation (i.e. phase serving the non-prioritized approach), the user must specify the minimum green time that must be provided for the phase.

4.5.3 Proportion of Arrivals During Phase i for Lane Group j (Platoon Progression)

The user can specify the proportion of vehicles arriving during a specific phase to account for platoon progression. Good progression would signify a higher proportion of vehicles arriving on the prioritized approach green interval, while poor progression would indicate a higher portion of vehicles arriving on the prioritized approach red interval. A default platoon progression can be used if the data for platoon progression is not available.

4.5.4 Evaluation Parameters

Finally, the user must specify a number of parameters that control the evaluation. These parameters include:

- The type of distribution of arrivals - deterministic (D/D/1) versus Poisson (M/D/1)

- The evaluation time period (which is determined by the average transit vehicle headway)

- The time required for the transit vehicle to travel from the detector location to the stop line

4.6 Chapter Conclusions

In this chapter, we have developed the delay expressions for green extension and red truncation TSP strategy. The expressions were developed based on the queue dissipation and termination times. The developed expressions permit the estimation of average delay per vehicle resulting from traffic signal (without or with TSP) operation. A fuel consumption and emission model was also presented. In the next chapter, we validate the model with existing analytical models and microscopic simulation.

Chapter 5

Analytical Model Validation

The proposed D/D/1 model(s) presented in the previous chapter were validated against the previous study and microscopic simulation results. The outcome of the validation is consolidated in the following sections.

- Validation against other analytical models

- Validation against VISSIM micro-simulation

5.1 Validation Case 1: Comparison to Liu et al. Model

The first validation test was to compare the results provided by Liu et al. [5] in their paper with those produced by the proposed D/D/1 model. The Liu et al. [5] model only considers the impacts of TSP during two signal cycles – the initial cycle in which TSP is granted and the subsequent cycle. Consequently, in this section we limit the analysis and comparison time to two cycles. Impacts beyond this time are ignored. Section 5.2 presents a comparison of results from the proposed D/D/1 model with results from the VISSIM simulation model in which these impacts are considered.

5.1.1 Validation Scenario

The validation scenario as described by Liu et al. [5] consists of a single isolated intersection with four approaches having the following characteristics:

- Each approach consists of a single through lane.

- The intersection is controlled by a two-phase fixed-time signal with a cycle length of 80 seconds.

- Each phase consists of 40 seconds of green. No amber or all red intervals are modeled.
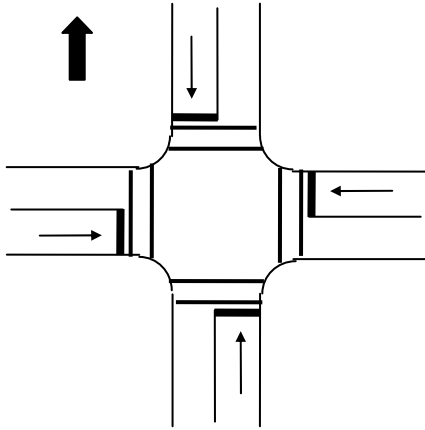
Figure 5.1: Intersection Geometry (Liu et al model)

- Saturation flow rate was 1800 pcphpl.

- TSP behaviour is a function of the time during the cycle the transit vehicle is detected and requests priority treatment. The buses were modeled to request priority 55 seconds into the signal cycle (i.e. 15 seconds into phase 2).

- TSP and no TSP control conditions were modeled.

- Each control condition was modeled for 11 different demand scenarios. For each demand scenario, volumes on the prioritized and non-prioritized approaches were equal and chosen to achieve a desired *v/c* ratio ranging from 0.2 to 0.95.

- The traffic volumes on each approach were calculated by multiplying v/c ratio with green-to-cycle ratio and saturation flow rate. For example at *v/c*=0.1 the volume can be calculated by (0.1 x (40/80) x 1800) = 90 vph. Similarly, the volumes at all 11 demand scenarios were calculated.

- The proposed D/D/1 model is deterministic and therefore only a single run needs to be carried out for each v/c ratio (11 runs in total).

- The impact of TSP was measured as a change in the non-prioritized approach as average delta vehicle delay (i.e. $d_{TSP} - d_{No\ TSP}$).

5.1.2 Estimates of Delay from Proposed Model

Figure 5.2 shows the average delays per vehicle for the non-prioritized approach as estimated by the proposed D/D/1 model under fixed time (no TSP) and TSP control. Delay increases non-linearly with v/c under fixed time control as expected. The reason for delay not being linear can be explained by Equation 4 that can be rewritten as:

$$d = \frac{\left[C\left(1-\frac{g}{C}\right)\right]^2}{2C\left(1-\frac{\lambda}{\mu}\right)} \tag{47}$$

An expanded form can be obtained as:

$$d = \frac{C^2\left(1-2\frac{g}{C}+\frac{g^2}{C^2}\right)}{2C\left(1-\frac{\lambda}{\mu}\right)} \tag{48}$$

For low values of g/C, the term g^2/C^2 is negligible and delay increases approximately linearly. As the g/C ratio increases, the contribution of this term becomes significant and delay increases non-linearly. In our application the $g/C = 0.5$, therefore a non-linear curve is expected. The relationship between delay and v/c ratio for TSP control is also not linear. The shape of this relationship depends on the non-prioritized approach arrival rate (assuming that transit vehicle arrival time is fixed). As the arrival rate increases there is a linear increase in delay until the approach becomes oversaturated in the first cycle and/or second cycle (this occurs for v/c ≥ 0.6 in Figure 5.2) after which delay increases in a non-linear fashion. The slope of the curve decreases after $v/c > 0.7$ because delay is only being calculated over two cycles and consequently as v/c becomes large, the approach becomes oversaturated for the second cycle, and delay impacts beyond the end of the second cycle are ignored.
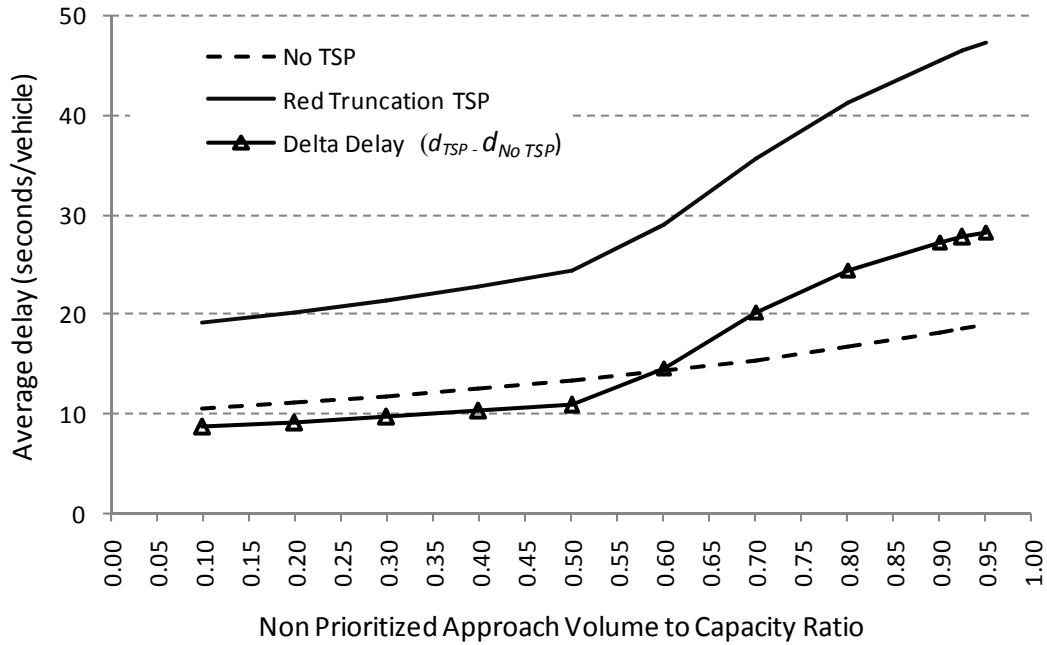
Figure 5.2: Proposed D/D/1 model estimates of average delay (Validation Case: 1)

5.1.3 Estimates of Delta Delay

In a recently published paper, Liu et al. [5] proposed an analytical approach for quantifying the delay impacts of TSP. Table 5.1 shows calculations of the individual terms in the Liu et al. equation. Column (D) is the second term in the equation (12). This term produced negative values for volume-to-capacity ratio of less than or equal to 0.5 which results in $\Delta D < 0$ for v/c $\leq$ 0.3.

For larger volume-to-capacity ratios, the value from the first term (A) becomes larger than the value from the second term (D) and ΔD becomes positive.

The negative values for ΔD (and Δd) indicate that the implementation of TSP decreases delay to vehicles on the non-prioritized approach. This result contradicts our expectation that with implementation of TSP there is an increase in delay on the non-prioritized approach because green time for the non-prioritized approach is reduced. At best, the implementation of TSP will not increase delay to vehicles on this non-prioritized approach. Liu et al. [5] equations on the other hand indicate that vehicular delays on the non-prioritized approach operating with TSP control for *v/c* ratio up to 0.3 are less than those obtained from fixed time control.

Table 5.1: Liu et al. [5] Equation

Equation 12	$\Delta D = \dfrac{\lambda g_{tr}(2r + g_{tr})}{2\lambda(1-\rho)} + \mu\left[\dfrac{r}{1-\rho} - (C - g_{tr})\right](r + g_{tr})$

Term (A): $\dfrac{\lambda g_{tr}(2r + g_{tr})}{2\lambda(1-\rho)}$; (B): $\dfrac{r}{1-\rho}$; (C): $(C - g_{tr})$; (D): $\mu\left[\dfrac{r}{1-\rho} - (C - g_{tr})\right](r + g_{tr})$

v/c	ρ	λ	Individual terms				ΔD	Δd
			(A)	(B)	(C)	(D)	(E)=(A)+(D)	(F)=(E)/2λC
							sec	sec/ veh
0.1	0.05	0.025	34.5	42.1	55.0	**-419.1**	**-384.5**	**-96.1**
0.2	0.1	0.05	72.9	44.4	55.0	**-343.1**	**-270.1**	**-33.8**
0.3	0.15	0.075	115.8	47.1	55.0	**-258.1**	**-142.3**	**-11.9**
0.4	0.2	0.1	164.1	50.0	55.0	**-162.5**	1.6	0.1
0.5	0.25	0.125	218.8	53.3	55.0	**-54.2**	164.6	8.2
0.6	0.3	0.15	281.3	57.1	55.0	69.6	350.9	14.6
0.7	0.35	0.175	353.4	61.5	55.0	212.5	565.9	20.2
0.8	0.4	0.2	437.5	66.7	55.0	379.2	816.7	25.5
0.9	0.45	0.225	536.9	72.7	55.0	576.1	1113.1	30.9
0.93	0.46	0.231	564.7	74.4	55.0	631.1	1195.8	32.3
0.95	0.48	0.238	593.8	76.2	55.0	688.7	1282.4	33.8

Figure 5.3 illustrates estimates of average Delta vehicle delay (Δd) as a function of non-prioritized approach volume-to-capacity ratio obtained from the proposed D/D/1 model and those developed by Liu et al. Note that in Figure 5.3 the negative values of Delta delay estimated by the Liu et al. [5] model have not been depicted.

Several observations can be made based on the results shown in Figure 5.3:

- The results obtained from the Liu et al. [5] model are negative for v/c < 0.40.

- The estimates from the Liu et al. model and the proposed D/D/1 model are identical for $v/c = 0.6$ and $v/c = 0.7$. The Liu et al. model is a special case of our proposed D/D/1 model.

The Liu et al. model estimates are larger than those from the proposed D/D/1 model for $v/c \geq 0.8$.
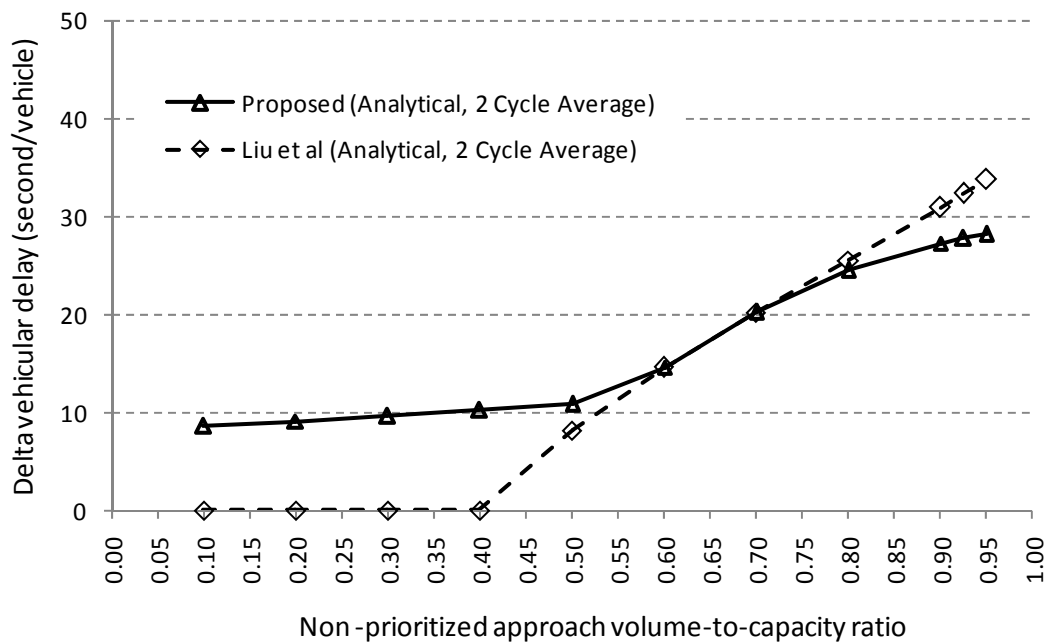
Figure 5.3: Comparison of Proposed Model Estimates (Validation Case 1)

5.1.4 Conclusions (Validation Case 1)

In the previous section, it was demonstrated that the values from the Liu et al. model are clearly incorrect for v/c < 0.4. Though this validation has demonstrated limitations of the Liu et al. model that does not exist in the proposed model, the comparison does not demonstrate that the proposed model results are valid. Consequently, additional validation was conducted by comparing the results from the proposed model to results obtained from the VISSIM simulation model.

5.2 Validation Case 2 (Comparison to VISSIM Model)

5.2.1 Modeling with VISSIM

The validation scenario was similar to the one used in validation Case 1. The details of the VISSIM modeling effort are as follows:

- To ensure consistent priority request times between the micro-simulation and the proposed delay expressions, buses were modeled to request priority 55 seconds into the signal cycle (i.e. 15 seconds into phase 2).

- TSP and no TSP control conditions for 11 different demand scenarios were modeled.

- The arrival traffic stream on each approach follow a Poisson distribution.

- The VISSIM manual indicates that the saturation flow rate can be altered by changing the driving behavior. However, even for a close estimate of saturation flow rate using calibrated driving behavior parameters there is a variation in Saturation Flow Rate estimates. In an attempt to minimize this impact, ten random seeds were taken that averaged closely to the targeted saturation flow rate of 1800 vphpl (Table 5.2). These random seeds were used to estimate the delay statistics.

- The default values of *bx_add* = 2.0 and *bx_mult* = 3.0 were used.

Table 5.2: VISSIM Seed and Saturation Flow Rates

VISSIM (Seed)	Saturation Flow Rate	VISSIM (Seed)	Saturation Flow Rate
50	1789	400	1787
100	1798	450	1791
200	1801	500	1788
250	1799	550	1803
300	1795	600	1804
Average			1796
Standard Deviation			6.40

- Each v/c scenario was replicated 10 times, each with a different random number seed (Table 5.2) for 220 simulation runs.

- Delays experienced by vehicles on the non-prioritized approaches were recorded from the simulation.

- Average delay per vehicle was computed as the sum of all delays experienced by all vehicles divided by the total number of vehicles passing through the intersection during the simulation.

- The average delta delay for each *v/c* scenario was computed as the average of the differences between no TSP and TSP (red truncation) for each of the 10 replications.

- The vehicle follow headway = 250 m.

- A single transit was modeled to arrive at 55 seconds in the 80-second cycle length. The transit time of arrival is on the non-prioritized approach green and a request for red truncation is granted.

Vehicle Actuated Program (VAP) code were developed to model TSP signal timings in VISSIM.

The delay statistic in VISSIM is computed as the difference between the ideal time for a vehicle to traverse a pre-defined travel time section and the time actually taken to traverse by the vehicle on the same travel time section. VISSIM computes the ideal time based on the specified speed distribution in the model. Due to the nature of the travel time section computation a vehicle not exiting the travel time section during the analysis period will not be included in the delay statistics. Therefore, the simulation time was extended to ensure all vehicles traversed the travel time section and delays recorded. For this part, we have used 400 seconds (5 cycles) to make sure each vehicle exits the travel time section and delay statistics are recorded.

5.2.2 Validation Case 2a:

Vehicles are generated in VISSIM to correspond to an arrival rate over 2 signal cycles and the results are compared to those obtained from the proposed D/D/1 model and Liu et al. model from validation Case 1.

The results indicate that the proposed D/D/1 model is better than the Liu et al. model, especially for *v/c* > 0.7. For *v/c* > 0.7, estimates from the Liu et al. model are greater than those from VISSIM and the proposed model (Figure 5.4).

The delay estimates obtained from the proposed model (Figure 5.2) were compared with VISSIM results (10-run average) in Figure 5.5. For fixed time signal control (i.e. no TSP), the proposed model results show the same trend as the VISSIM results albeit with a small shift (approximately 2 seconds/veh). For TSP control, the VISSIM estimates are comparable with estimates from the proposed model for *v/c* 0.4,0.5,0.9, and 0.925.
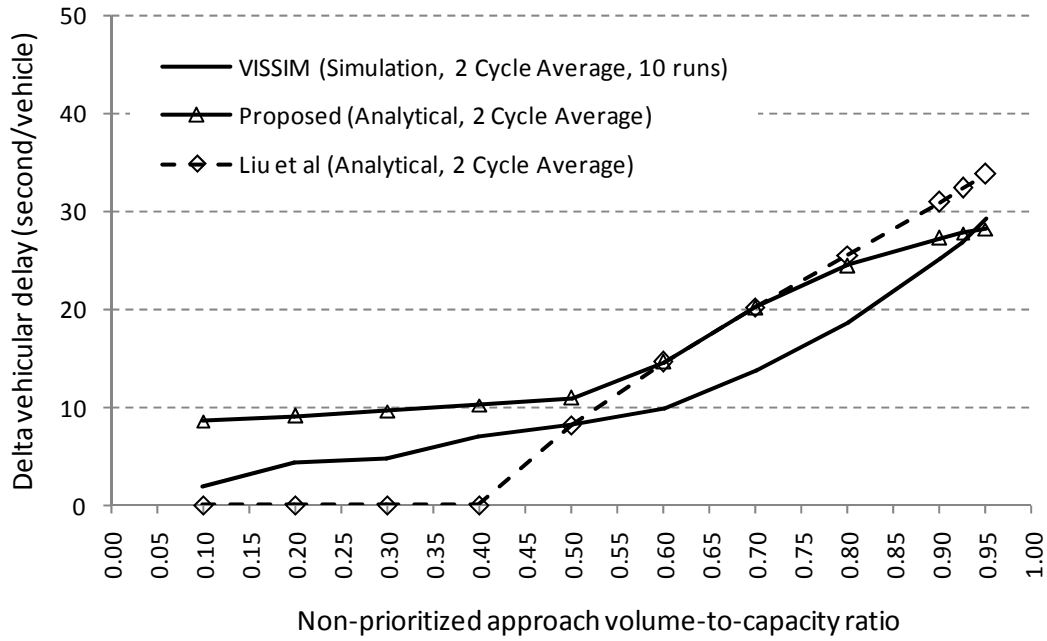
Figure 5.4: Comparison of proposed model estimates (Validation Case 2a)
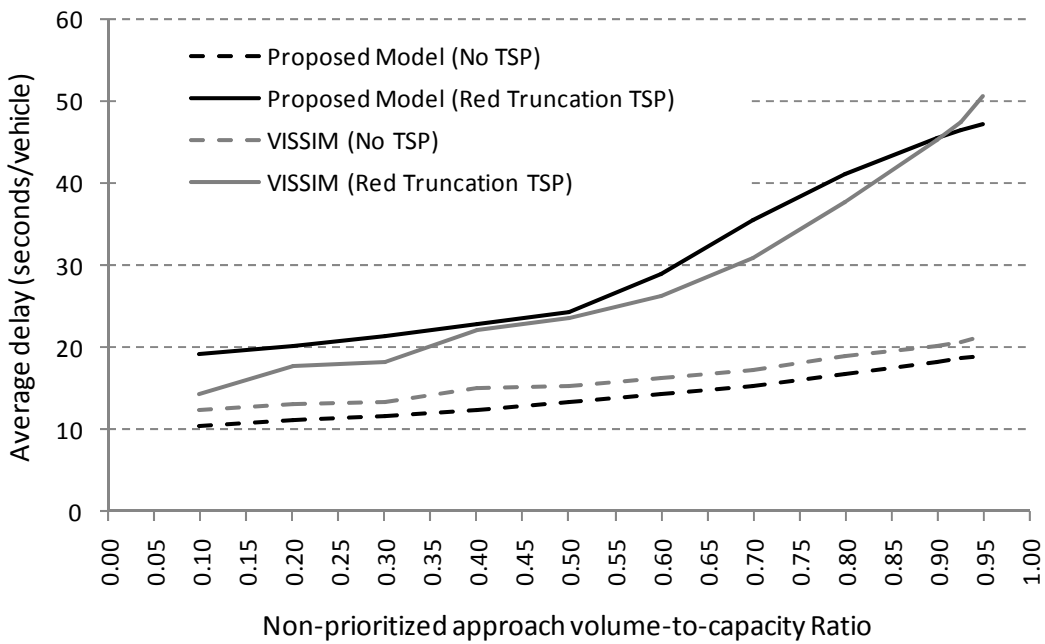
Figure 5.5: VISSIM and proposed model estimates of average delay per vehicle (validation Case 2a)

69

5.2.3 Conclusions (Validation Case 2a)

In this section, we have compared the delay estimates from the proposed D/D/1model with those from the model by Liu et al. [5] and from VISSIM for the condition that impacts are computed only over two signal cycles and impacts beyond these two cycles are ignored. The results indicate that the proposed model provides more reasonable estimates of delay than the model by Liu et al. [5] and that these estimates are quite similar to those obtained from the VISSIM model. The next section describes a comparison of the estimates of the proposed model with results obtained from VISSIM in which the impacts beyond the end of the second cycle are considered.

5.3 Validation Case 2b

This validation scenario was the same as validation Case 1a and Case 2a with one exception; the determination of delay was carried out for 11 cycles (average transit headway) instead of 2 cycles.

Figure 5.6 illustrates the results from VISSIM and from the proposed D/D/1 model for the non-prioritized and prioritized approaches. As expected, the implementation of TSP increases delays to non-prioritized approach traffic (i.e. delta delays are all positive). Increases in delay are relatively insignificant at low v/c ratios because even when the green interval for the non-prioritized approach is truncated when priority is provided to the transit vehicle, there is sufficient green time during the phase to serve the demand. However, as the v/c ratio increases, the likelihood that the implementation of TSP (via truncating the non-prioritized approach green) results in temporary oversaturation for the non-prioritized approach also increases and therefore the incremental delay due to TSP increases. The delta delay estimates from the proposed model are very similar to those obtained from VISSIM for v/c ≤ 0.7. However, for v/c > 0.7, the proposed model over-estimates the delta delay impact of TSP. It is speculated that this over-estimation is a result, at least in part, of the model assumption of deterministic arrivals. When arrivals are stochastic, then even small reductions in the arrival rate during the cycle in which TSP is granted can have a relatively large impact on the resulting delay.

Note that the average delta delays shown in Figure 5.6 were computed over 11 cycles while those in Figure 5.4 were computed over 2 cycles. Consequently, the delta delay values for high v/c ratios are higher in Figure 5.4 as the queues caused by granting TSP are not served before the end of the second cycle.
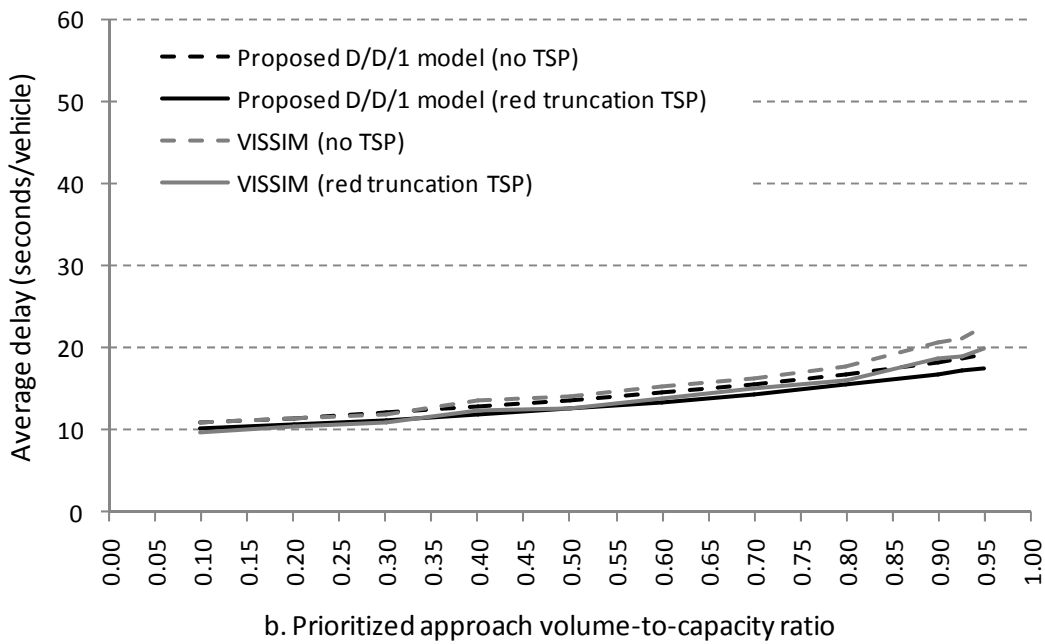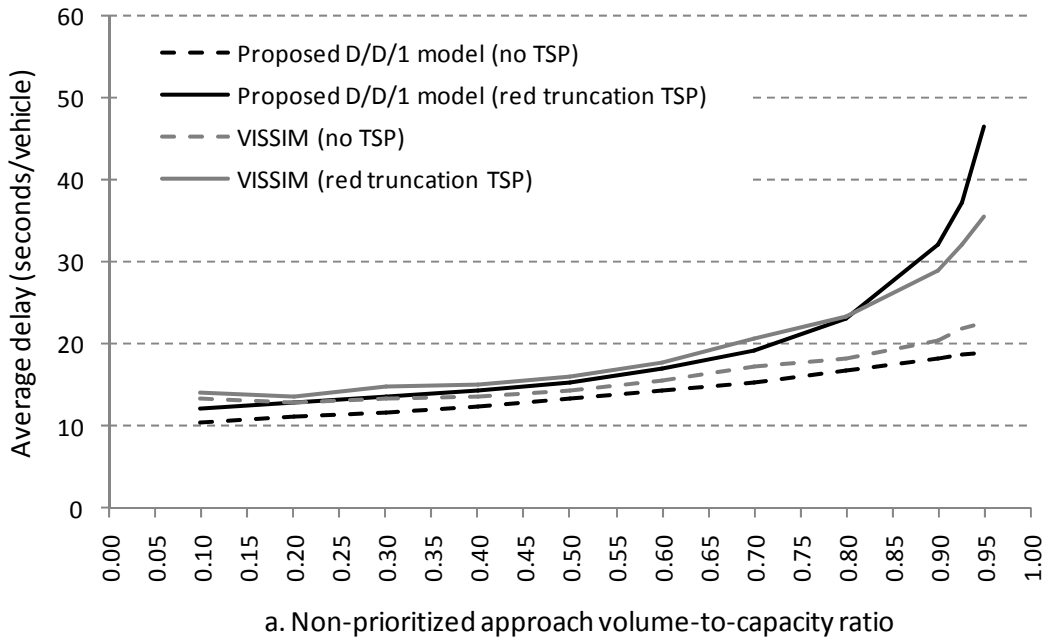
Figure 5.6: VISSIM and proposed D/D/1 model estimates of average delay per vehicle (validation Case 2b)

71

a. Non-prioritized approach volume-to-capacity ratio

b. Prioritized approach volume-to-capacity ratio
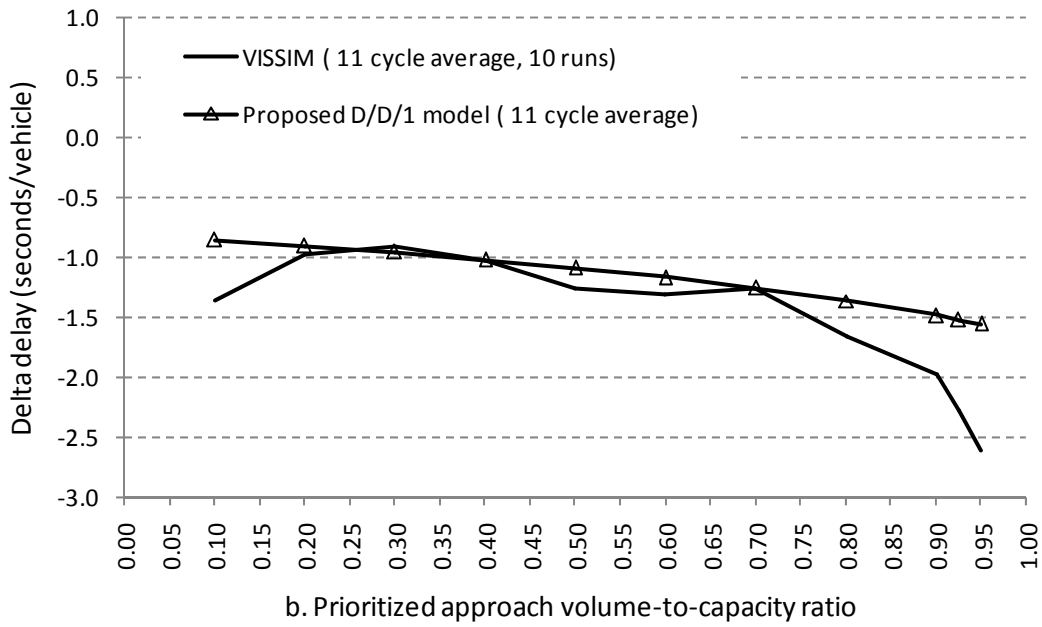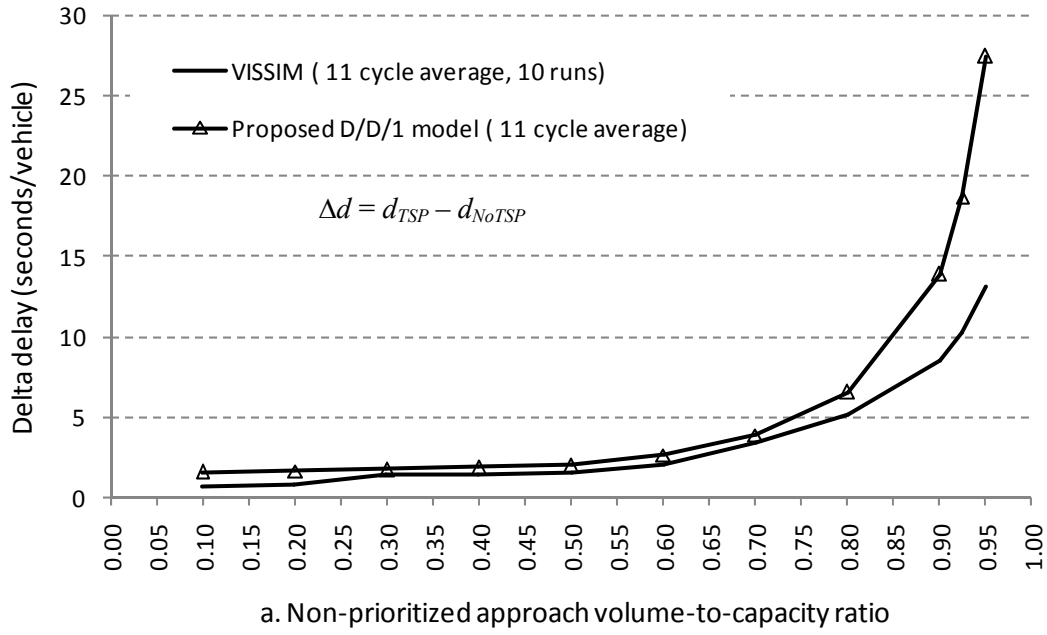
Figure 5.7: VISSIM and proposed model estimates of Delta delay per vehicle (validation Case 2b)

5.3.1 Conclusions (validation Case 2b)

In this section, we have compared the delay estimates from the proposed model with those from VISSIM for the condition that impacts are computed over eleven signal cycles (average transit headway). The results indicate that the delta delay estimates from the proposed D/D/1 model were very similar to those obtained from VISSIM for $v/c \leq 0.7$. The results were not similar for $v/c > 0.7$, and it is speculated that a model with random arrivals (stochastic) could improve the results.

5.4 Chapter Conclusions

In this chapter, the proposed D/D/1 model was validated with an analytical model in the literature and with microscopic simulation model results. The validation with the analytical model shows that the estimates are identical for $v/c = 0.6$ and $v/c = 0.7$ making Liu et al. [5] model a special case of our proposed D/D/1 model. The Liu et al. [5] model is clearly incorrect for $v/c < 0.4$. The validation with the VISSIM model shows that the proposed D/D/1 model results were very similar for low ratios ≤ 0.7, but appear to overestimate the increase in delay to vehicles on the non-prioritized approach and for $v/c \geq 0.7$ and underestimate the reduction in delays to vehicles on the prioritized approach. Consequently, in the next chapter a stochastic model is proposed.

Chapter 6

Development of an M/D/1 Analytical Model for Estimating Impacts of TSP on Vehicle Delay

6.1 Introduction

In the previous chapter, we proposed and evaluated a model based on D/D/1 queuing assumptions. However, in reality vehicles do not arrive with deterministic headway. The assumption of exponentially distributed times between the arrivals of successive vehicles (Poisson arrivals), gives a more realistic representation of flow than the assumption of (D/D/1) headways.

This leads to the adoption of an M/D/1 based model in which arrivals follow a Poisson process; service rates remain deterministic and a single server. Unfortunately, when adopting an M/D/1 model, it is no longer possible to derive analytical expression for delay as was done in the development of the proposed D/D/1 model (Chapter 4). Instead, it is necessary to evaluate delays for a specific cumulative vehicle arrive curve. The next section describes the proposed M/D/1 model.

6.2 Proposed M/D/1 Model

Unlike the D/D/1 model, the arrival stream in the M/D/1 model is stochastic. Consequently, it is necessary to generate a cumulative vehicle arrival curve that corresponds to a Poisson process. The exponential distribution is a continuous distribution and can be used to describe the distribution of time headways associated with vehicles that arrive according to a Poisson process.

$$P[T \geq t_a] = e^{-\lambda t_a} \tag{49}$$

where:

$P[T \geq t_a]$ = probability of time headway T being greater than or equal to time headway t_a

λ = average arrival rate over analysis period

t_a = time headway

The average time headway of a traffic stream with exponentially distributed headways can be obtained by:

$$\bar{t} = \frac{1}{\lambda} \tag{50}$$

The exponential distribution can be written as

$$P[T \geq t_a] = e^{-t_a/\bar{t}} \tag{51}$$

Solving equation 50 for headway t_a

$$h = -\ln(U)\bar{t} \tag{52}$$

where:

U = an independent uniform random variable between 0 and 1.0.

Figure 6.1 shows the steps for generating the cumulative vehicle arrival curve. The process is applied to each intersection lane group separately. The four steps in the process are applied for each cycle for which the arrival curve is to be generated. Each step is described in more details below:

Step 1: Estimate the total number of vehicles (N) arriving during the analysis period.

$$N = \frac{\lambda h}{60} \tag{53}$$

Because of coordination along a signalized corridor, the rate of vehicles arriving during the green interval may be higher (good progression) or lower (poor progression) than during the red interval. Therefore, it is necessary to estimate the number of vehicles that arrive at the signal during the green interval (N_g) and during the red interval (N_r).

$$N_g = \frac{P_g \lambda h}{60} \tag{54}$$

$$N_r = \frac{P_r \lambda h}{60} \tag{55}$$

$$N_r = N - N_g \tag{56}$$

Where:

λ = vehicle arrival rate (veh / hour),
h = analysis time period (minutes),
N = number of vehicles arriving during analysis period h
N_r = number of vehicles arriving during red interval during entire analysis period h
N_g = number of vehicles arriving during green interval during entire analysis period h
P_g = proportion of vehicles arriving during the green interval ($0 \leq P_g \leq 1.0$)

P_r = proportion of vehicles arriving during the red interval ($0 \le P_g \le 1.0$)

Step 2: The headways are generated using equation 52 for the green and red intervals during the entire analysis period. N_g headways are generated with an arrival rate of λ_g and N_r headways are generated with an arrival rate of λ_r. The arrival rates can be computed as:

```
┌──────────────────────────────────────┐
│   For Lane group i to Lane group N    │
└──────────────────────────────────────┘
                    │
                    ▼
        ┌──────────────────────────┐
        │   For Cycle i to Cycle N  │
        └──────────────────────────┘
                    │
                    ▼
```

Step 1

┌──┐
│ Determine number of vehicles arriving during │
│ the analysis period and during each phase   │
└──┘

Step 2

┌──┐
│   Generate N headways (h'_i; $i=1,N$)   │
│ $\lambda_g = P_g \lambda\, c/g$, $\lambda_r = P_r \lambda\, c/r$ │
└──┘

Step 3

┌──┐
│   Compute adjusted headways   │
│ $\beta = 60 P_g h/\sum h_i$, $\beta = 60 P_g h/\sum h_i$ │
│ $h_i = h'_i \beta$ │
└──┘

Step 4

┌──┐
│   Generate arrival curve based   │
│   on adjusted headways   │
└──┘
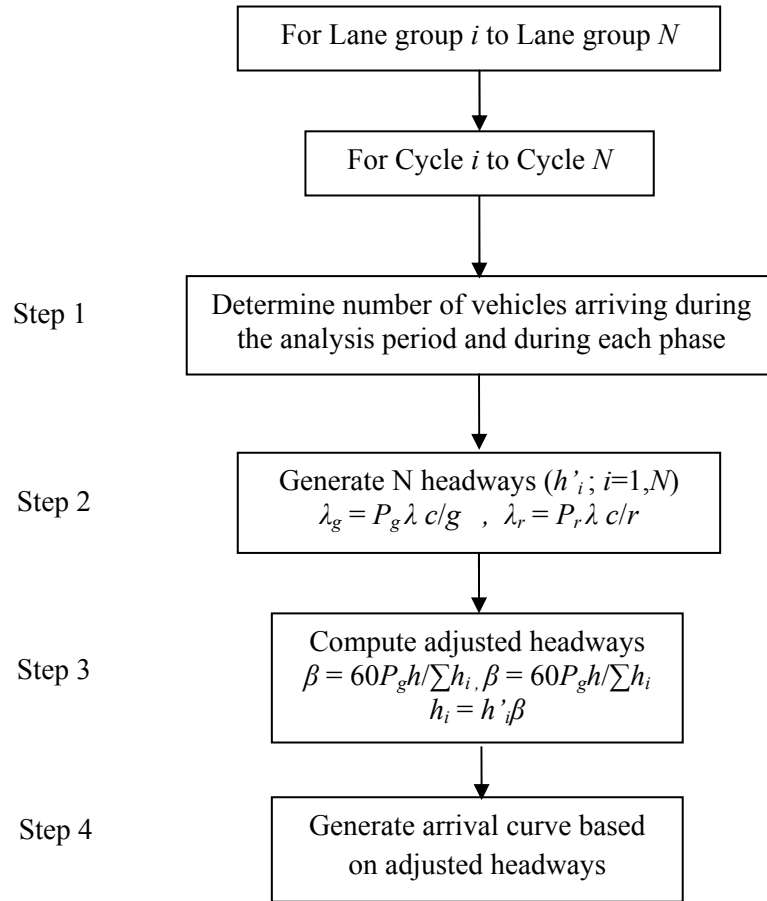
Figure 6.1: M/D/1 model for generating Poisson arrivals

$$\lambda_g = P_g \lambda \frac{C}{g} \tag{57}$$

$$\lambda_r = P_r \lambda \frac{C}{r} \tag{58}$$

Step 3: Consequently, two lists of headways are generated one for arrivals on green and the other for arrivals on red.

$$h_i' = -\ln(U_i)\frac{1}{\lambda_g}; \qquad i = 1, N_g \tag{59}$$

$$h_j' = -\ln(U_j)\frac{1}{\lambda_r}; \qquad i = 1, N_r \tag{60}$$

Headways are random variables and therefore the sum of all N headways may exceed the duration of the analysis period (i.e. h). The individual headways are adjusted to ensure the desired numbers of vehicles are generated within the analysis period. The adjustment factor is computed as:

$$\beta = \frac{60h}{\sum_{i=1}^{Ng} h_i' + \sum_{j=1}^{Nr} h_j'}; \qquad i = 1, N_r \tag{61}$$

where:

h_i' =   headways for vehicles arriving during green interval (seconds),

h_j' =   headways for vehicles arriving during red interval (seconds),

The adjusted headways are computed as:

$$h_i = h_i' \beta \qquad\qquad i = 1, N_g \tag{62}$$

$$h_j = h_j' \beta \qquad\qquad j = 1, N_r \tag{63}$$

Step 4: The arrival curve is developed by computing the arrival time of the ith vehicle

$$t_i = \sum_1^i h_k \tag{64}$$

If t_i falls into the green (or amber) interval, then the next headway is selected from the N_g list of headways (i.e. h_i). If t_i is associated with a red interval, then the next headway is selected from the N_r list of headways (i.e. h_j).

The resulting cumulative arrival curve is used instead of the deterministic curve from the D/D/1 model and delays are computed within the software tool numerically rather than using the equation developed in Chapter 4.

In the next section, the proposed M/D/1 model is validated with the VISSIM model.

6.3 Validation with VISSIM Model

The microscopic simulation model VISSIM [39] was used to validate the results from proposed M/D/1 model. The same hypothetical four legged intersection used in Chapter 4 to validate the D/D/1 model (section 5.1.1) was used to validate the proposed M/D/1 model. The intersection was evaluated for ten demand (*v/c*) scenarios ranging from *v/c* = 0.2 to *v/c* =0.95. For each scenario, the VISSIM model and the proposed M/D/1 model were run 10 times, each time with a different random number seed. The average delays from the 10 runs are depicted in Figure 6.2.

6.3.1 Prioritized Approach Vehicle Delay

The results (Figure 6.2a, Figure 6.2b) show that the ten run average delay results of the proposed M/D/1 model were quite similar to those obtained from the VISSIM microscopic simulation model for the prioritized approach when operating with and without TSP control.

As a second check delays in, the No TSP control case (Figure 6.2a) were estimated using the Highway Capacity Manual procedures [13]. The HCM results were consistently lower than the M/D/1 and VISSIM model results for low *v/c* ratios. However, for v/c $\geq$ 0.8, the HCM estimates of delay increase much more rapidly then do the VISSIM or M/D/1 model estimates. At *v/c* = 0.9 and *v/c* = 0.95 the estimates of HCM were close. The reason for this observation is that at low v/c ratio the uniform delay portion is more pronounced. The contribution of random delay is higher as *v/c* is increased.

6.3.2 Non-Prioritized Approach Vehicle Delay

Figure 6.3a and Figure 6.3b show the validation of the M/D/1 model with the VISSIM model for the non-prioritized approach. Similar to the results for the prioritized approach the models are comparable especially for low *v/c* ratios.
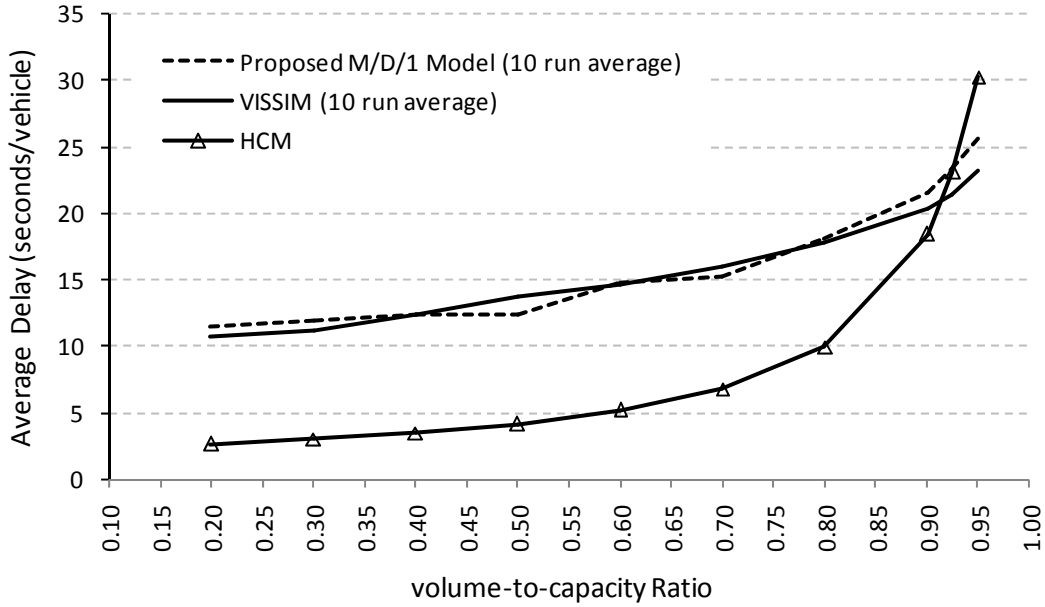
a. Fixed time (No TSP) Signal control
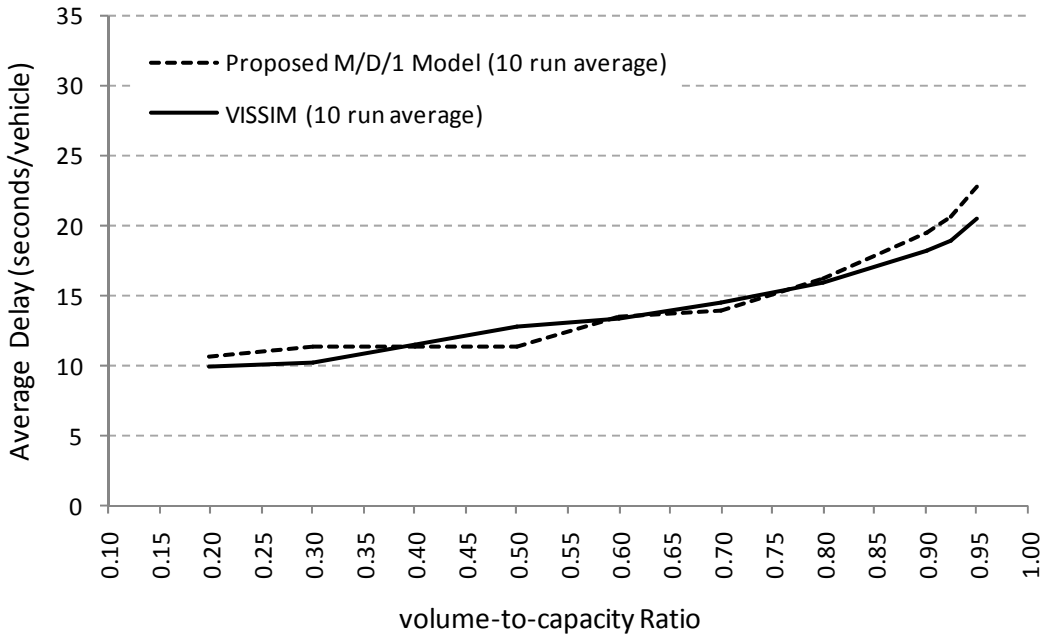
b. TSP Signal control

Figure 6.2: Vehicular Delays on Prioritized Approach (M/D/1 model validation)
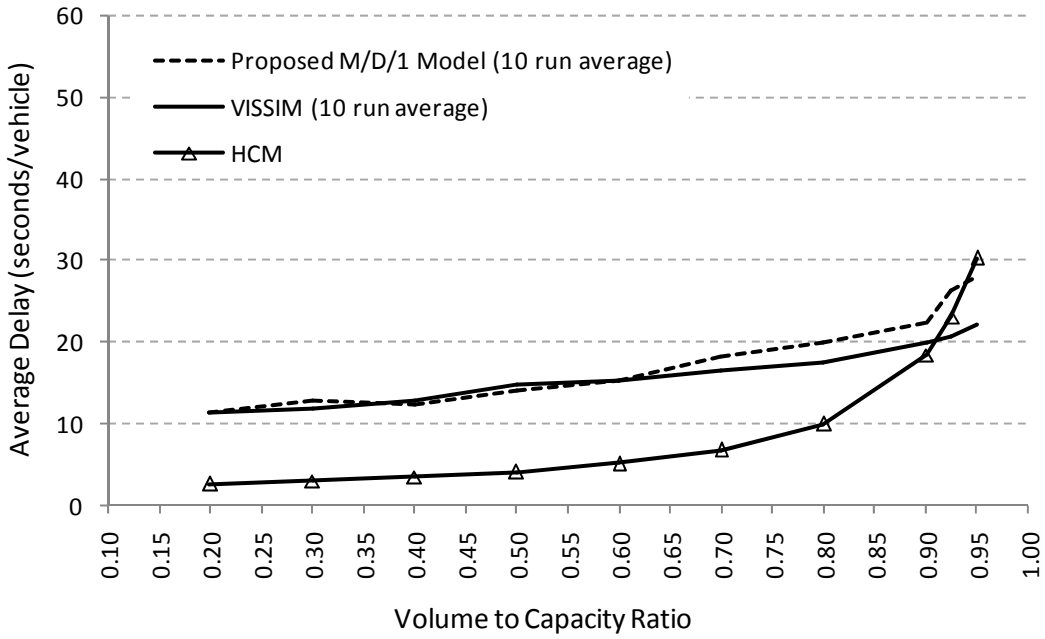
a. Fixed time (No TSP) Signal control
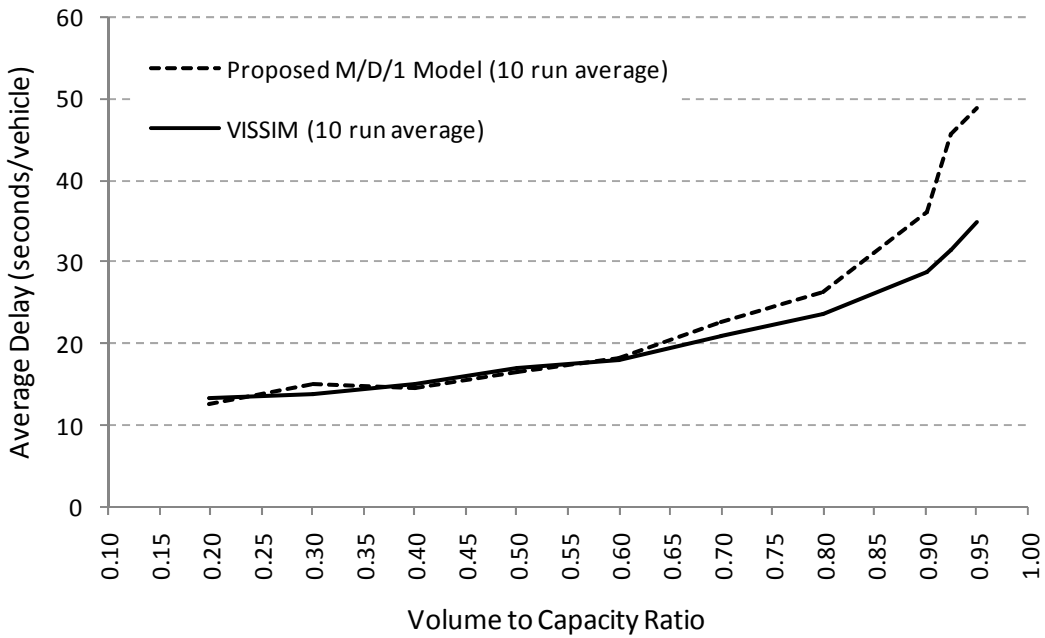
b. TSP Signal control

Figure 6.3: Vehicular Delays on Non-Prioritized Approach (M/D/1 model validation)

The M/D/1 model results show an odd discontinuity at $v/c = 0.95$. It is expected that this discontinuity result from variability in the stochastic process and would be eliminated if an average were obtained from a higher number of runs. The HCM delay estimates (No TSP) show a similar trend as was observed for the prioritized approach.

6.3.3 Delta Vehicle Delay

The delta delays obtained from the proposed M/D/1 model Δd ($d_{TSP} - d_{NoTSP}$) for the prioritized approach (Figure 6.4a) were quite similar to those obtained from the VISSIM model. The results for the non-prioritized approach (Figure 6.4b) were comparable for v/c ratios ≤ 0.8. However, for $v/c > 0.8$ the proposed M/D/1 model overestimates the delta delays for the prioritized approach.

An investigation was conducted to determine the cause for this difference. First, the individual, average (Figure 6.5a) and standard deviation (Figure 6.5b) of the delta delays were examined. From Figure 6.5b it can be observed that the standard deviation of individual delta delays from M/D/1 model is consistently larger than from VISSIM.

It was speculated that the variability of the VISSIM might be influenced by input parameter values. Consequently, in next section, we investigate the impact of various VISSIM input parameters on the average and standard deviation of delta delays.

6.4 Identification of Causes for Differences

6.4.1 VISSIM Input Parameters

An investigation was conducted to examine the impact that various VISSIM input parameters have on the resulting delta delays. The following input parameters were investigated:

- Desired speed distribution

- Acceleration and Deceleration profiles

- Start-up lost time due to driver perception reason times

- Link length

In each case, the input parameter value was varied while keeping all other model inputs unchanged. The model was run for the validation intersection for $v/c = 0.90$.
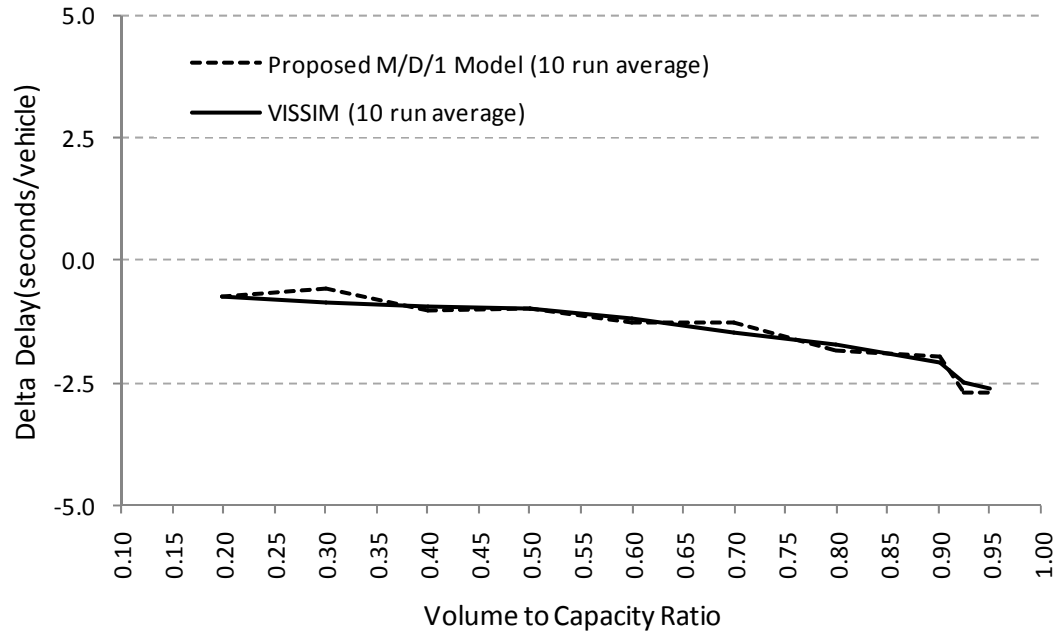
a. Prioritized Approach
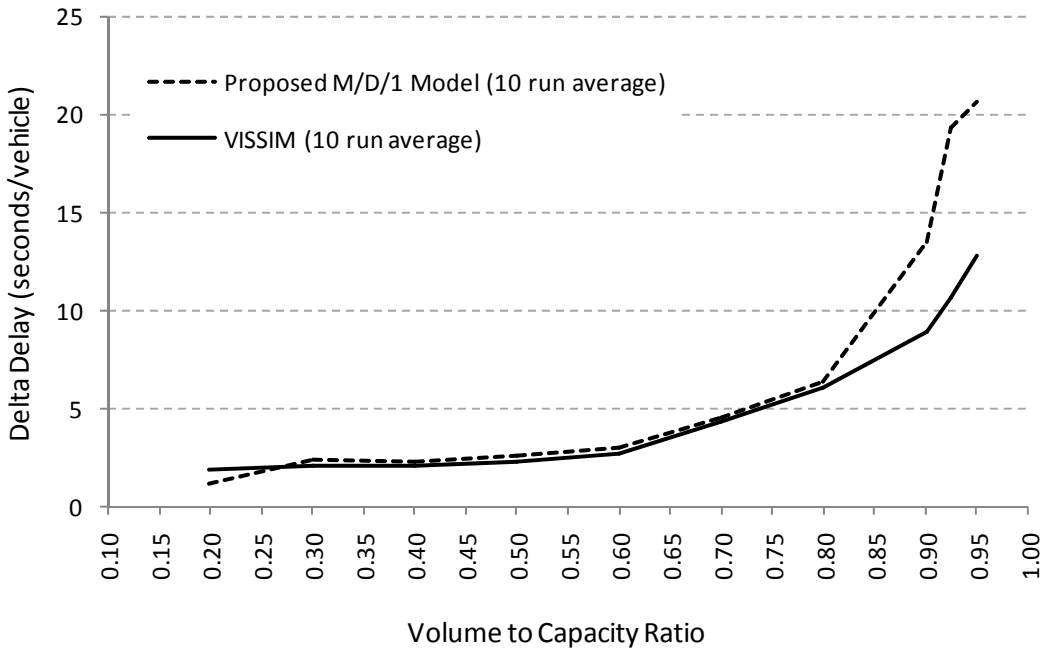
b. Non-Prioritized Approach

Figure 6.4: Delta Delays (M/D/1 model validation)

82
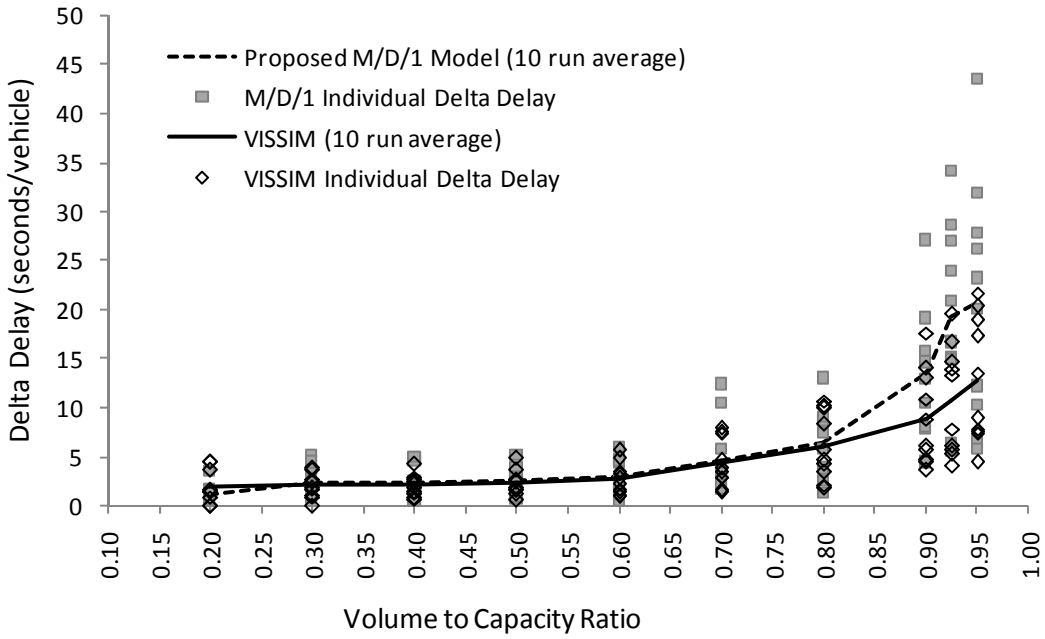
a. Individual and Average
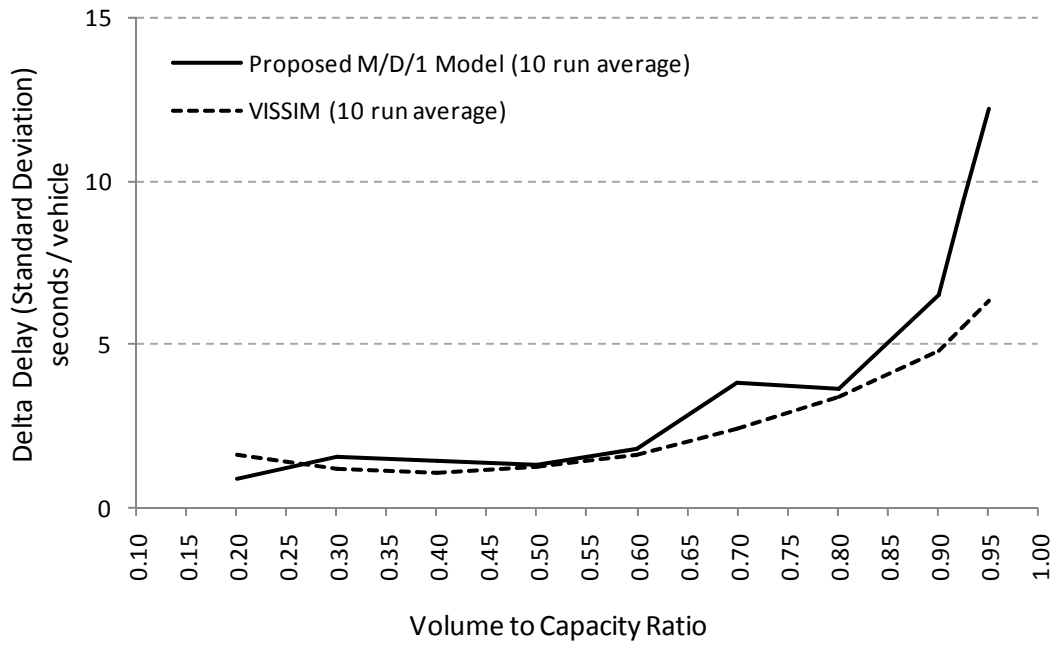
b. Standard Deviation

Figure 6.5: Statistics for Non-Prioritized Approach Delta Vehicular Delays

For all cases examined, the influence of the input parameter values was negligible and could not explain the discrepancies between the VISSIM results and the M/D/1 model results as exhibited in Figure 6.3b.

6.4.2 VISSIM Saturation Flow Rate

In the course of the investigations described in the previous section, it was observed that delta delay is quite sensitive to variation in the arrival curve. Consider Figure 6.6 that shows the cumulative arrival and departure curves from the M/D/1 model for two random runs.

In this example, the $v/c = 0.9$ TSP case is considered on the non-prioritized approach. The bus was modeled to arrive exactly at 15 seconds into the 40 seconds of non-prioritized approach green interval. The total number of vehicles were 198 ($g/C = 40/80$, saturation flow rate = 1800 pcphpl, interval time = 880 seconds).

The first run (Figure 6.6 a) shows a lower than average arrival rate in the initial cycles which results in an earlier dissipation of the queue. Average vehicle delay over the 11 cycles (880 seconds) is 30.4 sec/veh. The second run (Figure 6.6 b) exhibits a higher than average arrival rate in the first few cycles. As a result, the oversaturation queue does not dissipate until the 9th cycle. Average delay is 54.1 sec/veh.

An investigation was conducted to compare the arrival curves generated by VISSIM with those generated by the M/D/1 model. No differences in the arrival curve characteristics were found. As a result, attention focused on the departure curves. The cumulative arrival and departure curves were extracted from a VISSIM run (seed = 600). The arrival curve was used as input to the M/D/1 model, instead of randomly generating an arrival curve as per section 6.2. Figure 6.7 shows the arrival curve (the same was used for both VISSIM and M/D/1), M/D/1 departure curve, and VISSIM departure curve.

Several observations can be made:

- The VISSIM and M/D/1 departure curves are substantially different.

- The VISSIM saturation flow rate appears to vary from cycle to cycle. The variation in saturation flow rate appears to result in an increase in the saturation flow rate when the cycle is over-saturated.

Vehicular Delay = 30.4 sec /veh

a) M/D/1 run 1

Vehicular Delay = 54.1 sec /veh
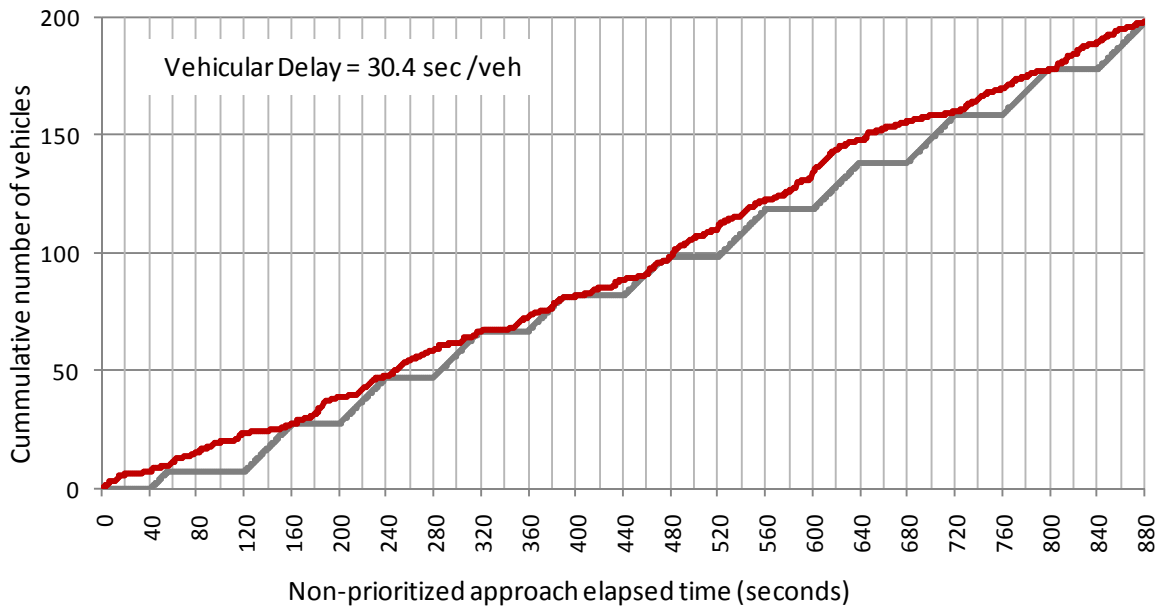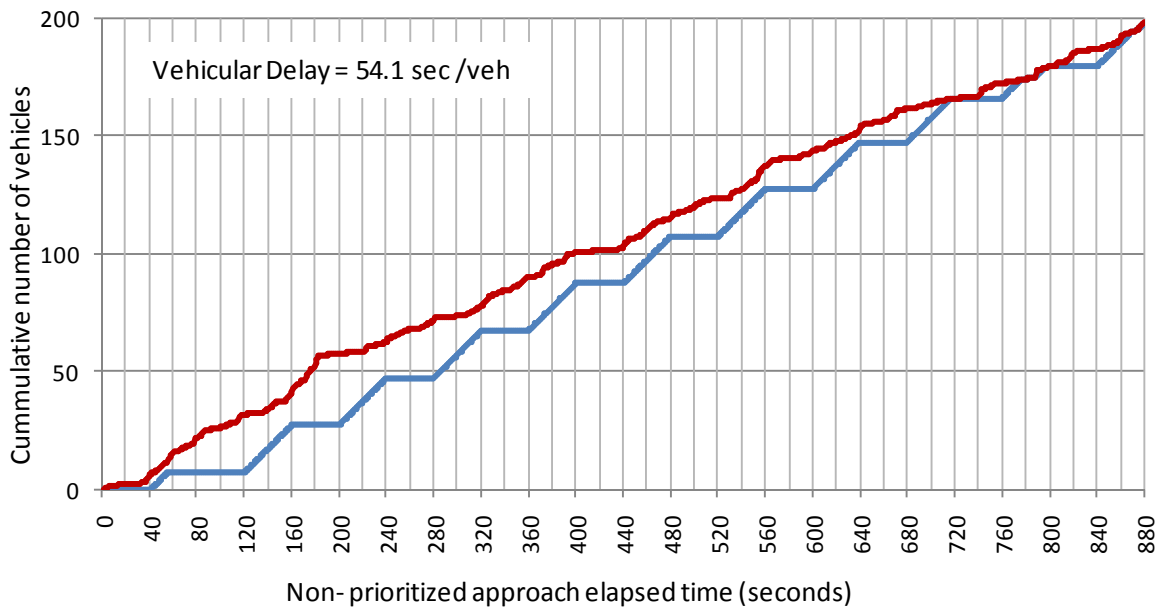
b) M/D/1 run 2

Figure 6.6: M/D/1 Arrival and Departure Patterns

The VISSIM cycle-by-cycle saturation flow rate can be obtained by estimating the number of vehicles that departed in a given cycle and available green time. Table 6.1 show the cycle-by-cycle saturation flow rate for VISSIM and M/D/1 departures. It is clear from the results that

- The saturation flow rate exhibited by VISSIM results in the dissipation of the oversaturated queue by the 4th cycle. The queue is not dissipated in the M/D/1 model until the 11th cycle.

- The average delay estimated by the M/D/1 model was 54.2 sec/veh substantially higher than the delay estimated by the VISSIM model (31.6 sec/veh).

- The VISSIM SFR has a high variation with respect to M/D/1 SFR especially for those cycles that are over saturated i.e. cycle 1, 2 and 3. These cycles are highlight by grey shade in Table 6.1

- At the end of cycle 4 (Time 320 seconds) the queue has dissipated, the saturation flow rate goes down to 1800 pcphpl

- Interestingly, in cycle 6 the saturation flow rate went to 2070 pcphpl while when we look at the cycle 6 (time 400 – 460) there is no residual queue concluding that there is no over saturation in cycle 6. Despite this fact, the saturation flow rate is as large as 2070 pcphpl.

From these observations, we found that

- VISSIM saturation flow rate increased for cycles that were over saturated. It is expected, as there is decreased opportunity for drivers there is an increase in driver aggressiveness. Although this aggressiveness is not tested, it is expected as the driver behaviour parameters are altered there is corresponding influence on driver response to decreased opportunities to clear the intersection.

- It is not clear why VISSIM flow rates fluctuate in cycle 6 when there is no residual queue.

These results suggest that the saturation flow rate within the VISSIM model is not constant and may increase under over saturated flow conditions. This explains the lower delays obtained from VISSIM for high *v/c* ratios as shown in Figure 6.2 and Figure 6.3.
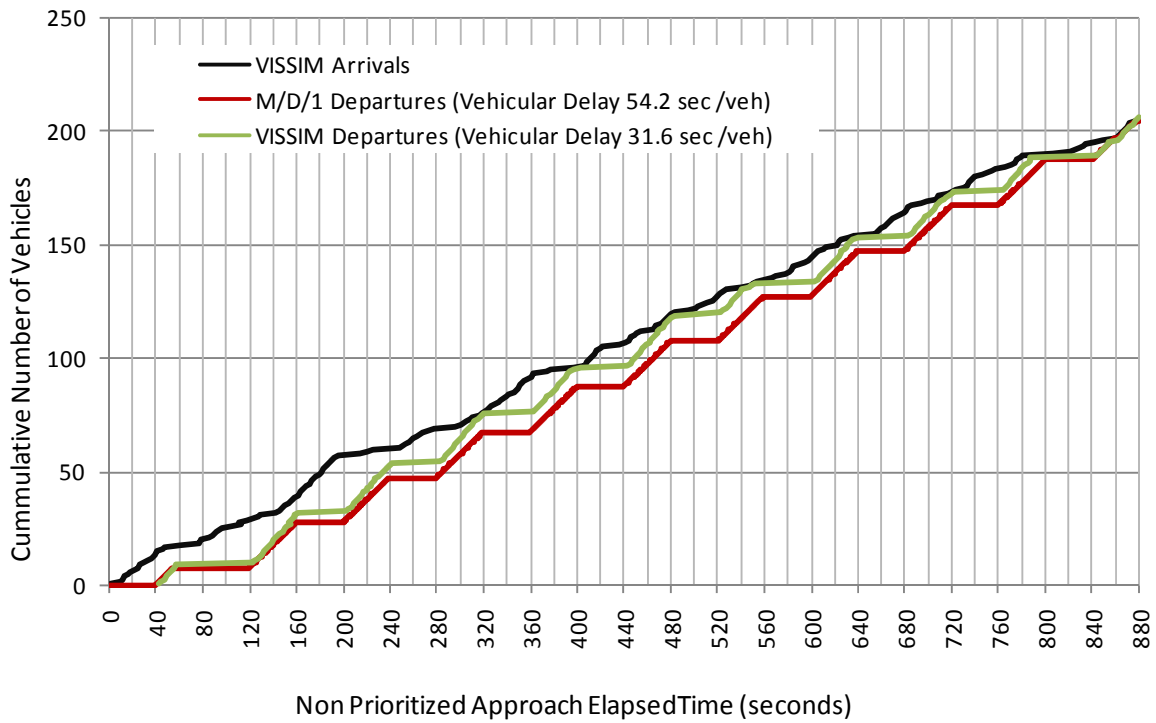
Figure 6.7: Comparison of VISSIM and M/D/1 Departure Patterns

Table 6.1: Cycle-by-Cycle Service Rates

Cycle	Non-prioritized approach		Vehicles served in cycle		Average service rate	
	Cycle end time	Green time	VISSIM	M/D/1	VISSIM	M/D/1
	seconds	seconds	vps	vps	vph	Vph
1	55	15	9	7.5	2160	1800
2	160	40	23	20	2070	1800
3	240	40	22	20	1980	1800
4	320	40	22	20	1980	1800
5	400	40	20	20	1800	1800
6	480	40	23	20	2070	1800
7	560	40	14	20	1260	1800
8	640	40	20	20	1800	1800
9	720	40	20	20	1800	1800
10	800	40	15	20	1350	1800
11	880	40	18	17	1620	1534

However, no conclusions can be made about the validity of this variation. No attempt has been made to collect empirical data to characterize driver behaviour. Furthermore, the underlying source of variation of saturation flow rate in the VISSIM model is unknown.

6.5 Comparison of M/D/1 and D/D/1 models

Figure 6.8 shows the delta delays estimates obtained from the D/D/1, M/D/1, and VISSIM model for the hypothesized validation intersection. From these results, it can be observed that:

- The Delta delay results (change in delay due to TSP compared to no TSP) were quite similar for the D/D/1 and M/D/1 model. The M/D/1 model provides results that are marginally more similar to the VISSIM results for *v/c* greater than approximately 0.8.

- However, due to the stochastic nature the of the M/D/1 model, this model requires much higher computing times than the D/D/1 model and consequently it is concluded that the proposed D/D/1 model is suitable for practical use. The next chapter describes in detail the application of the D/D/1 model to an actual intersection.
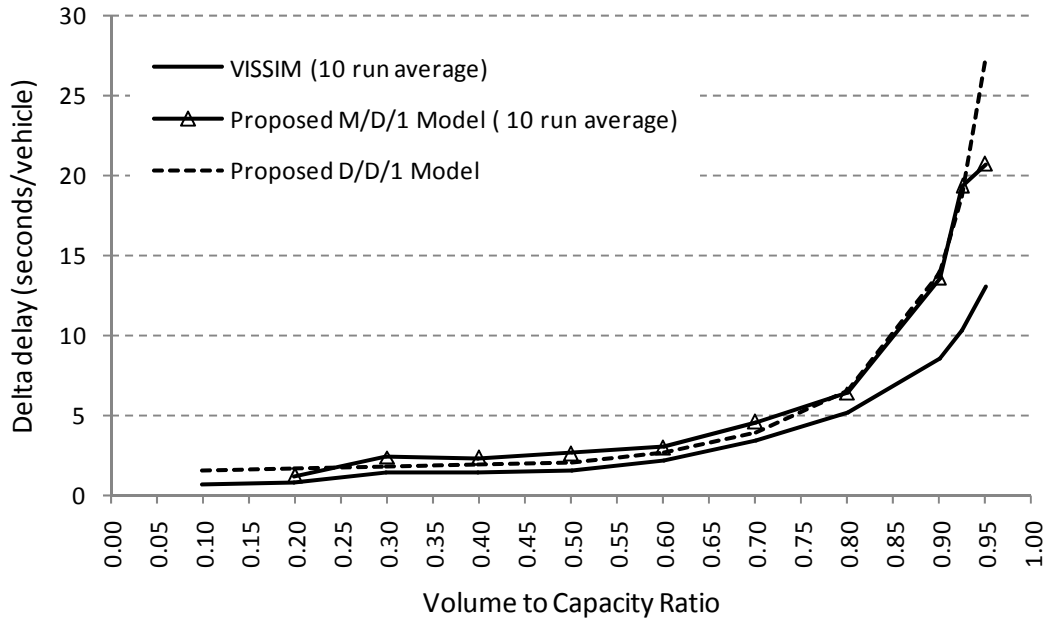
a. Non-Prioritized Approach
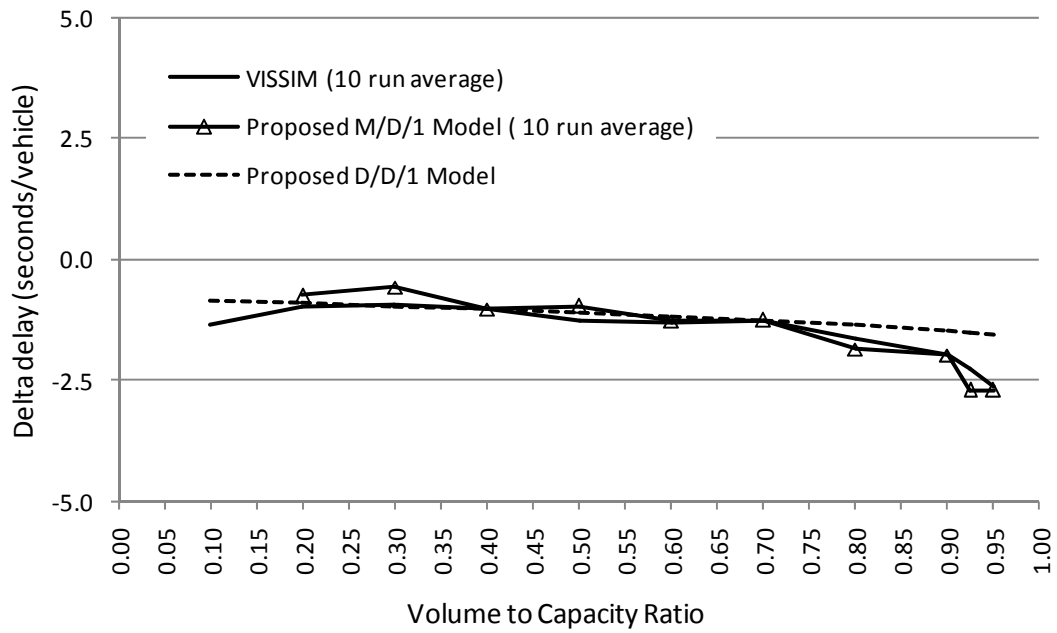
b. Prioritized Approach

Figure 6.8: Comparison of MD1 and DD1 Model

Chapter 7

Detailed Model Application

The usefulness of the proposed model for Transit Signal Priority pre deployment analysis relies on its applicability to wide range of geometric and traffic attributes. The model must be able to provide quantifiable measures of performance with respect to changes in influencing factors.

In this chapter, the proposed model is applied to a typical intersection in the Region of Waterloo. Chapter 8 describes a sensitivity analysis of the D/D/1 model. Chapter 9 presents the results of the application of the D/D/1 model to 16 signalized intersections along an express bus route in the Region of Waterloo. TSP performance is measured in terms of changes in delay, GHG emissions, fuel consumption, and variability of bus delay.

7.1 Description of Intersection

The intersection geometry of King Street at Union Street is depicted in Figure 7.1. King Street runs in the north bound/south bound direction, and Union Street runs in the east bound/west bound direction. The express bus route (iXpress) runs along King Street and therefore the northbound and southbound approaches are prioritized.
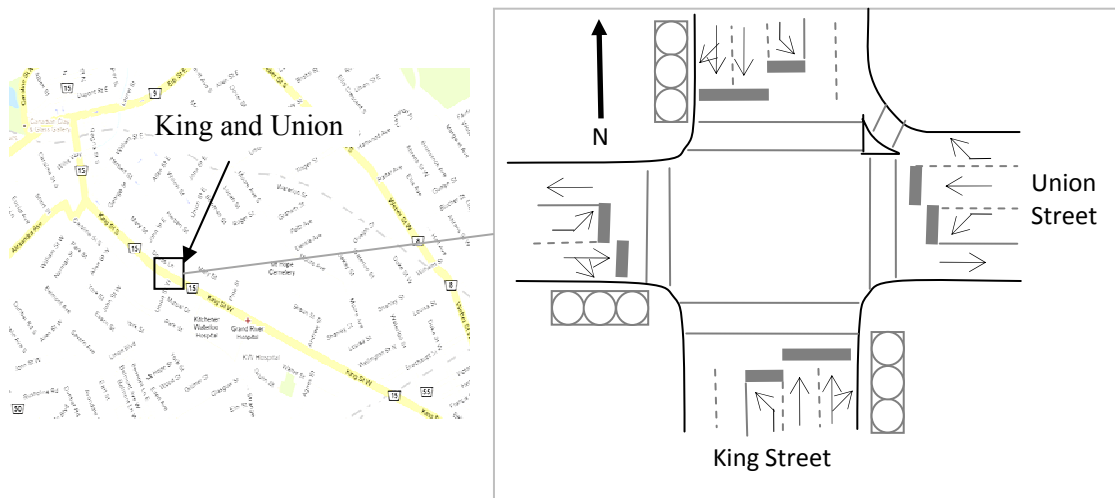
Figure 7.1: Intersection Geometry (Google maps)

The King and Union intersection operates on fixed time signal control with actuated left turn arrow operation on King Street north/south. The signal timing parameters were obtained from the traffic signal control group at the Region of Waterloo for the pm peak period. The timings are in effect from 1400 to 1900 hours from Monday to Friday. The detailed signal timing parameters at King Street and Union Street are depicted in Table 7.1.

Table 7.1: Signal Timing Parameters (King at Union)

Phase 1		Phase 2		Phase 3	
King Street (N-S Green Arrow)		King Street		Union Street	
	seconds		seconds		Seconds
Min	5.0	Green	32.0	Green	33.0
Ext	3.0	Amber	4.0	Amber	4.0
Max	12.0	All Red	2.0	All Red	2.0
All Red	1.0				
Total	Min = 6 Max = 13		Min = 38 Max = 51		39
		Walk	23.0	Walk	20.0
		FDW	9.0	FDW[1]	13.0
Cycle Length = 90 seconds					

[1] FDW = Flashing Don't Walk (pedestrian clearance time)

The pedestrian clearance times are preserved during the priority call. Therefore, there is (33-13) = 20 seconds of green time available on Union Street that can be truncated without reducing the pedestrian FDW time. Therefore, a maximum of 20 seconds can be reduced from Union Street during the green extension or red truncation. An aggressive green extension could have a maximum g_{ext} of 20 seconds. It is expected that a lower value of g_{ext} would result in smaller reductions to the non-prioritized approach green time, and therefore is less disruptive to the non-prioritized approach. For this application, the transit signal priority green extension g_{ext} was set to a maximum of 14 seconds to signify a less aggressive application.

Similarly, the Red Truncation TSP can reduce to a maximum of 14 seconds, i.e. the red truncation time g_{tr} was also set to 14 seconds.

Table 7.2 shows the saturation flow rate used for all lanes at King Street and Union Street. The saturation flow rate for the through lane is 1900 vphpl. The HCM [13] specifies a procedure to estimate the saturation flow rate for a specific lane configuration. A right turn lane saturation flow

rate would be impacted by the storage space. However, in the analysis we have assumed that there is no impact of this factor on the right lane, and therefore have used a saturation flow rate of 1900 vphpl for the shared right lane. In the analysis, an arrival and departure curve is created for each lane separately.

Table 7.2: Saturation Flow Rate (King at Union)

Street	Approach	Lane	Lane Configuration	Saturation Flow Rate
Union Street	East bound	1	Exclusive Left	449
		2	Shared Through + Right	1900
		-	-	-
	West bound	1	Exclusive Left	246
		2	Exclusive Through	1900
		3	Exclusive Right	1900
King Street	North bound	1	Exclusive Left	1805
		2	Exclusive Through	1900
		3	Shared Through + Right	1900
	South Bound	1	Exclusive Left	1805
		2	Exclusive Through	1900
		3	Shared Through + Right	1900

The intersection has an average annual daily traffic of 31,886 [47]. The turning movement counts for the PM peak hour are depicted in Table 7.3.

Table 7.3: Turning Movement Counts (King at Union, PM Peak hour 16:30-17:30)

	Approach	Volume (vph)			Approach Total (vph)
		Left	Through	Right	
Union Street	East Bound	194	559	50	803
	West Bound	69	511	106	686
King Street	**North Bound**	50	673	99	**822**
	South Bound	116	626	124	866

On the northbound and southbound approaches, the through traffic can use two lanes. One is an exclusive through lane and the other is a shared through and right turn lane. A portion of the through traffic uses the right lane and the remainder uses the exclusive through lane. These portions (lane volumes) must be determined for lane-by-lane analysis. In this analysis the lane volumes for

South bound and North bound shared through and right are calculated using the Canadian Capacity guide procedure for shared lane analysis [36] (Table 7.4) . Therefore, the northbound traffic of (673 through + 99 right turn) is divided so that 386 vph use the exclusive through lane and 375 vph (287 through + 99 right turn) use the shared lane. On the south bound approach 386 vph use the exclusive through lane and 375 (251 through + 124 right turn) use the shared lane. Allocation of flows to lanes is not required for the other movements, because they use an exclusive lane or share a single lane.

Table 7.4: Allocation of Flows to Lanes Using the Canadian Capacity Guide Procedure

Street	Approach	Exclusive left	Exclusive Through	Exclusive Right	Shared Right + Through	Total Volume
		vph	vph	vph	vph	vph
Union Street	East Bound	194	559	-	50	**803**
	West Bound	69	511	106	-	**686**
King Street	**North Bound**	50	**386**	-	375	**822**
	South Bound	116	386	-	375	**866**

7.1.1 Generation of Demand Scenarios

Day to day variation in peak hour demand was found to be normally distributed with a coefficient of variation of 0.087 (Chapter 3). This variation in demand is captured by evaluating TSP performance for five demand scenarios. The probabilities associated with each demand scenario were calculated using the probability density function of the normal distribution as follows:

$$f\left(x;\mu,\sigma^2\right) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}, \quad -\infty < x < \infty \tag{65}$$

Where:

μ =   mean of random variable x $(-\infty < \mu < \infty)$,

σ =   Standard deviation of random variable x

The diagram shows a bell curve (normal distribution) with the following annotations:

$P[\bar{x} - 0.5\sigma \leq x \leq \bar{x} + 0.5\sigma]$

$= 0.3829$

$P[\bar{x} + 1.5\sigma \leq x \leq \bar{x} + 0.5\sigma]$

$= 0.2417$

$P[\bar{x} - 1.5\sigma \leq x \leq \bar{x} - 0.5\sigma]$

$= 0.2417$

$P[x \leq \bar{x} - 1.5\sigma]$

$= 0.0668$

$P[x \geq \bar{x} + 1.5\sigma]$

$= 0.0668$

$\bar{x} - 1.5\sigma \qquad \bar{x} - 0.5\sigma \qquad \bar{x} + 0.5\sigma \qquad \bar{x} + 1.5\sigma$

$\bar{x} - 2\sigma \qquad \bar{x} - \sigma \qquad \bar{x} \qquad \bar{x} + \sigma \qquad \bar{x} + 2\sigma$

$P[\bar{x} - \sigma \leq x \leq \bar{x} + \sigma] = 0.68$
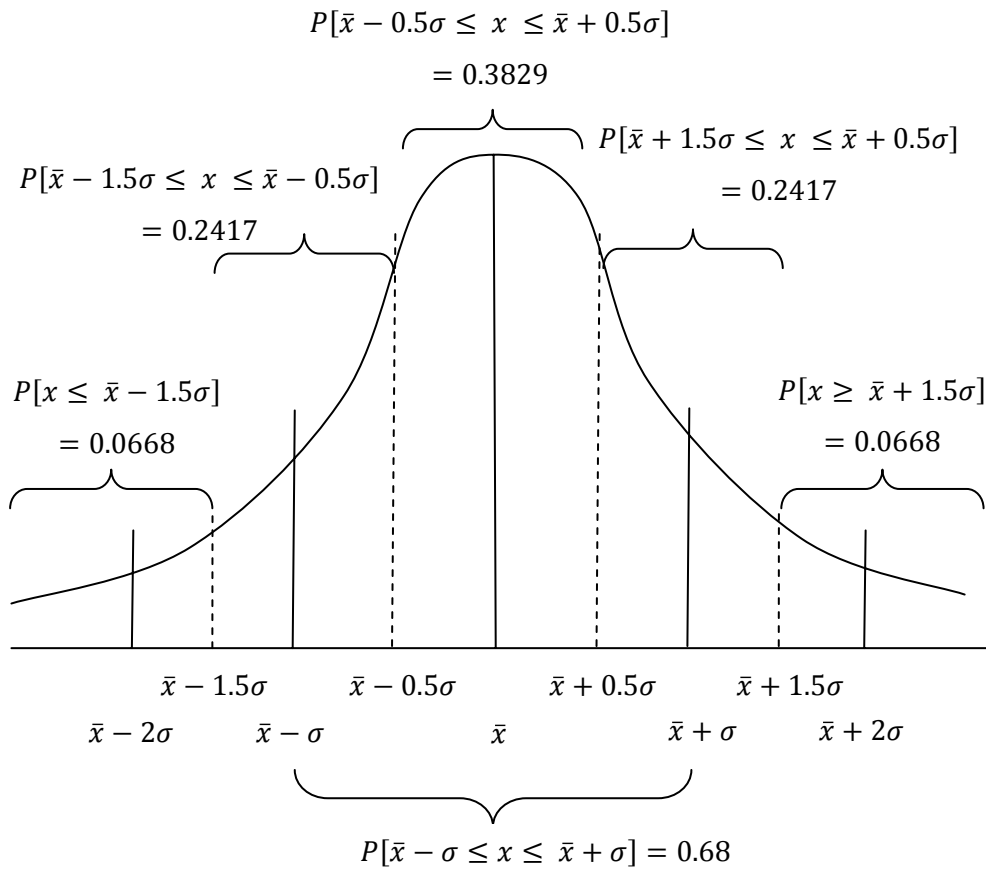
Figure 7.2: Demand Scenario probabilities

The five demand scenarios correspond to the mean peak hour volume $(\bar{x})$; $(\bar{x} \pm 1\sigma)$; and $(\bar{x} \pm 2\sigma)$. The probabilities of each demand occurring is illustrated in Figure 7.2 and summarized in Table 7.5.

Table 7.5: Probabilities of Five Demand Scenarios

Demand Scenario	PHV variability	Probability
1	$P[x \leq \bar{x} - 1.5\sigma]$	6.7%
2	$P[\bar{x} - 1.5\sigma \leq x \leq \bar{x} - 0.5\sigma]$	24.2%
3	$P[\bar{x} - 0.5\sigma \leq x \leq \bar{x} + 0.5\sigma]$	38.3%
4	$P[\bar{x} + 1.5\sigma \leq x \leq \bar{x} + 1.5\sigma]$	24.2%
5	$P[x \geq \bar{x} + 1.5\sigma]$	6.7%

For each intersection, the average turning movement volume observed in the field was assumed to be the average PHV ($\bar{x}$). Using the results ($COV = 0.087$) from Chapter 3, turning movement volumes for each of the five demand scenarios were calculated (Table 7.6).

Table 7.6: PHV Turning Movement Volumes for Five Demand Scenarios (King at Union)

Demand Scenario	Union Street (vph)		King Street (vph)	
	EB	WB	NB	SB
1	664	567	680	716
2	734	627	751	791
3	**803**	**686**	**822**	**866**
4	872	745	893	941
5	942	805	964	1016

7.3 Application Assuming Two Phase Operation

The equations developed in Chapter 4 assume the intersection is operating under a two phase fixed time signal timing plan. Consequently, we begin the analysis of this intersection by assuming the actuated protected left turn phase, (i.e. phase 1) is not triggered, and the signal timing is represented as a simple two-phase plan.

Figure 7.3 illustrates the cumulative arrival and departure curves for the exclusive NB through lane resulting from the application of the proposed D/D/1 models for demand scenarios operating with no TSP.
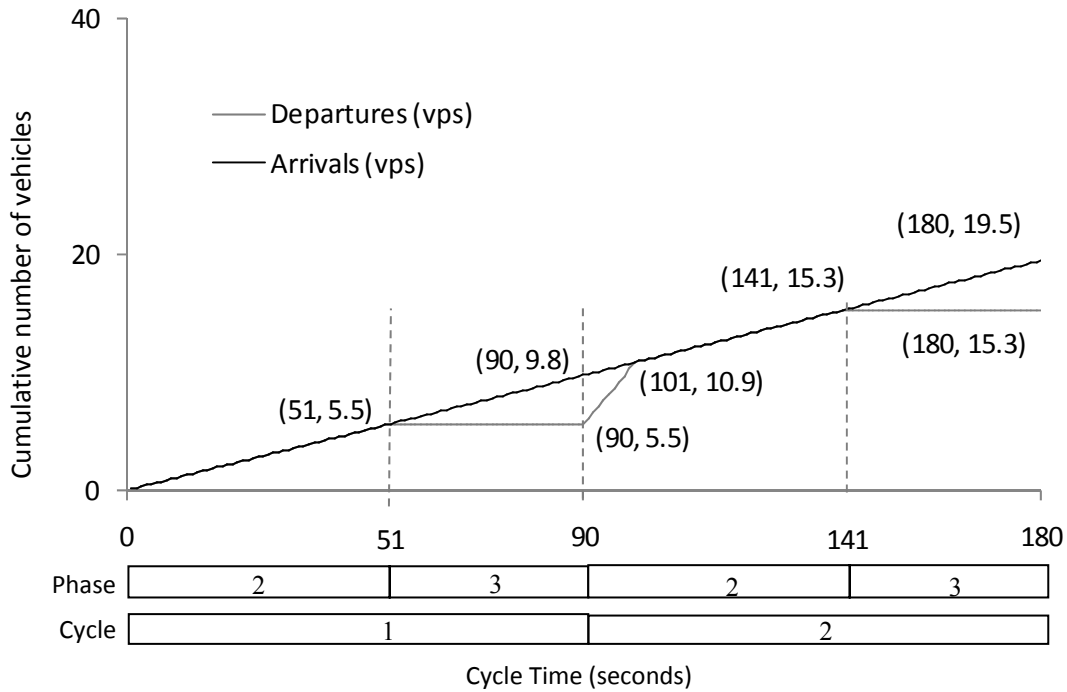
Figure 7.3: Total Delay Computation for No TSP on King Street

The total delay in cycle 1 (i.e. the area between the arrival and departure curves) is computed as $(0.5 \times (90-51) \times (10.90-5.58)) = 103.7$ seconds.

The delay can also be obtained using modified equation 14 as

$$D^p_{NoTSP} = 0.5 \frac{\lambda_p r_p^{\ 2}}{1-\rho_p}$$ (66)

Where:

λ_p =   North Bound 390 vph (0.1084 vps)

μ_p =   Saturation flow rate of 1900 vphpl, (0.5277 vpspl)

ρ_p = λ_p / μ_p = (0.205)

r_p =   39 seconds.

$$D_{no\ TSP} = \frac{0.5(0.108)(39)^2}{(1-0.205)} = 103.7 \text{ seconds}$$

These results show that the results obtained by equation 14 are identical to those obtained from the TSP evaluation tool. Analysis of the other lanes also confirms that the TSP evaluation tool

96

provides the same estimates of delay (for both TSP and no TSP operations) as do the equations developed in Chapter 4. In the next section, we apply the TSP evaluation tool to the intersection but with phase 1 (N-S green arrow).

7.4 Application Assuming Three Phase Operation

We now use the TSP evaluation tool to evaluate the impact of TSP at the King and Union intersection assuming a three-phase signal-timing plan. During the peak hour, we assume the actuated protected left turn phase (phase 1) is regularly extended to its maximum green time and therefore the signal timing is modeled as:

Phase 1 (Green time = 12s, All Red time = 1s)

Phase 2 (Green time = 32s, Amber time = 4s, All Red time = 2s)

Phase 3 (Green time = 33s, Amber time = 4s, All Red time = 2s)

Figure 7.4 depicts the cumulative arrive and departure curves for the exclusive NB through lane for demand scenario 3 operating under no TSP control.

A phase-by-phase delay is also depicted in Table 7.7. There are 40 cycles in an hour for a 90 seconds cycle length (3600 / 90 = 40).

Cycle 1

- Delay in phase 1 in cycle 1 = (0.5 x 13 x 1.4) = 9.2 seconds

- Delay in phase 2 in cycle 1 = 0.5 x (16-13) x (1.8-1.4) = 2.4 seconds

- Delay in phase 3 in cycle 1 = 0.5 x (90-51) x (9.8-5.5) = 82.4 seconds

- Total for cycle = 94.0 seconds

Cycle 2

- Delay in phase 1 in cycle 2 = 0.5 x (103-90) x [(9.8-5.5)+(11.1-5.5)] = 64.1 seconds

- Delay in phase 2 in cycle 2 = 0.5 x (116-103) x (12.7-5.5) = 37.9 seconds

- Delay in phase 3 in cycle 2 = 0.5 x (180-141) x (19.5-15.3) = 82.4 seconds

- Total for cycle = 184.4 seconds

Table 7.7: Total Delay Computation Assuming Maximum Phase 1 Times on King Street (no TSP, NB, through lane, phase by phase)

Cycle	Phase	Geometric Figure	Cycle Time	Departures	Arrivals	Total Phase Delay	Total Cycle Delay
			sec	vps	vps	sec	sec
1	1		13	0.0	1.4	9.2	94.0
	2		16	1.8	1.8	2.4	
	3		90	5.5	9.8	82.4	
2	1		103	5.5	11.2	64.1	184.4
	2		116	12.6	12.6	37.9	
	3		180	15.3	19.5	82.4	
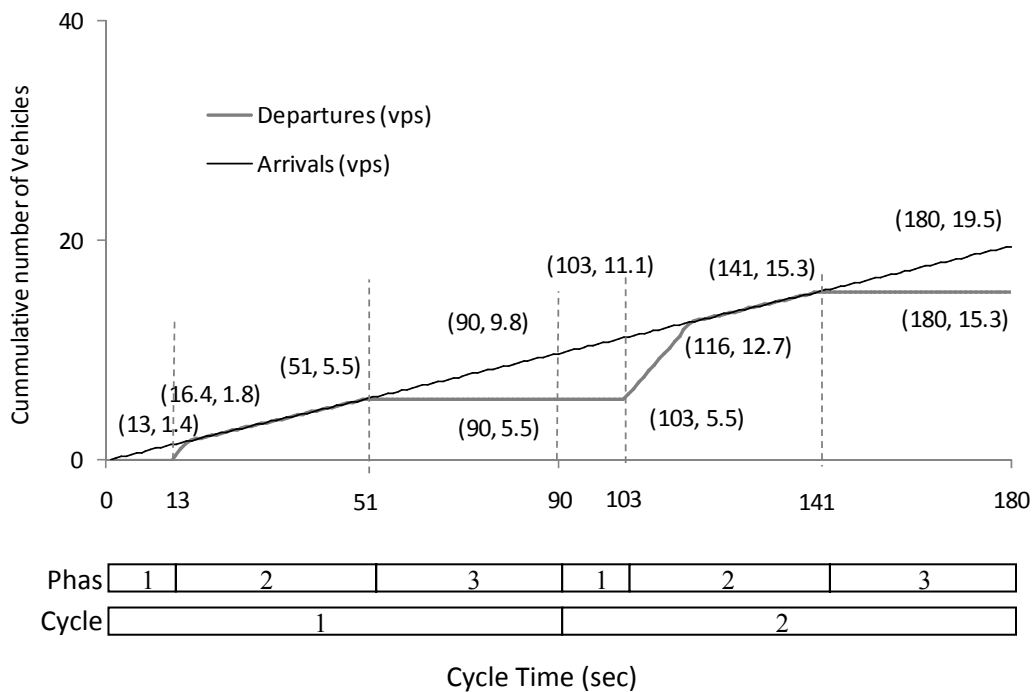
Figure 7.4: Total Delay Computation for NB Exclusive Through Lane on King Street Assuming Maximum Phase 1 Times (no TSP)

There are 40 cycles in an hour for a 90 second cycle length (3600/90 = 40). The delay in Cycles 3 through 40 will be the same as in Cycle 2 for 38 x 184.4 = 7,008.7 seconds. The total delay for the entire peak hour can be calculated as (94.0 + 184.4 + 7,008.7) = 7,287.1 seconds.

Now we illustrate (Figure 7.5) the calculation of delay for the same lane but operating under TSP control. The TSP signal timings are changed with respect to the bus time of arrival in the cycle. For each bus time of arrival there is a corresponding change in signal cycle. For this illustration, a bus is assumed to arrive at 67 seconds in the signal cycle. Note that any other bus time of arrival could also have served the same purpose but the TSP response would have been different and consequently, different delay would have resulted. The detailed bus delays for each bus time of arrival are discussed and depicted later in the section (Figure 7.8).

Similar to the calculations shown earlier, the phase-by-phase-vehicular delay can be computed (Table 7.8). Note that with TSP the delay in cycle 2 is changed in response to the TSP signal-timing plan.

TSP Cycle 1

- Delay in phase 1 in cycle 1 = (0.5 x 13 x 1.4) = 9.2 seconds

- Delay in phase 2 in cycle 1 = 0.5 x (16-13) x (1.8-1.4) = 2.4 seconds

- Delay in phase 3 in cycle 1 = 0.5 x (67-51) x (7.3-5.5) = 13.9 seconds

TSP Cycle 2

- Delay in phase 1 in cycle 2 = 0.5 x (80-67) x [(7.3-5.5)+(8.7-5.5)] = 31.7 seconds

- Delay in phase 2 in cycle 2 = 0.5 x (87.5-80) x (9.5-5.5) = 11.8 seconds

- Delay in phase 3 in cycle 2 = 0.5 x (180-141) x (19.5-15.3) = 82.4 seconds

TSP Cycle 3

- Delay in phase 1 in cycle 3 = 0.5 x (193-180) x [(19.5-15.3)+(20.9-15.3)] = 64.1 seconds

- Delay in phase 2 in cycle 3 = 0.5 x (206.4-193.0) x (22.4-15.3) = 37.9 seconds

- Delay in phase 3 in cycle 3 = 0.5 x (270-231) x (29.3-25.0) = 82.4 seconds

Table 7.8: Total Delay Computation on King Street (NB, through lane, phase by phase)

Cycle	Phase	Geometric Figure	Cycle Time	Departures	Arrivals	Total Phase Delay	Total Cycle Delay
			sec	vps	vps	sec	sec
1	1		13	0.0	1.4	9.2	25.4
	2		16	1.8	1.8	2.4	
	3		67	5.5	7.3	13.9	
2	1		80	5.5	8.7	31.7	125.9
	2		87	9.5	9.5	11.8	
	3		180	15.3	19.5	82.4	
3	1		80	15.3	20.9	64.1	184.4
	2		87	22.4	22.4	37.9	
	3		180	25.0	29.3	82.4	
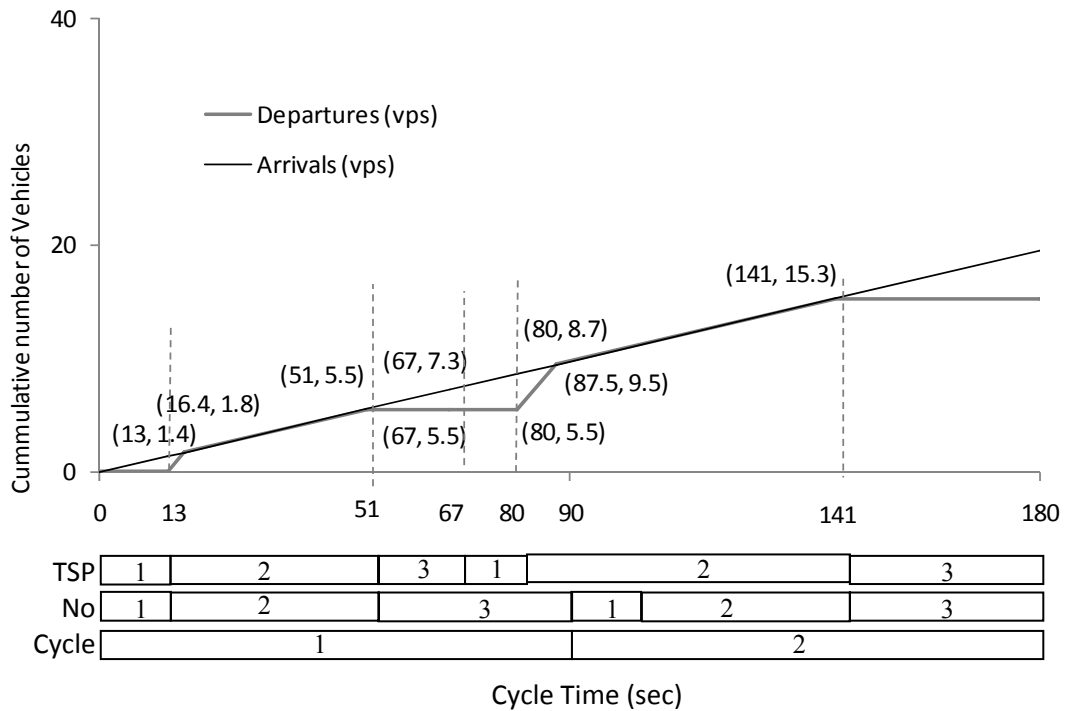
Figure 7.5: Vehicle Delay for TSP (Bus Arrival = 67 seconds, NB through + right lane demand scenario 3)

The delay in Cycles 3 through 10 is computed as 8 x 184.4 = 1475.2 seconds. The total delay for 15 minutes (bus headway) can be calculated as (25.4 + 125.9 + 1475.2) = 1626.5 seconds. The total delay for the entire hour can be computed as (1626.5 x 4) = 6506 seconds.

Note that the total delay with no TSP control does not change with the bus time of arrival. However, the total delay with TSP control does change with the bus time of arrival.

Figure 7.6 shows the calculation for bus delay for no TSP control (exclusive NB through lane). A bus is modelled to arrive at 67 seconds in the signal cycle (i.e. the bus faces a red signal as it arrives during phase 3) and must wait until the end of the subsequent Phase 1 (NB/SB green arrow). The queue ahead of the bus can be computed as the difference between the arrival and departure curve at the bus time of arrival (7.3-5.5 = 1.7 vehicles). The time required to serve a queue of 1.7 vehicles can be estimated by dividing it with the saturation flow rate (i.e. 1900 vph = 0.53 vps). The time required for queue dissipation is 1.7 / 0.53 = 3.3 seconds. Consequently, the bus is not served until time =103 + 3.3 = 106.3 seconds and therefore experiences a delay of (106.3-67) = 39.3 seconds.
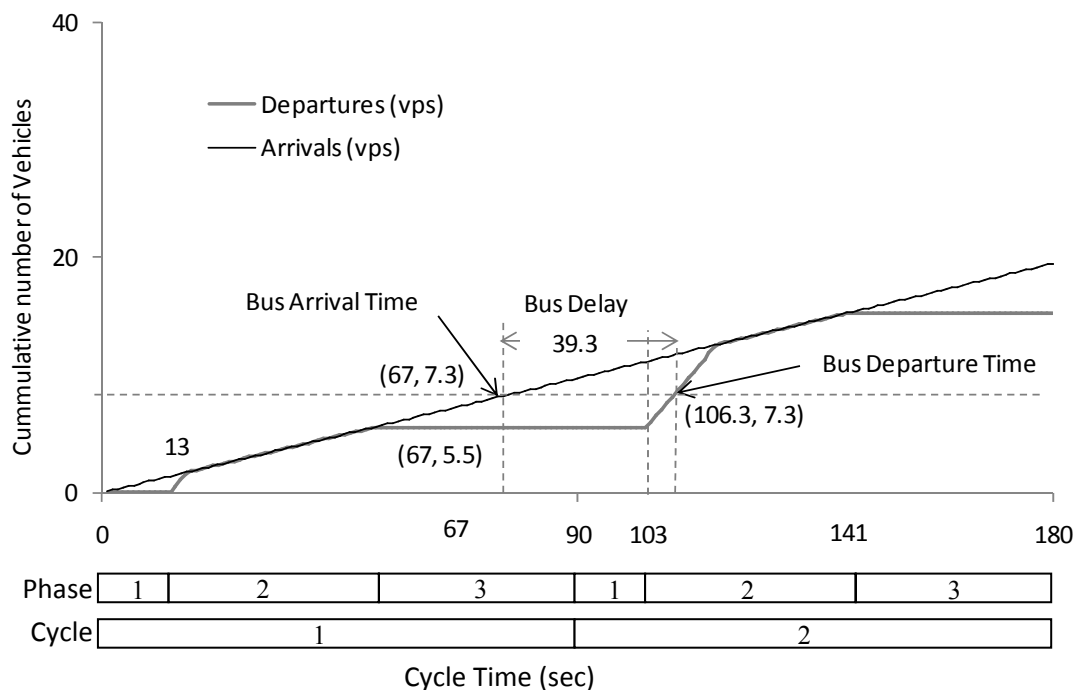
Figure 7.6: Bus Delay for no TSP (Bus Arrival = 67 seconds, NB, through lane, King Street)

We now examine the bus delay for the same condition with the exception that the signal is operating with TSP control (Figure 7.7). The impact of TSP control is to terminate phase early (at time 67). Consequently, the bus delay is only 16.3 seconds (wait time = 13 seconds for left green arrow and 3.3s to clear the queue). The total bus delay with TSP is much smaller than that without TSP because the green time on phase 3 is terminated earlier than it would with No TSP control.
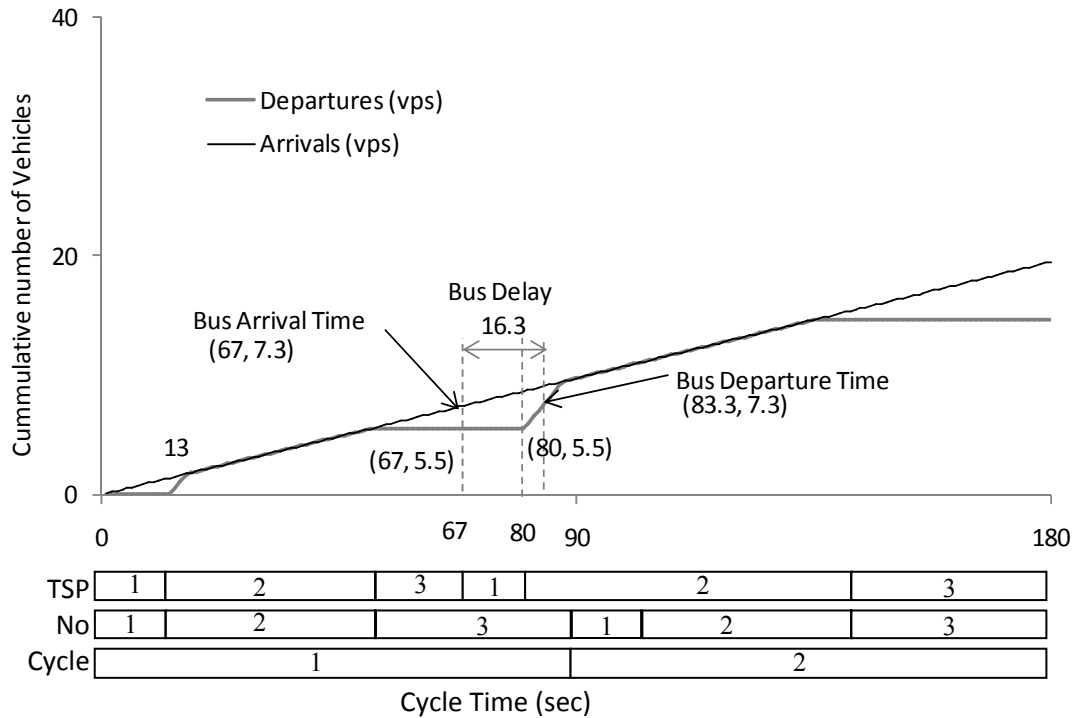
Figure 7.7: Bus Delay for TSP (Bus Arrival = 67 seconds, NB, through lane, King Street)

Delay calculations can be conducted in a similar way for all other approaches and lanes. The above section detailed a single bus time of arrival (67 seconds in the signal cycle). Figure 7.8 shows bus delay for every second of bus arrival time in the signal cycle. The figure also depicts the bus delays computed from Figure 7.6 and Figure 7.7.

In the following section, we give examples of no TSP bus delays for different bus arrival times to interpret the results in Figure 7.8. Note that there are four buses with headway of 15 minutes arriving during the analysis hour. These results are for the first bus arriving in the analysis hour.

A bus arriving in the phase 1 at time = 1 second experiences a signal delay of 12 seconds and queue delay of 0.2 seconds (Figure 7.5) before it can depart. Therefore, the bus delay is 12.2 seconds. At

bus time of arrival = 20 seconds in the cycle the bus will not experience any delay, because the bus arrives during the phase 2.

After phase 2 (time = 52 second), any bus arriving will have to wait for the cross street (Union Street) phase (i.e. phase 3) and phase 1 (north south green arrow) before being able to discharge. With no TSP control, the bus delay is (103-52) = 51 seconds and the queue delay is 0.2 seconds. The total bus delay at 52 seconds in the signal cycle is 51.2 second.
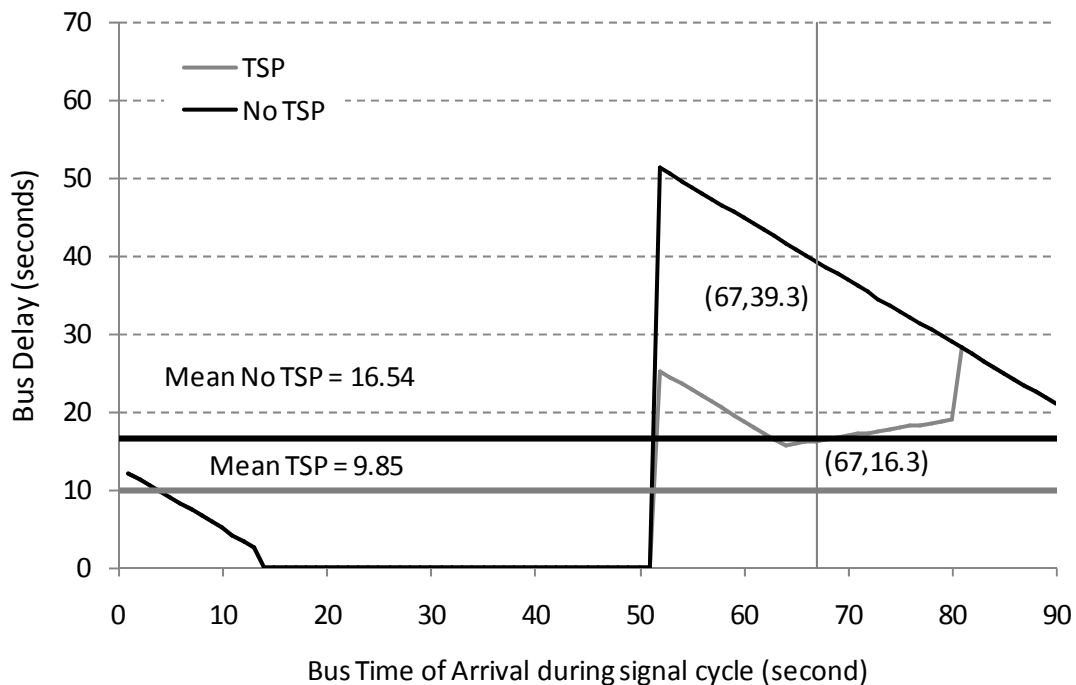
Figure 7.8: Relationship between Bus Delay and Bus Time of Arrival (King Street, demand scenario 3)

The average and standard deviation of the bus delays are computed in Table 7.9. The standard deviation of bus delay is computed across the signal cycle for TSP and No TSP. As expected, implementation of TSP results in decreasing variability of bus delays in this case from 22.7 seconds to 8.9 seconds, a 60.5% reduction.

Figure 7.9 shows the process flow chart for the software implementation of the proposed D/D/1 model. Note that in previous sections we have shown the calculation for a single bus time of arrival during the signal cycle. This corresponds to point "A" in Figure 7.9.

Table 7.9: Bus Delay for Demand Scenario 3 and all Bus Arrival Times

Arrival time	TSP	No TSP	Arrival Time	TSP	No TSP	Arrival Time	TSP	No TSP
sec	sec	sec	sec	sec	sec	Sec	sec	sec
1	12.2	12.2	31	0.0	0.0	61	18.1	44.1
2	11.4	11.4	32	0.0	0.0	62	17.3	43.3
3	10.6	10.6	33	0.0	0.0	63	16.5	42.5
4	9.8	9.8	34	0.0	0.0	64	15.7	41.7
5	9.0	9.0	35	0.0	0.0	65	15.9	40.9
6	8.2	8.2	36	0.0	0.0	66	16.1	40.1
7	7.4	7.4	37	0.0	0.0	67	16.3	39.3
8	6.6	6.6	38	0.0	0.0	68	16.5	38.5
9	5.8	5.8	39	0.0	0.0	69	16.7	37.7
10	5.1	5.1	40	0.0	0.0	70	16.9	36.9
11	4.3	4.3	41	0.0	0.0	71	17.1	36.1
12	3.5	3.5	42	0.0	0.0	72	17.3	35.3
13	2.7	2.7	43	0.0	0.0	73	17.5	34.5
14	0.0	0.0	44	0.0	0.0	74	17.7	33.7
15	0.0	0.0	45	0.0	0.0	75	17.9	32.9
16	0.0	0.0	46	0.0	0.0	76	18.1	32.1
17	0.0	0.0	47	0.0	0.0	77	18.3	31.3
18	0.0	0.0	48	0.0	0.0	78	18.5	30.5
19	0.0	0.0	49	0.0	0.0	79	18.8	29.8
20	0.0	0.0	50	0.0	0.0	80	19.0	29.0
21	0.0	0.0	51	0.0	0.0	81	28.2	28.2
22	0.0	0.0	52	25.2	51.2	82	27.4	27.4
23	0.0	0.0	53	24.4	50.4	83	26.6	26.6
24	0.0	0.0	54	23.6	49.6	84	25.8	25.8
25	0.0	0.0	55	22.8	48.8	85	25.0	25.0
26	0.0	0.0	56	22.0	48.0	86	24.2	24.2
27	0.0	0.0	57	21.2	47.2	87	23.4	23.4
28	0.0	0.0	58	20.4	46.4	88	22.6	22.6
29	0.0	0.0	59	19.6	45.6	89	21.8	21.8
30	0.0	0.0	60	18.8	44.8	90	21.0	21.0

Average Bus Delay with TSP (seconds/per bus in peak hour)	7.95
Average Bus Delay with No TSP (seconds/ per bus in peak hour)	19.36
Bus Delay Variability with TSP (seconds/ per bus in peak hour)	8.94
Bus Delay Variability without TSP (seconds/ per bus in peak hour)	22.65
Delta Bus Delay Variability (seconds/ per bus in peak hour)	13.71
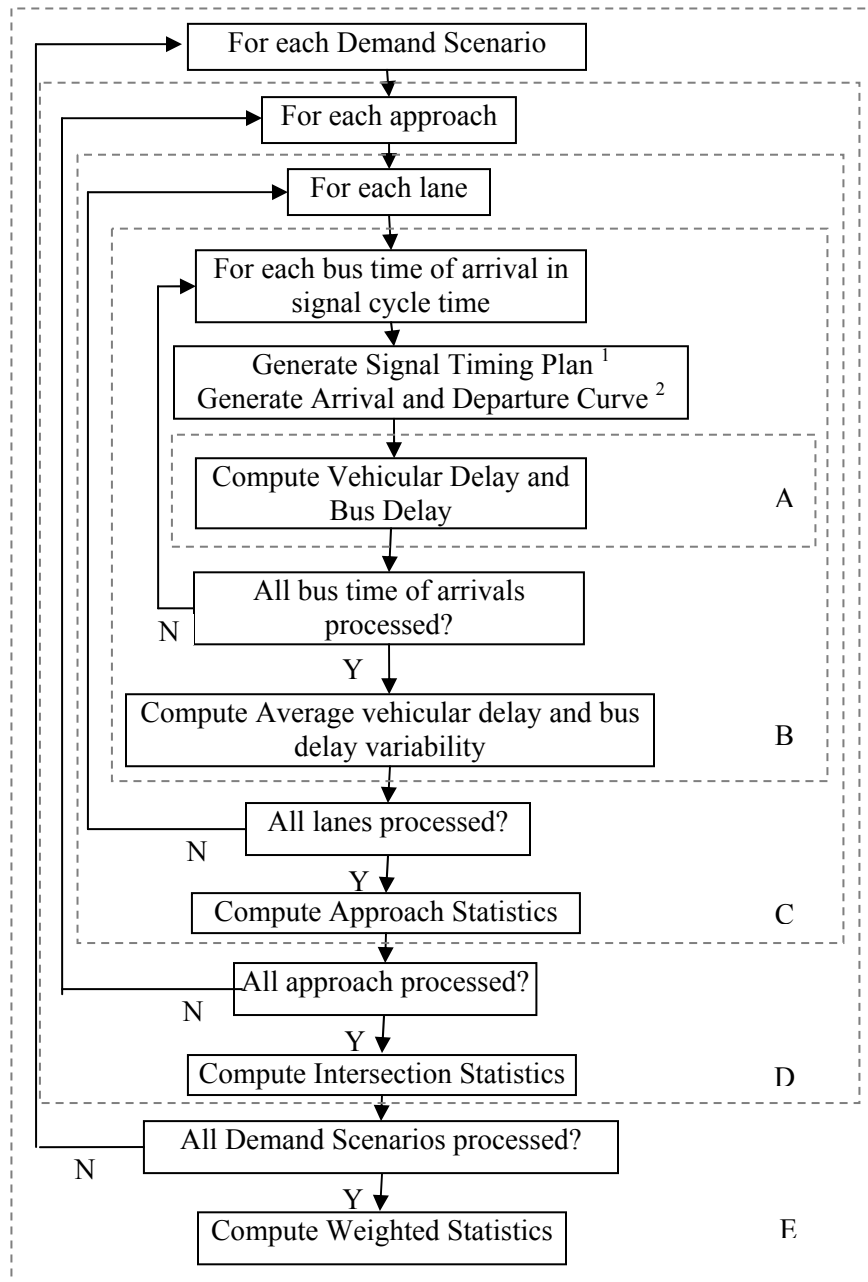
Figure 7.9: Process Flow Chart

[1] Appendix B (Signal Timing Module)
[2] Appendix C (M/D/1 and D/D/1 Module)

Recall that for bus time of arrival = 67 seconds we have computed TSP delay = 6506 seconds and No TSP delay = 7287.1 seconds (section 7.4). There are 90 bus time of arrivals each associated with a TSP and No TSP delay. An average of these 90 delays would be similar for No TSP delay as there is no impact on the signal-timing plan, however the average would be different for TSP delay as the signal timing plan changes in response to the bus time of arrival. The TSP average delay (Table 7.10) is 7032.8 seconds and No TSP average delay (Table 7.10) is 7191.6 seconds. These observations correspond to point "B" in Figure 7.9. Note that the No TSP average computed in Section 7.4 is 7287.1 seconds while that computed by the TSP evaluation tool is 7191.6 seconds. The difference in results is due to the use of a limited number of significant digits in Section 7.4. These results are similar if 16 digits after the decimal are used for manual calculations.

Table 7.10 shows the result for each lane point "B" (Figure 7.9). The average delay (seconds / veh) is computed by dividing the total delay with number of vehicles.

Table 7.10: Auto Delay for all Lanes (demand scenario 3)

Approach	Lane	Lane Configuration	Saturation Flow Rate	Delay (seconds)			Average Delay (seconds/veh)	
				TSP	No TSP	Delta Delay (TSP - No TSP)	TSP	No TSP
East bound	1	Exclusive Left	449	12371.4	4936.2	7,435.2	63.8	25.4
	2	Shared Through + Right	1900	13905.2	12951.7	953.5	22.8	21.3
West bound	1	Exclusive Left	246	1458.9	1385.8	73.1	21.1	20.1
	2	Exclusive Through	1900	10608.0	10101.8	506.2	20.8	19.8
	3	Exclusive Right	1900	1678.1	1622.3	55.8	15.8	15.3
North bound	1	Exclusive Left	1805	1703.8	1694.7	9.1	34.1	33.9
	2	Exclusive Through	1900	7032.8	7191.6	-158.9	18.0	18.4
	3	Shared Through + Right	1900	7032.8	7191.6	-158.9	18.4	18.8
South bound	1	Exclusive Left	1805	4101.7	4079.9	21.8	35.4	35.2
	2	Exclusive Through	1900	6783.5	6936.8	-153.2	17.8	18.2
	3	Shared Through + Right	1900	6783.5	6936.8	-153.2	18.3	18.8

The exclusive left turn on east bound on Union Street is most significantly impacted by the implementation of TSP. The average vehicle delay increased from 25.4 seconds to 63.8 seconds when TSP is implemented. All other lanes on Union Street experienced a modest increase in delay ranging from 1% - 7%. Since the northbound/southbound exclusive through-lane and the shared through-lane and right turn lane have the same arrival rate and the same saturation flow rate, the Delta vehicular delays are similar (-158.9 seconds and -153.2 seconds). The NB and SB left turn lanes experience a small increase in delay because of TSP implementation. Table 7.11 shows the volume weighted approach delay on the north bound for demand scenario 3.

Table 7.11: Volume Weighted Approach Delay (north bound, demand scenario 3)

Lane	lane volume (vph)	Delay (seconds)		
		TSP	No TSP	Delta Delay (TSP - No TSP)
1	50	1703.8	1694.7	9.1
2	386	7032.8	7191.6	-158.9
3	386	7032.8	7191.6	-158.9
Volume Weighted Approach average	822	6,708.6	6,857.3	-148.7

Table 7.12 shows the calculations for volume weighted intersection delay for demand scenario 3. This corresponds to point "D" in Figure 7.9.

Table 7.12: Volume Weighted Intersection Delay (demand scenario 3)

Approach	Approach Volume (vph)	Delay (seconds)		
		TSP	No TSP	Delta Delay (TSP - No TSP)
East bound	803	13534.7	11015.2	2519.5
West bound	686	8307.9	7914.9	393.0
North bound	822	6708.6	6857.3	-148.7
South bound	866	6424.3	6554.1	-129.8
Volume Weighted Intersection average	3,177	8,701.8	8,053.9	647.8

Table 7.13 and Table 7.14 show the weighted average across all demand scenarios. This corresponds to point "E" in Figure 7.9. The weighted average was computed by summing the products of probability and MOE (Delay, Fuel Consumption, and Emission).

The results of weighted average delta delay (Table 7.13) were compared with No TSP for Demand Scenario 3 for Average vehicle delay, Average bus delay, Person Delay and Bus Delay Variability. There was 7.1% increase in Average vehicle delay. There was a reduction of 58.9%, 10.4%, and 60.5% in Average bus delay, Person Delay, and Bus delay variability respectively.

The vehicular delays were 118 seconds and 191.1seconds for demand scenario 1 and 2. However, the delays increased to 647.8 seconds for demand scenario 3 and to 1047.3 seconds for demand scenario 5. This reflects the impact that variations in peak hour demand have on intersection performance.

Table 7.13: Intersection Auto and Person Delay (All Demand Scenarios)

Demand Scenario		1	2	3	4	5	Weighted Average
Associated Probability		6.6%	24.1%	38.5%	24.1%	6.6%	
Intersection Volume (auto)		2,627	2,902	3,177	3,452	3,727	
Intersection Volume (Persons)[1]		3,332	3,662	3,992	4,322	4,652	
Average Vehicle Delay (seconds)	TSP	6,395.6	7,329.7	8,701.8	11,589.8	14,646.6	571.3
	No TSP	6,277.6	7,138.6	8,053.9	10,766.0	13,599.3	
	TSP - No TSP	118.0	191.1	647.8	823.8	1,047.3	
Average Bus Delay (seconds)	TSP	31.1	31.5	31.8	32.2	32.5	-45.6
	No TSP	76.7	77.1	77.4	77.8	78.1	
	TSP - No TSP	-45.6	-45.6	-45.6	-45.6	-45.6	
Person Delay (seconds)	TSP	9,075.0	10,211.4	11,873.4	15,354.6	19,038.1	-1367.2
	No TSP	10,986.6	12,035.2	13,149.2	16,419.2	19,834.6	
	TSP - No TSP	-1,911.6	-1,823.8	-1,275.8	-1,064.6	-796.5	
Bus Delay Variability (seconds)	TSP	8.8	8.8	8.9	9.0	9.1	-13.7
	No TSP	22.5	22.6	22.6	22.7	22.8	
	TSP - No TSP	-13.8	-13.7	-13.7	-13.7	-13.6	

[1] Bus Occupancy = 45 pers / veh , Bus Frequency = 4 / hour, Auto Occupany = 1.2 pers / veh

The implementation of TSP on King and Union Street resulted (Table 7.14) in an increased average intersection fuel consumption (7.4%, 280.5 mL) and GHG Emission (7.4%,195.1 mg). Note that there is a reduction in person delays of 10.4% but the fuel consumption and GHG emission are increased. Ideally, a transit planner or operator would like to reduce bus delay variability while not adversely influencing the vehicular delays, person delays, fuel consumption, and emission.

Table 7.14: Intersection Fuel Consumption and GHG Emissions (All Demand Scenarios)

Demand Scenario		1	2	3	4	5	Weighted Average
Associated Probability		6.6%	24.1%	38.5%	24.1%	6.6%	
Average Fuel Consumption (mL)	TSP	2492.3	3155.2	4100.7	5934.5	8097.0	
	No TSP	2446.3	3072.9	3795.5	5512.7	7518.1	
	TSP - No TSP	46.0	82.3	305.3	421.8	579.0	280.5
Average GHG Emissions (mg)	TSP	1733.4	2194.5	2852.1	4127.5	5631.6	
	No TSP	1701.4	2137.3	2639.8	3834.2	5228.9	
	TSP - No TSP	32.0	57.2	212.3	293.4	402.7	195.1

Chapter 8

Sensitivity Analysis of TSP Performance

8.1 Introduction

Transit Signal Priority (TSP) gives transit vehicles a little extra green time or a little less red time at traffic signals to reduce the time they are slowed down by traffic signals. It is a cost-effective method to enhance regional mobility by improving transit travel times and reliability, thereby increasing the attractiveness of transit as an alternative to single-occupant vehicle travel.

TSP performance benefits are not always guaranteed. In following sections, a sensitivity analysis is conducted using the proposed D/D/1 model. The main objective of this chapter is to determine the sensitivity of TSP performance as a function of three factors namely:

- Degree of progression
- TSP parameter values
- Bus headway

Progression reflects the likelihood that vehicles arriving at the signalized intersection do so when the signal display is green for that approach.

Progression can be measured in terms of the proportion of vehicles that arrive at the intersection during the green interval. Table 8.1 show the HCM 2000 [13] definition of quality of progression. The poorest progression (Arrival Type 1) is observed if over 80 percent of the approach volume arrives during the red interval. The best progression (Arrival Type 6) is observed if over 80% of the approach volume arrives during the green interval.

According to the HCM 2000 [13], there is a significant impact of arrival type on delay estimates. The HCM delay equation accounts for this impact using a progression adjustment factor (*PF*) which influences the uniform delay (*d*). The progression adjustment factor can be obtained from Equation (9) where *P* is computed as:

Table 8.1: Selected Arrival Types (HCM 2000, 13)

Arrival Type	Description
1	Dense platoon containing over 80 percent of the lane group volume, arriving at the start of the red phase. This AT is representative of network links that may experience very poor progression quality because of conditions such as overall network signal optimization.
2	Moderately dense platoon arriving in the middle of the red phase or dispersed platoon containing 40 to 80 percent of the lane group volume, arriving throughout the red phase. This AT is representative of unfavourable progression on two-way streets.
5	Dense to moderately dense platoon containing over 80 percent of the lane group volume, arriving at the start of the green phase. This AT is representative of highly favourable progression quality, which may occur on routes with low to moderate side-street entries and which receive high priority treatment in the signal-timing plan.

$$P = R_P \left(\frac{g}{C} \right) \tag{67}$$

where:

P = proportion of all vehicles in movement or lane group arriving during green interval (P may not exceed 1.0),

g = green interval duration for approach (seconds),

C = cycle length (seconds)

R_p = platoon ratio, the values of R_p are estimated for a given arrival type using HCM [13].

Pre-TSP implementation studies requires specification or selection of TSP parameters of two parameters, namely the maximum green extension time (g_{ext}) and the maximum time by which the non-prioritized approach green can be reduced to facilitate an early green (g_{tr}). These parameters are important determinant in final evaluation of TSP performance. Typically, an aggressive setting of these parameters would facilitate the transit movement; however have adverse impacts on the non-prioritized approach. Therefore, it is important to determine the parameter values that achieve an overall goal of reducing transit delay while not adversely compromising on the non-prioritized approach general vehicle delay.

Transit agencies strive to improve the transit experience in their jurisdictions. In doing so, they decide on various planning decisions including bus headways. It is important to determine that if a TSP implementation decision were made at an intersection with specific bus headway on the prioritized

approach, would the decision to implement TSP be altered if the bus headways were changed in the future.

The following section the evaluation intersection and performance measures are illustrated. This is followed by sensitivity analysis on progression quality, TSP parameters, and bus headways. Finally, the chapter concludes the sensitivity analysis results.

8.2 Evaluation Intersection and Measure of Effectiveness

A hypothetical four-legged intersection was modeled. All approaches consist of a single lane. All lane widths, grade, curb radii, etc. were considered to be ideal with no on-street parking, and adequate storage and discharge space. Ten *v/c* scenarios were considered ranging from 0.2 to 0.95.
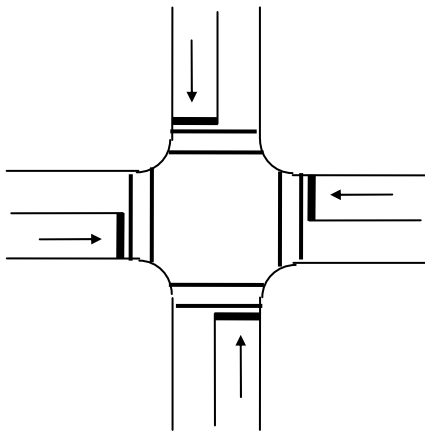
Figure 8.1: Intersection Geometry

The cycle length was set to 80 seconds with a 2-phase signal operation. The signal plan was Phase 1 green time = Phase 2 green time = 36 seconds with 2 seconds of amber and 2 seconds of all red intervals. The saturation flow rate was 1800 pcphpl.

Once a bus is detected, there is a corresponding response on the signal-timing plan. There is a definite signal-timing plan for a specific bus arrival time. Therefore, for each specific bus time of arrival there is a corresponding vehicular and bus delay. Consequently, TSP performance is quantified based on expected (average) TSP impact assuming the probability of the bus arriving is uniformly distributed across the cycle.

The D/D/1 model is applied for each different bus time of arrival. Bus times of arrivals are evaluated for each second within the cycle. Therefore, the average vehicle and average bus delays are computed using equation 68 and 69 respectively.

$$d_{veh} = \frac{\sum_{i=1}^{C} d_{i,veh}}{C}$$ (68)

$$d_{transit} = \frac{\sum_{i=1}^{C} d_{i,transit}}{C}$$ (69)

where:

C = cycle length (seconds),
$d_{i,transit}$ = bus delay for i^{th} bus time of arrival (sec/veh),
$d_{i,veh}$ = intersection auto delay for i^{th} bus time of arrival (sec/veh),
$d_{transit}$ = bus delay (sec/veh),
d_{veh} = intersection auto delay (sec/veh).

The performance measures were examined by computing the percentage change in intersection person delay due to implementation of TSP control. The intersection person delay was computed as:

$$d_{pers} = \frac{d_{veh} V_{int} O_a + d_{transit} F_{transit} L_{transit}}{V_{int} O_a + F_{transit} L_{transit}}$$ (70)

where:

d_{pers} = intersection person delay (sec/pers),
$d_{transit}$ = bus delay (sec/veh),
d_{veh} = intersection auto delay (sec/veh),
$F_{transit}$ = transit frequency = 4 (vph),
$L_{transit}$ = transit occupancy = 45 (persons/ transit veh),
O_a = auto occupancy rate = 1.2 (persons/ veh),
V_{int} = intersection vehicular volume (vph),

Intersection person delay (Δd_{pers}) was computed for the TSP ($\Delta d_{TSP, pers}$) and no TSP control ($\Delta d_{NoTSP, pers}$) strategies. The delta person delay was computed as:

$$\Delta d_{pers} = d_{TSP,pers} - d_{NoTSP,pers}$$ (71)

where:

$$\Delta d_{\,pers} \quad = \quad \text{delta intersection person delay (sec/pers),}$$

$$d_{\,TSP,\,pers} \quad = \quad \text{intersection person delay with TSP control (sec/pers),}$$

$$d_{\,NoTSP,\,pers} = \quad \text{intersection person delay with no TSP control (sec/pers),}$$

8.3 Sensitivity to Quality of Progression

For the sensitivity analysis of progression quality, four arrival types were defined using HCM characterization methodology identified in Table 8.1. Arrival type 1 consists of dense platoon containing over 80 percent of the lane group volume, arriving at the start of the green phase (Figure 8.2). Arrival type 2 consists of dense to moderate platoon arriving in the middle of green phase containing 60% of the lane group volume. In arrival type 3 and 4, 40% and 20% of the lane group volume arrive during the green interval respectively.
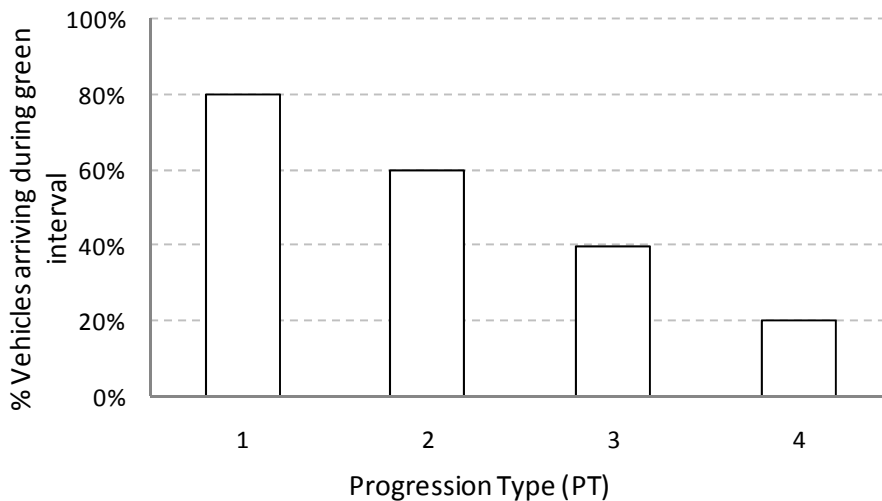
Figure 8.2: Progression Types Defined for D/D/1 Model

The selected progression levels were tested using the hypothetical intersection described in section 8.2. Additional inputs are outlined below:

- The intersection is controlled by a two phase fixed time signal equipped to implement green extension and red truncation TSP strategies.

- It is assumed that four buses per hour arrive with uniform headway of 15 minutes.

114

- Intersection performance was evaluated as a function of the *v/c* ratio (10 levels); progression type (4 levels); and with and without TSP control.

Figure 8.3 shows the impact of progression on increase in delay. The results show the percentage increase in average delay compared to PT 1 (best progression) for TSP and no TSP control strategy. From Figure 8.3, we can observe that

- Regardless of the signal control type, as progression becomes poorer (i.e. PT increases) there is a corresponding increase in average delay.

- The difference in average delays obtained from TSP and no TSP becomes more prominent as the progression becomes poorer.
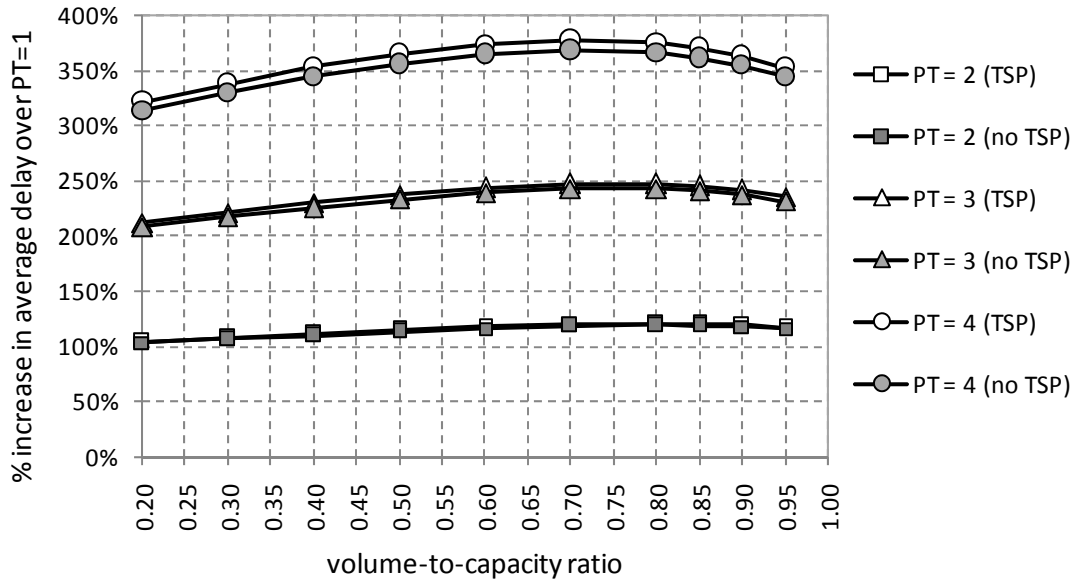
Figure 8.3: Impact of Progression on Average Intersection Vehicle Delay

Further examinations were conducted on transit delay. Figure 8.4 show the impact of progression on Transit Delay with and without TSP control. As expected, transit vehicles benefit from the implementation of TSP signal control. The negative values indicate that there is a reduction in transit delays compared to no TSP transit delays. The benefit of TSP in terms of reducing transit vehicle delays is not impacted by quality of progression.
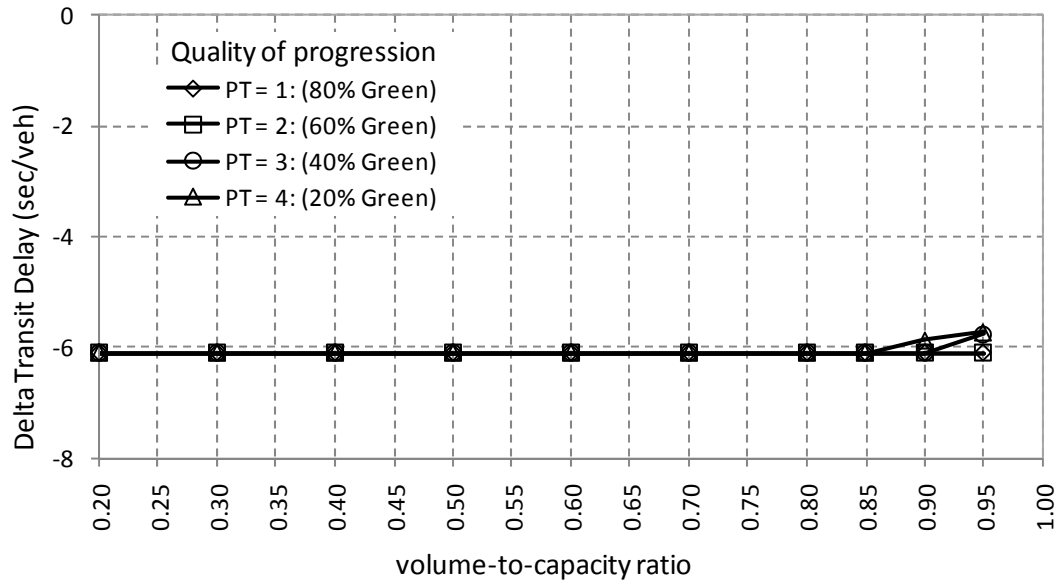
Figure 8.4: Impact of Progression on Delta Transit Delay

Figure 8.5 shows the intersection person delay for all progression levels under TSP and no TSP signal control. We can conclude that

- For all progression types as the volume to capacity ratio increases, the intersection person delay obtained with TSP becomes closer to those obtained without TSP control.

- As the volume-to-capacity ratio increases the TSP benefits in terms of reduction in person delay decreases.

- The intersection person delays are higher for poor progression (PT 4) compared to good progression (PT 1).

The results depicted in Figure 8.5 were used for estimating the change in intersection person delay compared to no TSP control strategy using Equation 67. When interpreting the results in Figure 8.6, negative values of ΔD_{pers} imply an overall reduction in person delay because of TSP. It can be observed from Figure 8.6 that progression has a negligible impact on the delta intersection person delay.
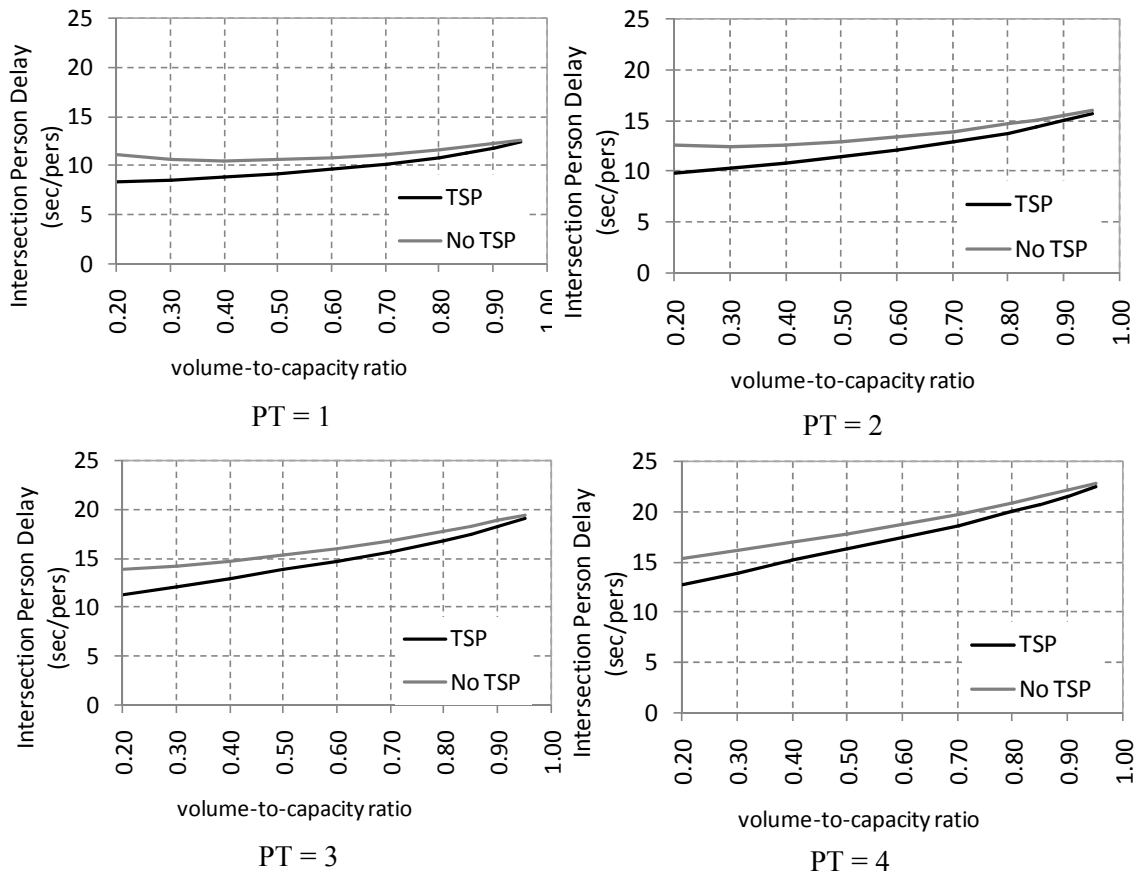
Figure 8.5: Impact of Progression on Intersection Person Delay
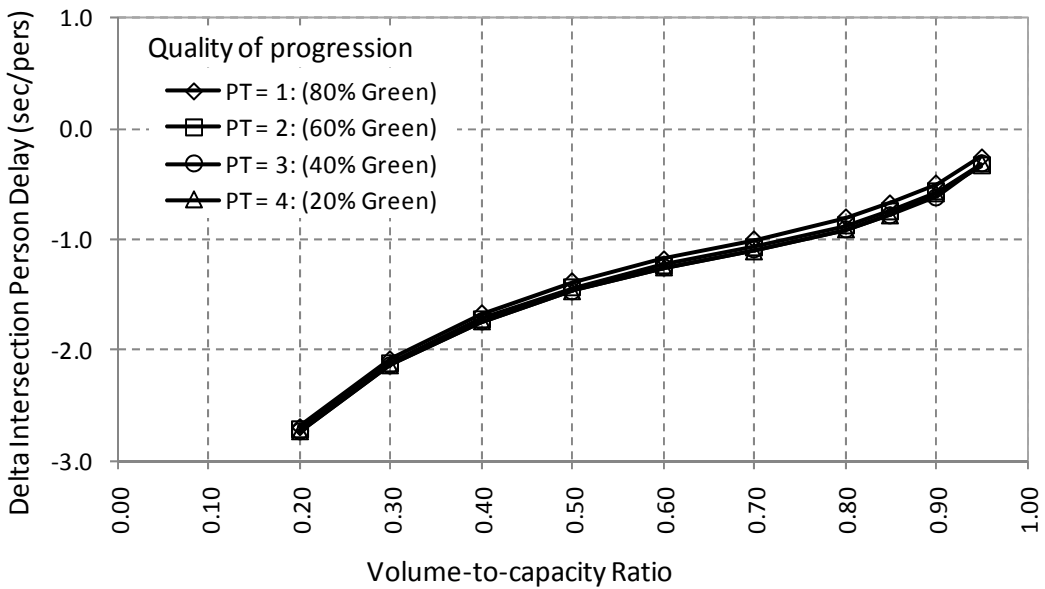
Figure 8.6: Impact of Progression on Delta (TSP – No TSP) Intersection Person Delay

8.4 Sensitivity to TSP Parameters

Three sets of TSP parameter values were evaluated as defined in Table 8.2. These scenarios were used to investigate aggressive, moderate, and conservative TSP control strategies. Any percentage or value could have served the same purpose of illustrating the impact of TSP control parameters on TSP performance.

Table 8.2: TSP Parameter Scenarios

Control strategy		Max green extension (g_{ext})		Red truncation (g_{tr})
		% of cycle length	seconds	seconds
1	Conservative	15%	12	15
2	Moderate	20%	16	20
3	Aggressive	25%	20	25

Figure 8.7 shows the impact of TSP parameters on:

- Delta auto vehicle delay on prioritized approach (sec/veh)

- Delta auto vehicle delay on non-prioritized approach (sec/veh)

- Delta transit vehicle delay (sec/veh)

- Delta intersection person delay (sec/pers)

From the results, we can make the following observations:

- There is an impact of TSP parameters on the prioritized approach and non-prioritized approach vehicle delay.

- The reduction in transit vehicle delay increases, as the TSP parameters are more aggressive.

- The benefits in terms of intersection person delay are higher for aggressive TSP parameters. However, the benefits become less pronounced with increasing v/c ratio.
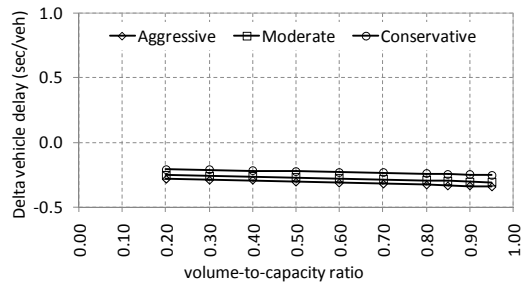
118

Prioritized approach
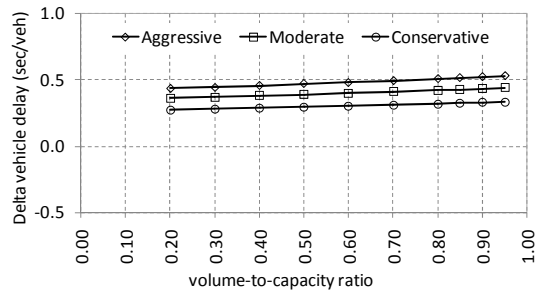
Non-prioritized approach
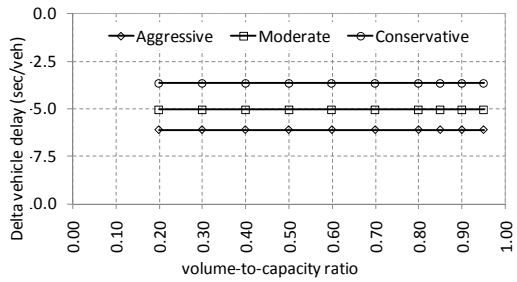
Transit vehicle
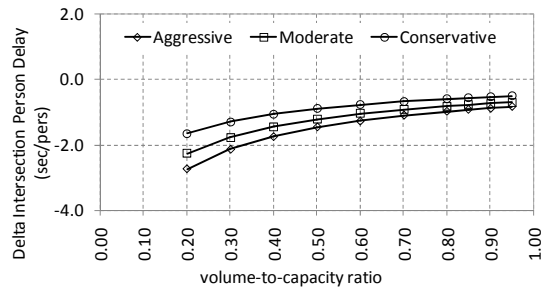
Intersection Person Delay

Figure 8.7: Impact of TSP parameters on Delta Delays

8.5 Sensitivity to Bus Headways

In this section, we evaluate the impact of bus headway on TSP performance. The sensitivity analysis considers the following:

- Bus headways are evaluated (5, 10, 15 minutes),

- Only standard green extension and red truncation strategies are considered. No cycle recovery algorithms [28] that compensate the non-prioritized approach in the subsequent cycles are considered.

- Several TSP applications consider applying a restriction on the number of TSP requests that can be granted in a given time period. In this analysis, an unconditional TSP that does not restrict TSP requests is considered.

Figure 8.8 shows the impact of bus headways on delta delays. From the results, we can conclude that:

- In general, provision of TSP to buses resulted in net benefit to the prioritized approach,

- TSP has a negative impact on the non-prioritized approach. The impact is larger for shorter bus headways,

- Bus headway has no impact on the delta transit delay,

- Bus headway has negligible impact on intersection person delay at *v/c* ratios < 0.6. However, at *v/c* ratios greater than 0.6, bus headway has a more pronounced impact.

Prioritized approach

Non-prioritized approach

Transit vehicle

Intersection Person Delay
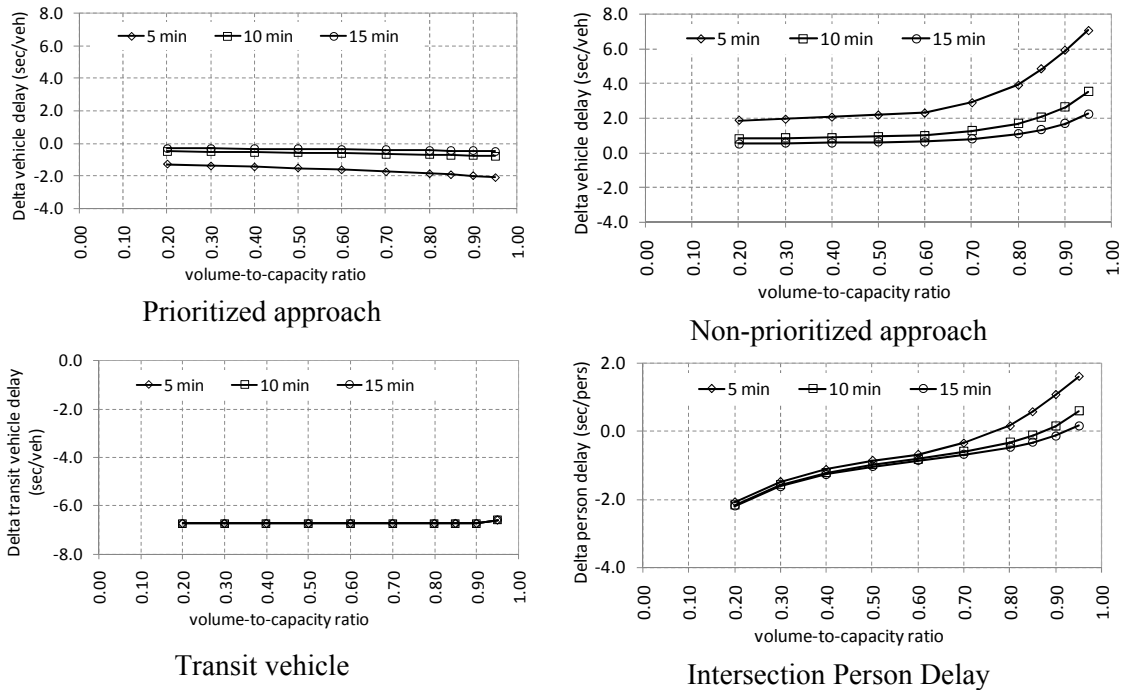
Figure 8.8: Impact of Bus Headways on Delta Delays

8.6 Chapter Conclusions

Transit agencies conduct TSP evaluation studies for demonstrating the benefits of a TSP system, to assess its impact on non-prioritized approach general traffic, and to determine the specific conditions under which TSP is most cost effective. These evaluations also help in determining the future direction of TSP in the transit agency. In this chapter, a sensitivity analysis is conducted to determine the impact of progression, TSP parameters, and bus headway on the performance of TSP. These are all important determinant for TSP implementation and operational analysis. The following summarize the conclusions of the sensitivity analysis:

- The impact of progression on TSP performance is important as it quantify the influence of upstream traffic signal. The sensitivity analysis shows that there is negligible impact of progression on delta transit delay and delta intersection person delay. This signifies that the performance of TSP signalized intersection with close by traffic signals is similar to an isolated intersection performance. Based on the sensitivity analysis results we conclude that the change in TSP performance estimated for isolated intersections can be used for TSP implementation and operations.

- The results show that there is an impact of TSP parameters on delta vehicle delay, delta transit delay and delta intersection person delay. The selection of TSP parameters green extension time (g_{ext}) and red truncation time (g_{tr}) is important both for pre-TSP implementation studies and for post-TSP operational studies. These parameters control the amount of green time reduced from the non-prioritized approach and therefore directly relates impact of TSP on general vehicular delay on the non-prioritized approach.

- The results of the sensitivity analysis show that the impact of bus headways on the intersection person delay is negligible at *v/c* ratios < 0.6, but start to increase at *v/c* ratio is greater than 0.6. The bus headway selection is a critical component in transit planning. The bus headways may be increased due to growing transit passenger on the transit route. The increase in headway suggests higher number of TSP calls from the transit vehicles. The higher number of TSP calls results in adverse impacts on the non-prioritized approach vehicular delay. The effect of increasing bus frequencies on TSP operation is that the intersection person delay increases at lower v/c ratios. This suggests that when frequencies become relatively high, there is increasing need to transform transit from operating on mixed use right of way to an exclusive right of way.

In the next chapter, we apply the model to 16 signalized intersections in the Region of Waterloo and use the results to prioritize these intersections for TSP implementation.

Chapter 9

Model Application to Prioritize TSP Deployment in Waterloo Region

The usefulness of the proposed model for TSP performance relies on its ability to capture the overall level of turbulence for different transportation scenarios as a function of a number of geometric and traffic attributes. The proposed model must be able to provide meaningful insights about TSP performance.

In this chapter, the proposed model is used to evaluate TSP performance at sixteen signalized intersections on the iXpress bus route in the Region of Waterloo. The results of the model application are compared with a previous study [31].

In the following sections, first the study area is depicted along with the intersection geometries. This is followed by estimation of aggregated results such as those in Table 7.13 and Table 7.14. Finally, using a prioritization mechanism the intersections are prioritized. The intersection prioritization results are compared with those in the earlier study [31].

9.1 Previous TSP study [31]

In 2005, the Region of Waterloo started Urban Transportation Showcase Program (UTSP) to demonstrate, evaluate, and promote effective strategies to reduce greenhouse gas (GHG) emission from urban transportation. Waterloo region developed a multi-tiered innovative concept to address this challenge on 33.4 kilometre Central Transit Corridor (CTC) Express service under the UTSP project. Transit Signal Priority is one of the key assignments in the project initiatives. The CTC corridor includes 62 signalized intersections. Thirteen of these intersections were selected for TSP implementation. The study method of prioritization is explained in following text.

A ranking scheme was developed for selecting intersections for TSP implementation. Each intersection was given a composite score based on its overall Level of Service (LOS), transit movement LOS, and mode of control. Scores for intersection LOS and transit movement were awarded as follows:

- LOS A or LOS B scores 1;
- LOS C or LOS D scores 2; and
- LOS E or F scores 3.

The study justified that at intersections with an intersection LOS and transit movement LOS in the E to F range requires TSP since the intersection is heavily congested, and the transit vehicle

movement is operating at a poor LOS. The study scored intersection based on the mode of control as follows:

- Fixed time or pedestrian actuated timings score 1; and
- Full and semi-actuated timings score 3.

The study suggested that fixed time intersections in Waterloo are typically located in central business district. These intersections are typically in a grid with close intersection spacing and short cycle lengths, which are not preferred for TSP deployment. Intersections at which the transit makes a right turn were assigned a score of 0. The intersections that received the highest composite scores were identified as the best candidate for TSP implementation.

There were two routes considered: a northbound route, and a southbound route. Two peak times were also distinguished: AM and PM. These considerations lead to four possible composite scores for each intersection along the route. For each combination at a particular intersection, a composite score greater than or equal to six resulted in that combination being flagged for potential TSP deployment.

Based on the composite scores a ranking is conducted and thirteen intersections were ranked for TSP deployment.

In following sections, the proposed model is applied and a ranking is carried out based on the performance measures. The ranking results are compared with the results of previous study [31].

9.2 Study Area

The selected intersections are on the 33.4 kilometre long iXpress bus route in the Region of Waterloo. The locations of 16 intersections are depicted in Figure 9.1. The intersection geometry of each of these intersections is depicted in Figure 9.2 and Figure 9.2(b). There are fourteen four-legged intersections and two three-legged intersections. Fourteen of these intersect at 90 degrees and two of these intersections are skewed. In all intersections, the prioritized approach run on north south bound, and the non-prioritized approach runs on the east west bound.
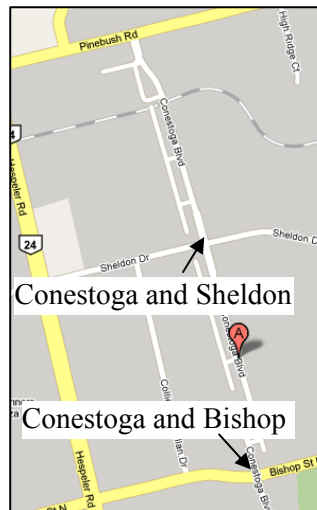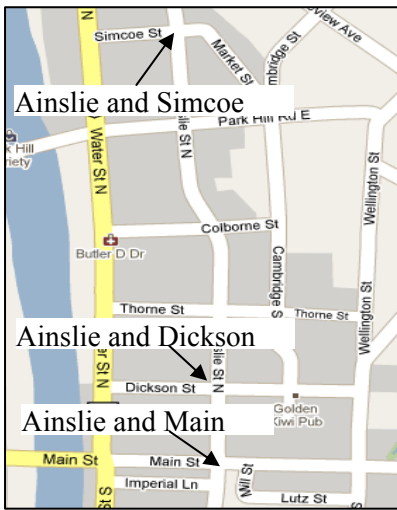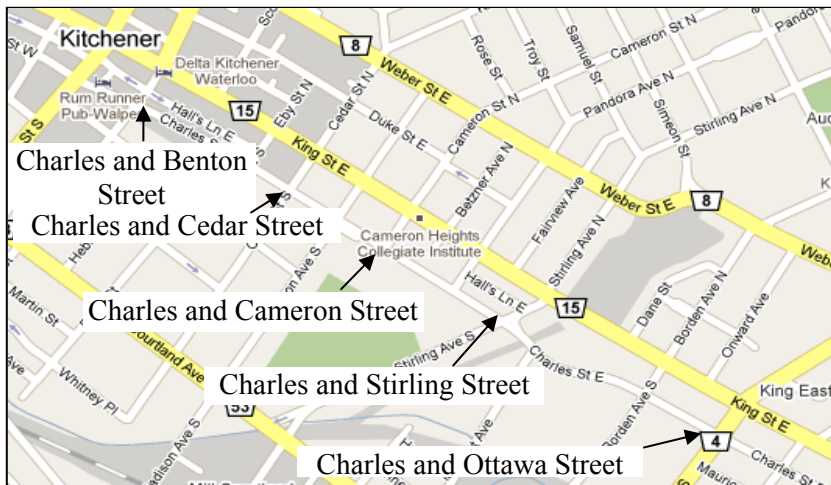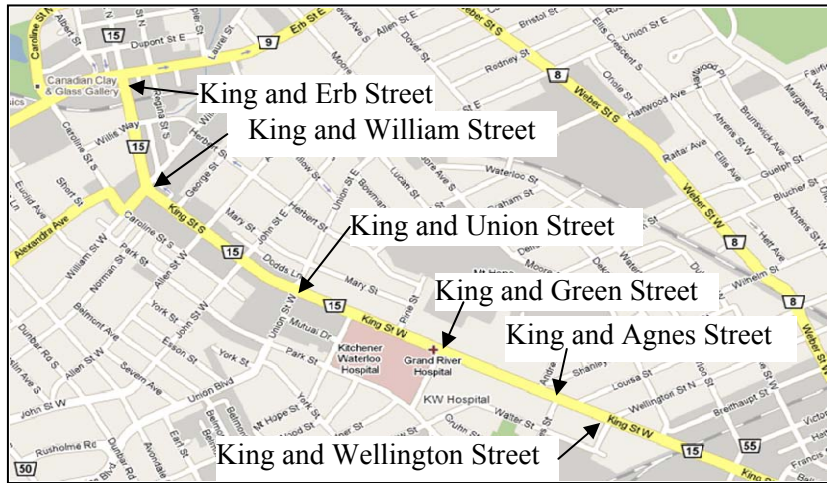
Figure 9.1: Intersection Locations (Google Maps)

King and William

King and Green

King and Agnes

King and Wellington

King and Union

King and Erb

Charles and Cedar

Charles and Cameron

Charles and Stirling
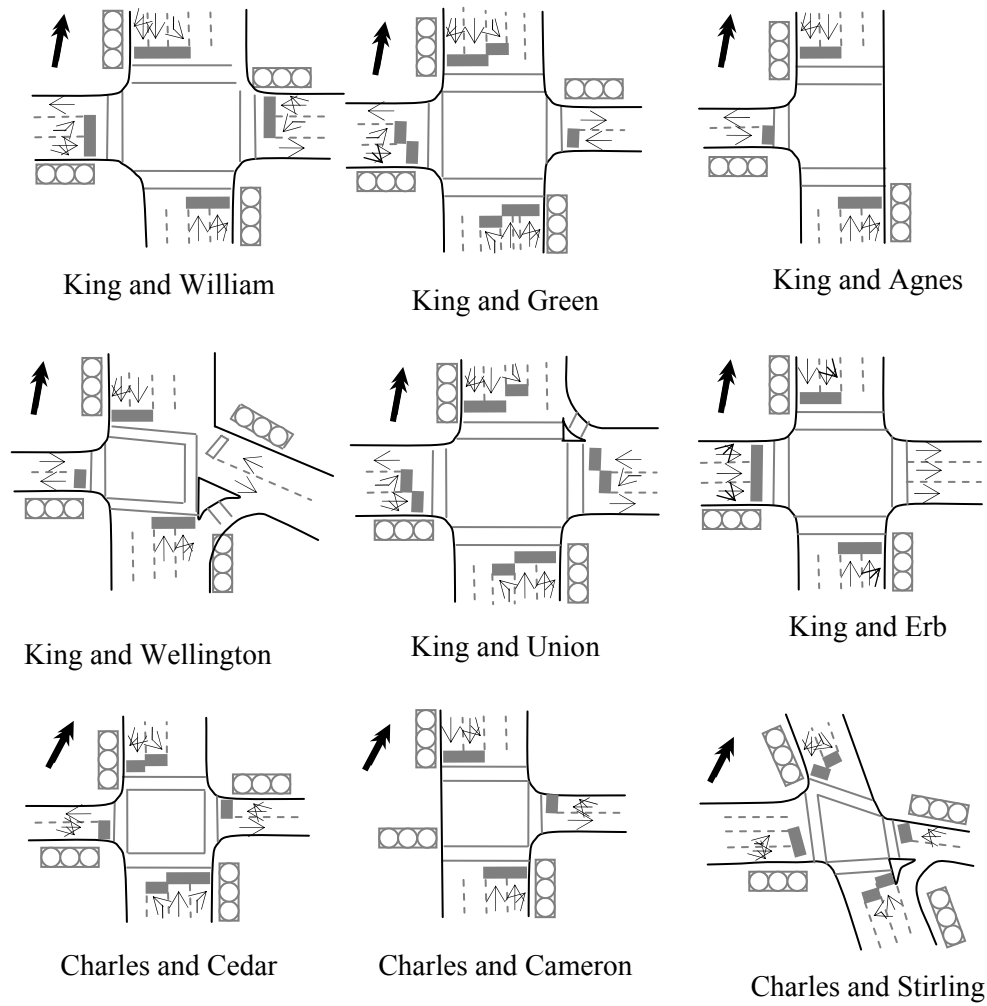
Figure 9.2(a): Intersection Geometries
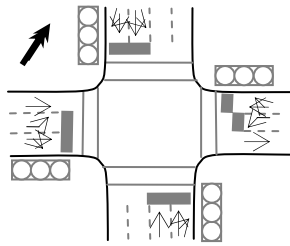
Charles and Ottawa
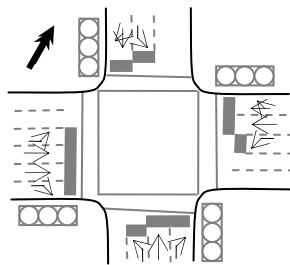
Charles and Benton
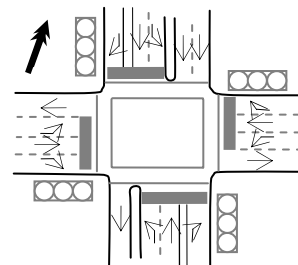
Conestoga and Sheldon
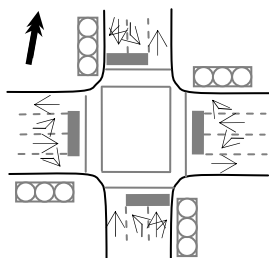
Conestoga and Bishop
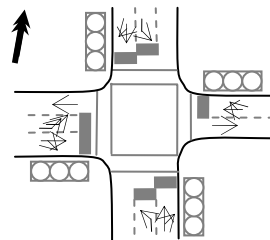
Ainslie and Dickson street
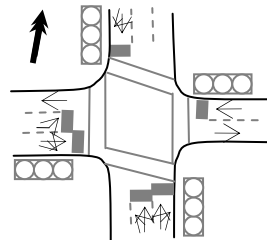
Ainslie and Simcoe
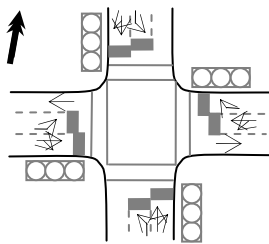
Ainslie and main street

Figure 9.2(b): Intersection Geometries

9.3 Traffic and TSP Parameters

Table 9.1 shows the vehicular volumes, pedestrian volumes, and signal timings obtained from Region of Waterloo [47]. The prioritized approaches are King Street, Charles, Ainslie, and Conestoga. These approaches in North Bound (NB) and South Bound (SB) directions carry the major traffic stream along with the prioritized bus. The cycle length ranges from 80 seconds to 100 seconds [47]. The bulk of intersections operate at an intersection Level of Service (LOS) of D or better. Two of these intersections are operating poorer than LOS D.

Table 9.1: Traffic and Volume Attributes

Intersection	Volume (vehicles per hour) [1]								Control Parameter	
	Vehicle				Pedestrian				Cycle (s)	Inters. LOS[2]
	non-prioritized approach		prioritized approach		non-prioritized approach		prioritized approach			
	EB	WB	NB	SB	EB	WB	NB	SB		
King at William	313	388	611	555	39	37	28	26	90	2
King at Green	223	41	609	548	30	46	77	31	90	1
King at Agnes	100	0	590	700	0	17	39	13	90	1
King at Wellington	152	192	483	621	16	9	5	1	90	1
Charles at Cedar	96	196	378	713	2	15	32	15	90	2
Charles at Cameron	0	31	444	828	0	0	12	4	90	1
Charles at Stirling	305	280	371	775	3	10	2	4	80	2
Ainslie and Simcoe	270	44	919	290	7	2	19	4	80	3
Ainslie and Main	237	337	448	423	54	45	71	48	80	2
Ainslie and Dickson	78	155	524	432	31	39	34	23	80	1
King at Union	803	686	822	800	29	7	15	33	90	2
King at Erb	969	0	538	673	77	123	59	61	80	2
Charles at Benton	254	520	369	530	37	52	36	49	80	1
Charles at Ottawa	523	601	207	682	9	8	21	11	90	2
Conestoga at Sheldon	334	647	307	435	0	0	1	3	80	1
Conestoga at Bishop	485	559	249	586	1	0	0	0	100	3

[1] PM Peak hour from 17:00 to 18:00 is taken for analysis

[2] 1 = LOS A and B, 2 = LOS C and D, 3 = LOS E and F [31]

The TSP parameters were selected such that they are consistent across the intersection application. The maximum reducible amount of green time on the non-prioritized approach was computed and compared with 15% of cycle time (Table 9.2) [31]. A minimum is selected as TSP parameter for Green extension and Red Truncation.

Table 9.2: Green Extension and Red Truncation Parameters

	Non Prioritized Approach (seconds)				
	Flash Don't Walk Time	Green Time	Reducible Green Time	15% of Cycle [31]	Used in TSP
			A	B	Min{A,B}
King at William	20	36	16	14	14
King at Green	11	26	15	14	14
King at Agnes	10	28	18	14	14
King at Wellington	8	28	20	14	14
Charles at Cedar	11	22	11	12	11
Charles at Cameron	9	27	18	14	14
Charles at Stirling	16	26	10	14	10
Ainslie and Simcoe	9	20	11	12	11
Ainslie and Main	7	25	18	12	12
Ainslie and Dickson	14	22	8	12	8
King at Union	13	33	20	14	14
King at Erb	11	26	15	12	12
Charles at Benton	13	24	11	12	11
Charles at Ottawa	12	51	39	14	14
Conestoga at Sheldon	18	31	13	12	12
Conestoga at Bishop	8	30	22	15	15

9.4 Aggregated Results

Table 9.3 shows the aggregated results for change in person delay, fuel consumption, GHG emission, and bus delay variability. The results shown here also depict the volume-to-capacity ratio for prioritized approach, non-prioritized approach and for the intersection.

The results show that there is a net benefit in intersection person delay due to TSP implementation for all intersections. The benefits were highest for the intersection of King and Union Street and lowest for the intersection of Ainslie and Simcoe Street. Note that King and Union Street was selected for detailed application in Chapter 7.

Table 9.3: Intersection Performance Measures (for PM peak hour)

Intersection	v/c ratio			Intersection Volume		Average delta (TSP - No TSP)			Bus Delay Variability	Mean Bus delay
	Intersection	Prioritized Approach	Non prioritized Approach			Person delay	Fuel consump.	GHG emissions		
				vehicles	persons	seconds	mL	mg	seconds	seconds
King and William	0.32	0.31	0.34	1,867	2,285	-342.0	-9.4	-6.5	-8.7	-29.5
King and Green	0.30	0.33	0.21	1,421	1,750	-303.5	-61.3	-42.6	-7.0	-19.3
King and Wellington	0.52	0.59	0.30	1,448	1,783	-300.5	-30.0	-20.9	-8.3	-23.5
King and Agnes	0.63	0.66	0.18	1,397	1,721	-409.6	-111.7	-77.7	-7.9	-22.7
King and Union	0.67	0.54	0.80	3,177	3,992	-1367.2	280.5	195.1	-13.7	-45.6
King and Erb	0.44	0.38	0.51	2,180	2,661	-285.7	-52.2	-36.3	-7.2	-21.1
Charles and Cedar St	0.44	0.47	0.34	1,392	1,715	-227.8	-35.6	-24.8	-6.0	-15.7
Charles and Cameron St	0.33	0.34	0.06	1,303	1,609	-312.6	-53.1	-36.9	-7.8	-20.5
Charles and Benton St	0.30	0.29	0.31	1,673	2,053	-198.1	6.5	4.5	-6.5	-18.3
Charles and Ottawa	0.49	0.48	0.50	2,013	2,461	-470.7	277.3	192.8	-16.5	-66.2
Charles and Stirling Avenue	0.51	0.54	0.44	1,731	2,122	-233.8	-44.1	-30.7	-6.0	-16.3
Ainslie and Dickson Street	0.37	0.41	0.22	1,189	1,472	-236.5	-26.2	-18.2	-6.2	-17.1
Ainslie and Main Street	0.39	0.46	0.29	1,445	1,779	-276.3	-31.4	-21.8	-2.3	-20.7
Ainslie and Simcoe	0.43	0.38	0.61	1,523	1,873	-169.9	-9.2	-6.4	-5.4	-14.0
Sheldon at Conestoga	0.37	0.40	0.35	1,723	2,113	-263.1	8.8	6.1	-1.7	-24.3
Bishop at Conestoga	0.58	0.66	0.52	1,879	2,300	-183.6	92.2	64.1	-3.1	-24.9
Minimum						-1367.2	-111.7	-77.7	-16.5	-66.2
Maximum						-169.9	280.5	195.1	-1.7	-14.0

The implementation of TSP resulted in reducing the mean bus delays to a maximum of 66.2 seconds. A total bus delay savings of 399 seconds (approximately 6.5 minutes) can be achieved if TSP is implemented at all 16 intersections. Thus, it is anticipated that the cycle time along the iXpress route (i.e. time to complete a round trip) could be reduced by approximately 13 minutes through the implementation of TSP at all 16 intersections. The bus headway on this route is 15 minutes; therefore the implementation of TSP at all 16 intersections is expected to reduce average bus delays by an amount almost large enough to reduce the fleet size requirements for this route by one bus – a substantial operational cost savings for Grand River Transit.

The implementation of TSP resulted in increase in fuel consumption and GHG emission on four of the sixteen intersections. The highest increase in fuel consumption and emission was observed on King and Union Street. This observation suggests that while the TSP implementation resulted in person delay net benefits it also resulted in dis-benefits in terms of fuel consumption and GHG emissions.

On twelve intersections the implementation of TSP resulted in decreasing person delay, fuel consumption, GHG emission, and bus delay variability. Four intersections showed that implementation of TSP resulted in decrease in person delay and bus delay variability, however there was an increase in fuel consumption and GHG emissions.

In the next section, the person delay, fuel consumption, GHG emission, and bus delay variability is used for prioritizing the intersections.

9.5 Intersection Prioritization

In this section, the TSP performance measures are normalized into a range of 0 and 1. There are several ways to normalize. For this research, the following normalization method is used [65]:

$$\delta = \frac{\left(MOE_i - \min\{MOE_1, MOE_n\}\right)}{\left(\max\{MOE_1, MOE_n\} - \min\{MOE_1, MOE_n\}\right)} \tag{72}$$

Where:

δ =   Normalized values for selected TSP performance measure in range of 0 and 1
MOE_i =   MOE for i^{th} intersection
MOE_n =   MOE for n^{th} intersection

130

If $MOE_i = MOE_{min}$, then $\delta = 0$. If $MOE_i = MOE_{max}$, then $\delta = 1$. A special care must be taken to avoid division by zero when MOE_{max} is zero. If the value of MOE_i is always zero or positive and the MOE_{max} is known then we can set $\min\{MOE_1, MOE_n\} = 0$ and the equation can be simplified into

$$\delta = \frac{MOE_i}{\max\{MOE_1, MOE_n\}} \tag{73}$$

The individual normalized values for each MOE are summed for each intersection. The intersections are ranked using the sum of normalized values as follows:

$$\delta_{int} = \sum\nolimits_{MOE,i}^{MOE,n}(\delta) \tag{74}$$

Where:

δ_{int} =   sum of the normalized values from intersection MOE's.

The results from the study [31] described in 9.1 are presented in Table 9.4. The study used composite scores (described in section 9.1) to rank the intersections.

Table 9.4: TSP Implementation using composite scores

Intersection	NBAM	NBPM	SBAM	SBPM	Highest composite score
King and William	3	5	3	4	5
King and Green	5	5	5	5	5
King and Wellington	3	3	3	3	3
King and Agnes	5	5	5	5	5
King and Union	3	5	3	4	5
King and Erb	3	4	3	5	5
Charles and Cedar St	3	4	3	5	5
Charles and Cameron St	5	5	5	5	5
Charles and Benton St	4	3	3	3	4
Charles and Ottawa	4	4	4	5	5
Charles and Stirling Avenue	3	4	3	6	6
Ainslie and Dickson Street	3	3	3	3	3
Ainslie and Main Street	4	5	3	5	5
Ainslie and Simcoe	9	9	7	7	9
Sheldon at Conestoga	5	6	5	6	6
Bishop at Conestoga	8	8	8	9	9

Out of the composite score analysis, six potential areas were identified based on a combination of an intersection receiving multiple flags and geographic priority of the intersection to another with similar traffic characteristics. The study suggests that greater the number of intersections in service the more likely travel timesaving can be realized.

The results from Table 9.4 suggest that four out of sixteen intersections received a composite score of six or more. According to the report, these intersections are considered for TSP implementation. This implementation decision is based on the composite scores obtained using intersection level of service, movement level of service and mode of control. Several issues need to be addressed in this composite scoring method:

- Would the decision of TSP implementation be changed if the overall intersection level of service and movement level of service were grouped differently? For example, if level of service E is assigned a composite score of three and level of service F is assigned a composite score of four, it is likely that the composite scores will change. This will results in changing the TSP implementation decision. Therefore, the TSP implementation is subjective to the composite scoring scheme.

- The fixed time signal is assigned a composite score of one and actuated control is assigned a score of three. Would the composite scores be biased if the intersection were operating near capacity?

- The composite scores have no relation with the impact of TSP implementation. For example, what would be the impact of TSP implementation on the prioritized approach, non-prioritized approach, and transit delay? What change we expect in intersection person delay, fuel consumption, and GHG emissions? These are important determinant in TSP implementation; however, none of these are addressed in the composite scoring method.

The Intersection performance measures obtained from Table 9.3 are ranked in Table 9.5 using equation 72 and equation 73. The ranking scheme is based on person delay, fuel consumption, GHG emissions, and bus delay variability. The proposed method ranking results indicate that the first intersection for TSP implementation is Bishop and Conestoga and second is Charles and Ottawa. Note that using the composite scores from previous study both methods received same priority for TSP implementation (i.e. composite score of 9). Similarly, two intersections received a composite score of six

and nine intersections received a composite score of five. Using the composite score obtained from previous study [31], no conclusions can be made on prioritization of intersection having similar composite scores. Moreover, due to issues address above the composite scoring method is subjective.

Table 9.5: Intersection Prioritization

Intersection	Equation 72			Bus Delay Variability	Composite Scores	
	Person Delay	Fuel Consumption	GHG Emissions		Proposed Model (Eqn. 73)	previous Study Results [31] (Section 9.1)
King and William	0.9	0.3	0.3	0.5	1.9	5
King and Green	0.9	0.1	0.1	0.6	1.8	5
King and Wellington	0.9	0.2	0.2	0.6	1.9	3
King and Agnes	0.8	0.0	0.0	0.6	1.4	5
King and Union	0.0	1.0	1.0	0.2	2.2	5
King and Erb	0.9	0.2	0.2	0.6	1.8	5
Charles and Cedar	1.0	0.2	0.2	0.7	2.1	5
Charles and Cameron	0.9	0.1	0.1	0.6	1.8	5
Charles and Benton	1.0	0.3	0.3	0.7	2.3	4
Charles and Ottawa	0.7	1.0	1.0	0.0	2.7	5
Charles and Stirling	0.9	0.2	0.2	0.7	2.0	6
Ainslie and Dickson	0.9	0.2	0.2	0.7	2.1	3
Ainslie and Main	0.9	0.2	0.2	1.0	2.3	5
Ainslie and Simcoe	1.0	0.3	0.3	0.7	2.3	9
Sheldon and Conestoga	0.9	0.3	0.3	1.0	2.5	6
Bishop and Conestoga	1.0	0.5	0.5	0.9	2.9	9

Figure 9.3 show the comparison of composite scores from proposed model and previous study [31]. The results from IBI study show that nine intersections received a composite score of 5. Therefore, all nine intersections are equally likely candidate intersections for TSP implementation. The proposed model composite scores ranged from 1.4 to 2.7. Three intersections received a composite score of 1.8 using the proposed model. The results of proposed model show that the first intersection that should be prioritized from these nine intersections is Charles and Ottawa and the last being King and Agnes.
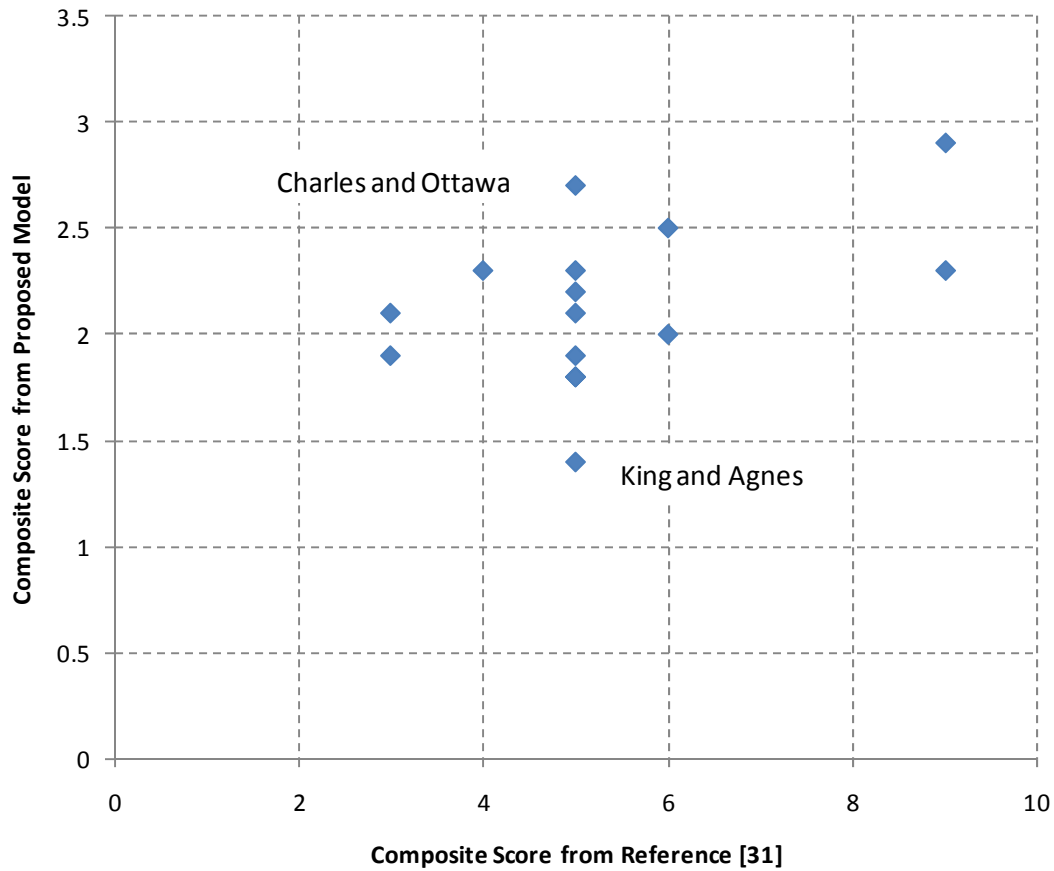
Figure 9.3: Comparison of composite scores (IBI and proposed model)

9.6 Generalized Results

The delta vehicular delays presented in Table 9.3 can be used to generalize the results (Figure 9.4, Figure 9.5, Figure 9.6, Figure 9.7 and Figure 9.8). Using the contour plots the TSP impacts can be related with combination of prioritized and non-prioritized approach v/c ratio results. The contour plots provide a simpler way of estimating TSP impacts.
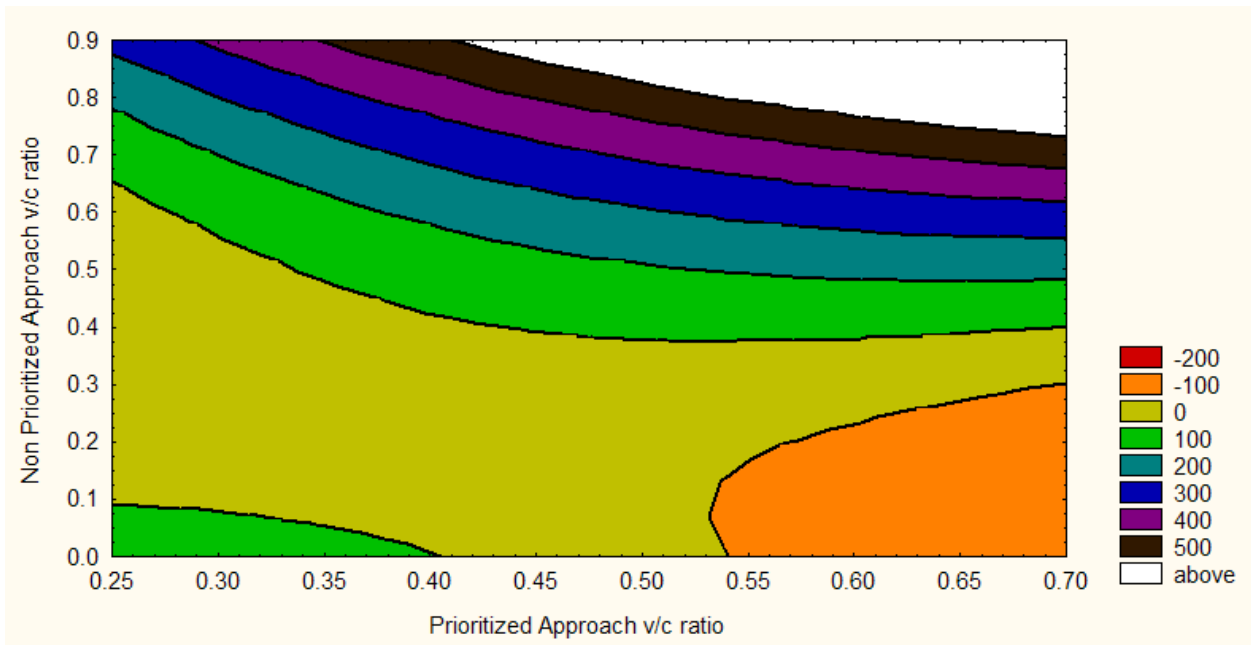
Figure 9.4: Delta Vehicular Delay (seconds/PM peak hour) (positive = net increase in delay)
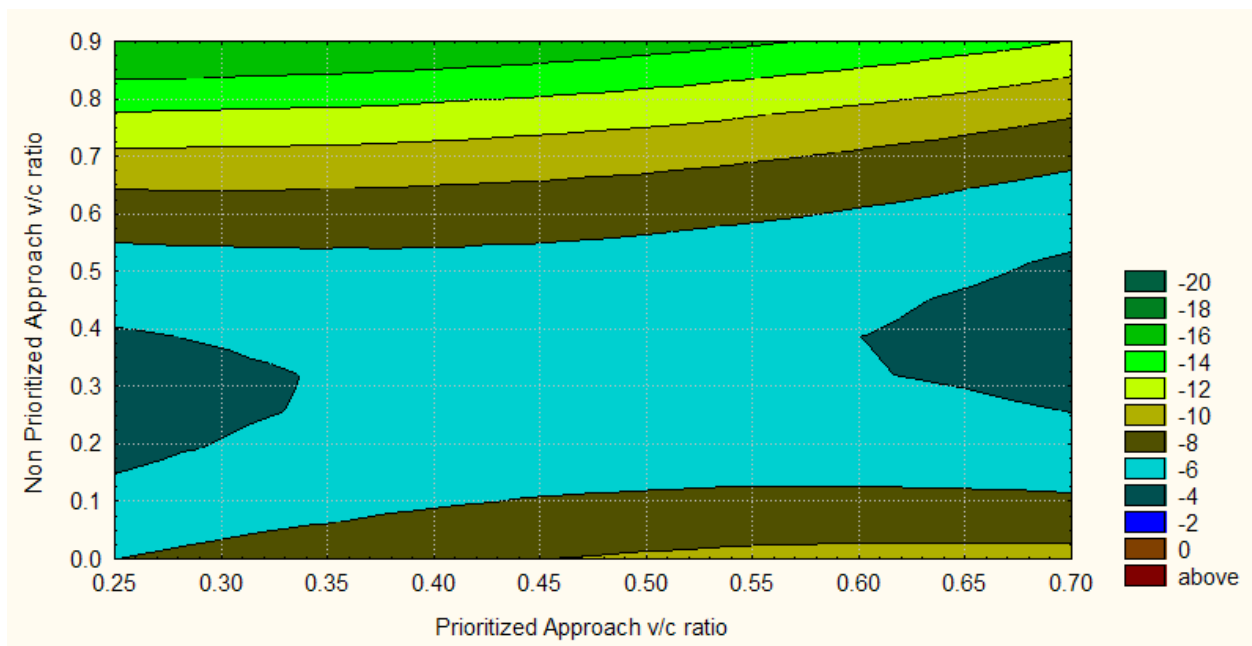
Figure 9.5: Delta Bus Delay Variability (seconds/PM peak hour)
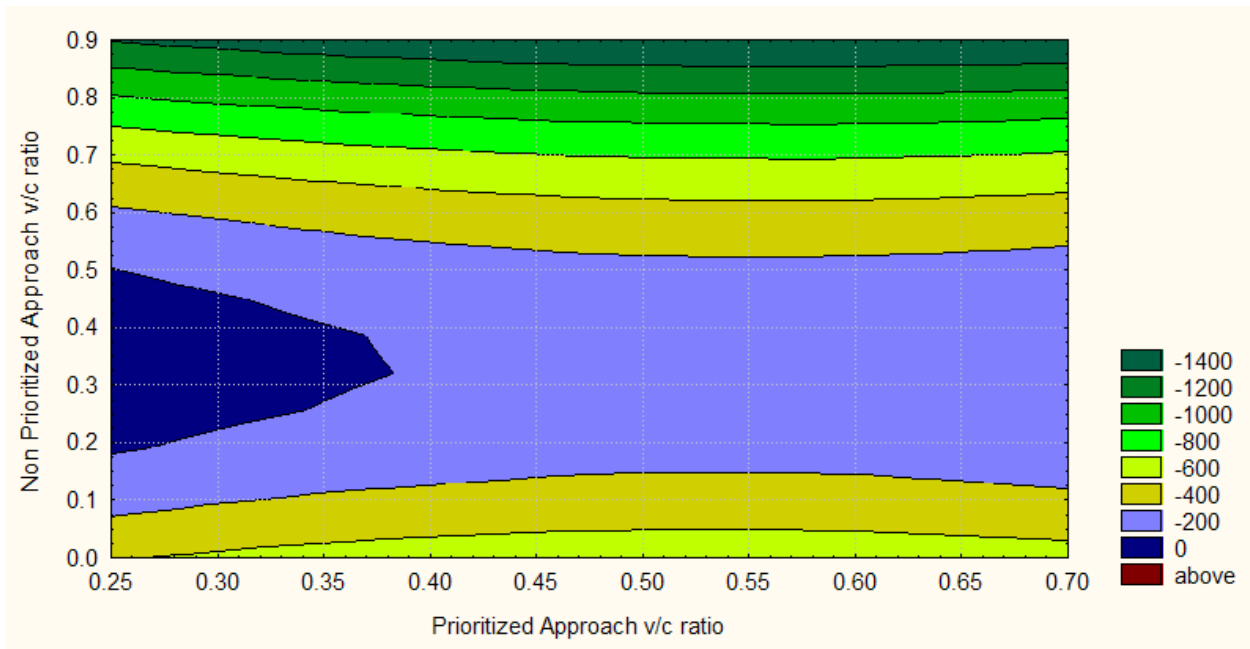
Figure 9.6: Delta Intersection Person Delay (seconds/PM peak hour)
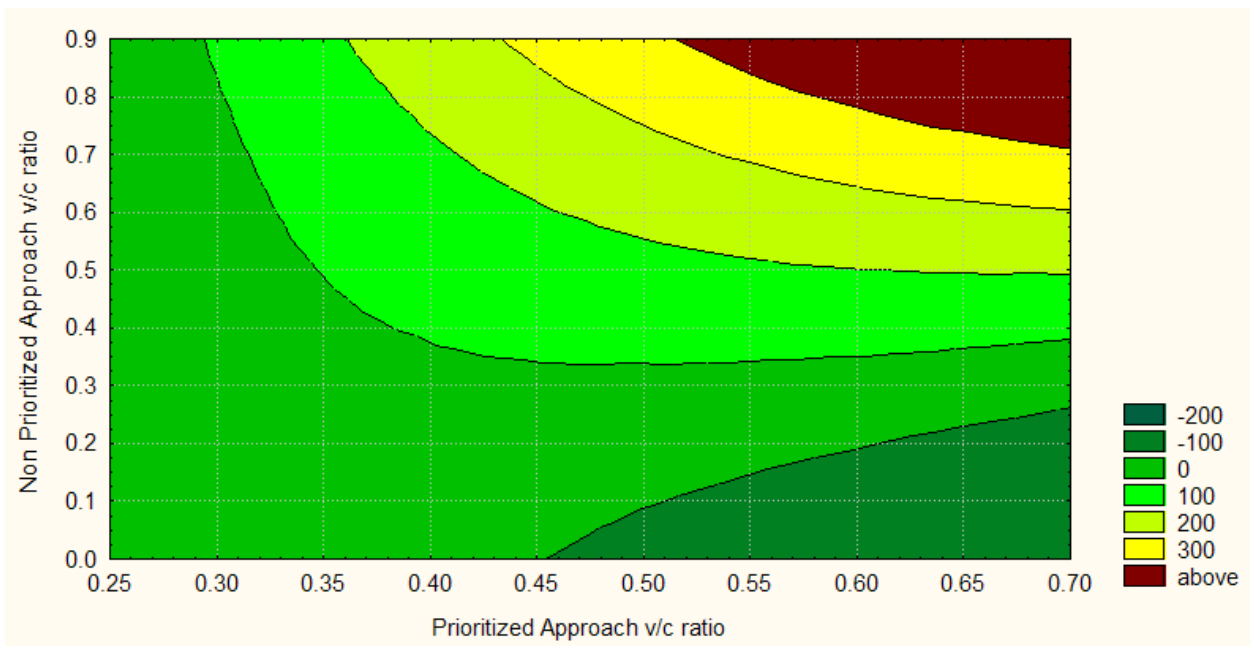
Figure 9.7: Delta Fuel Consumption (mL/PM peak hour)

136
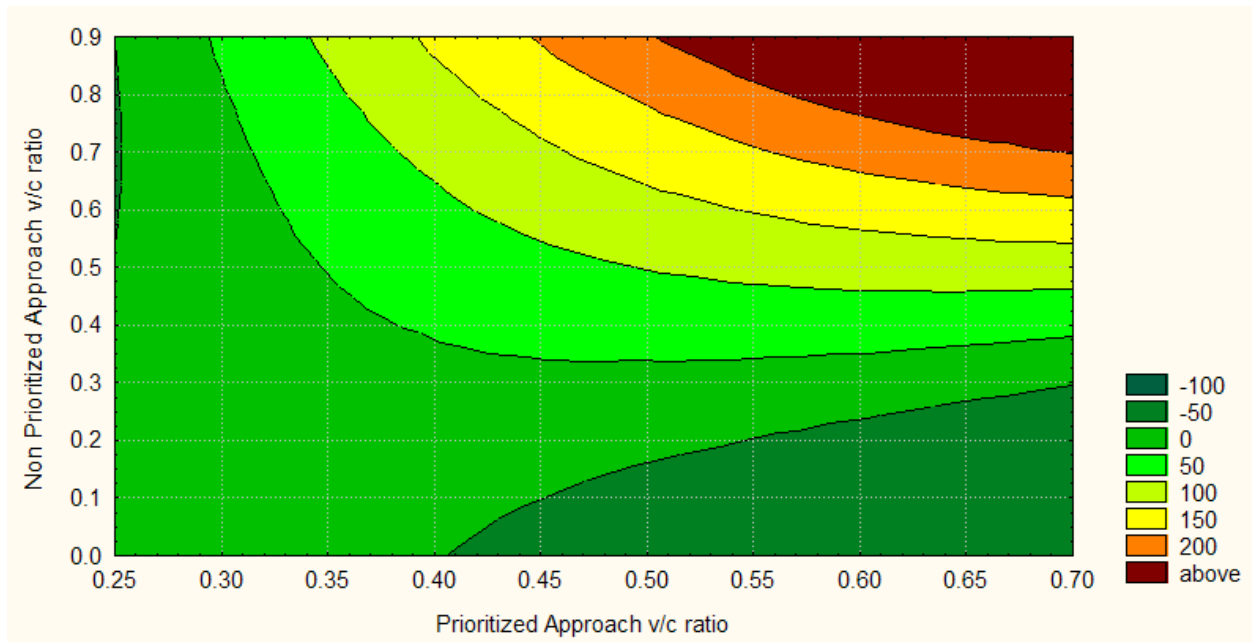
Figure 9.8: Delta GHG Emission (mg/PM peak hour)

Regression models were fit on results in Table 9.3. Table 9.6 show the regression model parameters. About 57% of the variation in the data can be explained by regression for delta vehicular delay. Only 9% of the variation in data can be explained by model regressed for bus delay variability.

Table 9.6: Regression on the generalized results

Performance measure	Multiple coefficient of determination	Intercept	Prioritized approach coefficient	Non prioritized approach coefficient
Delta Vehicular Delay	0.57	-241.50	27.40	676.84
Delta Bus Delay	0.19	-9.64	-10.13	-28.78
Delta Person Delay	0.30	58.15	-253.34	-782.97
Delta Fuel Consumption	0.49	-155.60	24.06	421.17
GHG Emissions	0.49	-108.22	16.73	292.94
Bus Delay Variability	0.09	-4.98	0.44	-6.30

Generalized results can be used for TSP implementation studies using the regressed equations depicted in Table 9.6. Care should be observed by observing the amount of variation in the data explained by the regressed model.

Chapter 10
Conclusions and Recommendations

Transit Signal Priority (TSP) is an important ITS component for improving transit service, transit system efficiency, and reliability (schedule adherence). Transit agencies seeking to improve transit service performance are increasingly considering the deployment of TSP. The estimation of TSP performance is not a trivial task as the impact of TSP on transit service and on the general traffic stream is a function of many factors, including: intersection geometry, signal timings, traffic demands, TSP strategies and parameters, transit vehicle headways and time when transit vehicles arrive at the intersection. Despite the great research effort on TSP pre-deployment and post-deployment studies, implementation of TSP is still based on intuitive methods. A major reason is greater reliance on simulation and absence of in house expertise of the same.

Due to financial constraints, transit agencies are often able to deploy TSP at only a portion of all of the candidate intersections. A better understanding of TSP performance providing a trade off between the person delay and GHG emissions could provide a more rational basis for prioritization of TSP implementation. Unfortunately, this type of information is not readily available. Consequently, there is a need to develop methods that quantify the estimation of TSP performance and its environmental impacts.

Analytical TSP models have been proposed to assess the TSP performance on signalized intersection. However, these studies have not fully addressed some of the fundamental issues of TSP modeling that influence TSP performance, such as impact of TSP strategies for the entire analysis period, impact of bus time of arrival during the signal cycle, impact of level of progression and impact of day-to-day variability of peak hour volume on delay

In this dissertation, we have explored the use of analytical queue models in developing and evaluating TSP green extension and red truncation control strategies. This chapter highlights the main contributions of this thesis research and presents directions for future work using the proposed analytical TSP model.

10.1 Major Contributions

The major contribution of this research concerns the conceptual aspects of the use of analytical TSP queue models for estimation of TSP performance in order to assist in prioritization of candidate intersections for TSP implementation.

The specific contributions made in this dissertation are as follows:

1. The dissertation work quantified the impact of day-to-day variability of intersection peak hour approach volumes on intersection delay. Demonstrated that this impact is not insignificant, and therefore should not be ignored. Specifically, showed with evidence that computing the intersection delay based on the average volumes, and ignoring the variability of these volumes, under-estimates the true average intersection delay.

2. Established using field data, the characteristics of the distribution of approach peak hour volume (i.e. the distribution is normally distributed with coefficient of variation of 0.087).

3. Developed and validated a set of analytical equations that can be used to estimate the impact of TSP on vehicle delays for two phase fixed time signal operation. The derivation of analytical model for evaluation of TSP performance using the green extension and red truncation TSP strategies has been conducted. These model permits estimation of delay occurring at a signalized intersection operating with or without TSP control. A validation of derived models with analytical study and microscopic simulation is also conducted to show that the results from proposed queue representation based analytical models are reasonable.

4. Expanded the proposed analytical model to consider the following:

   o Up to 8 phase fixed time signal control

   o Deterministic and Poisson arrival distributions

   o Quality of progression

   o Distribution of bus arrival times within the cycle

   o Variability of Peak Hour Volume

The use of analytical transit signal priority models in TSP implementation and operation studies is only possible if existing analytical models are able to capture, with reasonable accuracy, the complex interactions of the factors that influence TSP performance. Therefore, a fundamental prerequisite to increase the scope of analytical models applied to TSP performance is to ensure that important factors have been accurately applied based on observational data and that analytical TSP models produce estimates of TSP performance that can be verified from microscopic simulation or real world observations. An enhanced use of queue representations to examine impact on TSP performance for TSP implementation and intersection prioritization has been proposed in this thesis. The proposed model provides an alternative analytical TSP modeling platform to microscopic simulation or field studies. The proposed model considers the interactions between transit detection time, time required for transition signal timings and queue dissipation time.

The generalized model was embedded into a software module. The module permits user to specify wide range of factors that influence TSP performance.

5. Developed a model to estimate the impact of TSP on fuel consumption, GHG emissions, and variability of bus delays. A link between the TSP performance and environmental impacts is developed.

6. Used the proposed model to confirm that the quality of progression has negligible impact on performance of TSP. TSP impacts are sensitive to TSP parameters and to approach v/c values. Implementation of TSP may results in positive or negative impacts (in terms of vehicle delay, person delay, fuel consumption, and emissions). TSP may reduce person delay while simultaneously increasing fuel consumption and GHG emissions (although it is possible for TSP to result in net benefits in all measures).

7. Demonstrated the use of the proposed model to prioritize TSP deployment. The model was applied on 16 intersections in Waterloo Region to demonstrate the application of the proposed model. A prioritization was conducted based on the estimated TSP performance measures. The proposed model was applied to sixteen different intersections each with specific traffic volume, geometry, and operational attributes.

The models developed in this thesis do not consider all impacts of TSP and therefore the following limitations must be considered when applying the models and interpreting their results:

1. The developed models do not consider the impact of modal shift due to TSP implementation and consequently long term TSP benefits are likely underestimated – particularly when TSP is deployed at a sufficient number of intersections along a route that the cumulative effect in terms of reductions in mean bus delay and bus delay variability is substantial.

2. The performance measures provided by the models do not reflect the impact that TSP may have on reducing transit agency operating costs due to the potential to reduce fleet size requirements as a result of reduced route travel times.

10.2 Future Research

The results from this dissertation work demonstrate that an analytical queue representation based platform can be useful in prioritization of signalized intersections for TSP implementation. Some of the specific research problems for further research are identified as follows:

1. The module can be configured to model high frequency bus arrivals with in single cycle by altering the signal-timing generator. This area is important for transit agencies with high frequency transit. It is recommended that a future research be conducted examining high frequency transit arrivals with multiple TSP requests within a single signal cycle.

2. The current practice of TSP operation is no compensation to the non-prioritized approach after the TSP has been granted. No recovery transition is provided in order to compensate the non-prioritized approach. Abdy and Hellinga [65] showed that even relatively naïve-compensating operation resulted in TSP performance improvements. It is recommended that this module be used to examine the impact of non-prioritized approach green time compensation in subsequent cycle and the results be compared with those estimated in literature [64].

3. Several transit agencies employ a recovery transition after the signal has been interrupted due to emergency vehicle pre-emption. This recovery transition spans over several signal cycles with a goal of smoothly transition the signal operations. It is recommended that similar cycle recovery transition is investigated using this developed module. The study will be a milestone in reducing the TSP negative impacts.

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Appendices M/D/1 and D/D/1 Module

```
' M/D/1 and D/D/1 Delay Calculations
' Developed by Abdy (2008)

Option Explicit   ' Making sure there is no undefined quantity in the program
Option Base 1     ' Making sure that all arrays start from 1 and not from 0

Sub DelayCalculations()

Dim bta, SIGNALFLAG, colid, rowid, gid, flag, aa, bb, phaa, md1 As Integer
Dim pointa1() As Single
Dim pointa2() As Single
Dim pointa3, pointa4, pointa3res, pointa4res, greentimeres, greencuml, greencum2 As Single
Dim delay, lanedelay, vehdelay As Single
Dim Cycledelay, btadelay, detbtaphase, pervolume, pervol, totdelay, nototdelay As Range
Dim phase, sat, btaphase As Integer
Dim cycle, Cyclelength, pos, Tsp, lowerbound, upperbound, lbdsum, pointdiss As Integer
' pos = counter used to indicate phase number (1 <= pos <= 8)

Dim lanegroup, phid, interval, buspresence, iterid, sumgreen, phpresence As Integer
Dim greentime, resflag, initflag, nophase, i, percentile, busgreen, busg1, iterate As Integer
Dim initq, resq, lambda, mu, mubus, busdelay, busdelay1, busqueue, grem, btt, totaldelay, busarrival As Single
Dim tspdown, tspup, perup, perdown, lnup, lndown As Integer
Dim depsum As Double
Dim qq, cmgr As Integer

' Bus delay estimation declaration
Dim lanebusdelay, busac, busdc, busdel, busqu As Single
Dim buspp, busdepart, busquf As Integer

    Application.ScreenUpdating = False

' Estimation of run time
    Dim Start, Finish, TotalTime
    Start = Timer

    'TSP DELAY ESTIMATION

      'Obtain the Current signal timings
        'Application.Calculation = xlCalculationManual
        'Module1.TSPtimings
        'Application.Calculation = xlCalculationAutomatic

      cycle = ThisWorkbook.Sheets("upstream").Cells(80, 6)
      Cyclelength = ThisWorkbook.Sheets("upstream").Cells(39, 13)
      nophase = cycle * 8
      interval = ThisWorkbook.Sheets("upstream").Cells(86, 13)

      ReDim pointa1(nophase, 12) As Single
      ReDim pointa2(nophase, 12) As Single


      Sheets("upstream").Range("BR5:CD15").ClearContents
      Sheets("upstream").Range("BR20:CD30").ClearContents

      Sheets("upstream").Select
      Set totdelay = Range("BR5:CD5")
      Set nototdelay = Range("BR20:CD20")

      Sheets("upstream").Select
      Set pervol = Range("AN5:AY5")  ' THIS SEEMS TO DESIGNATE THE FIRST LINE OF LANGE GROUP VOLUMES AS PERVOL

'For percentile = 1 To 10  ' [ABDY] Jun 02-09 This loop runs different percentiles or different v/c ratio levels.
For percentile = 1 To 2


      ' We need pervol to select different v/c ratios when running a full model.
      Sheets("upstream").Select
      pervol.Select
      Selection.copy
      Sheets("upstream").Select
      Range("B13").Select
      ' This copies the volumes from first row of LG volumes as a function of v/c ratio to lane group arrival rate input range (B13 - M13)

      Selection.PasteSpecial Paste:=xlPasteValuesAndNumberFormats, Operation:= _
      xlNone, SkipBlanks:=False, Transpose:=False

    'MD1 creation of the arrival curve
    '**********************************************************************************
    '**********************************************************************************
    'Declaration
    Dim lg, cyc, sumphase, sumg, green, laneiden, tt As Integer
    Dim SIGNALFL(12, 400) As Double ' ZRA changed dimension from 240 to 400 on March 4-09
     ' generating the cummulative times on the main and cross street
    '**********************************************************************************
```

```
Application.Calculation = xlCalculationManual
Sheets("Sheet2").Range("C5:II16").ClearContents

'ReDim SIGNALFL(12, ((cycle + 1) * 8))
laneiden = 0

For lg = 1 To 12   ' lanegroups
        tt = 1
        laneiden = laneiden + 1
            ThisWorkbook.Sheets("Sheet2").Cells(4 + laneiden, 3) = "Lane Group" & lg

        sumg = 0    ' initializing the cummulative time line
        For cyc = 1 To (cycle + 1) ' no of cycles within the bus headway
            For sumphase = 1 To 8   ' no of phase
                If ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg) > 0 Then
                    green = ThisWorkbook.Sheets("upstream").Cells(42, 1 + sumphase)
                      If green > 0 Then
                      sumg = sumg + green
                      ThisWorkbook.Sheets("Sheet2").Cells(4 + laneiden, 3 + sumphase + ((cyc - 1) * 8)) = sumg
                        If ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1 Then
                        SIGNALFL(lg, tt) = 1
                         tt = tt + 1
                       ElseIf ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) <> 1 Then
                        SIGNALFL(lg, tt) = 2
                        tt = tt + 1
                       End If
                      ElseIf green <= 0 Then
                       ThisWorkbook.Sheets("Sheet2").Cells(4 + laneiden, 3 + sumphase + ((cyc - 1) * 8)) = sumg
                      SIGNALFL(lg, tt) = 0
                      tt = tt + 1
                    End If
                  ElseIf ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg) <= 0 Then
                       ThisWorkbook.Sheets("Sheet2").Cells(4 + laneiden, 3 + sumphase + ((cyc - 1) * 8)) = sumg
                    SIGNALFL(lg, tt) = 0
                    tt = tt + 1
                  End If
              Next sumphase
          Next cyc
      Next lg

'************************************************************************************************
'Cummulative green time generated on the Sheet2 at this point

' Now we need to generate
    ' Proportion of vehicles arrving during green / red (Pg, Pr)
    ' Number of Vehicles (Ng, Nr),
    ' exponential headways (tg,tr), and
    ' adjusted beta exponential headways (adjbetag, adjbetar)

'Declaration
Dim gr, red, Ng(12), Nr(12), zz As Integer
Dim pg(12), pr(12), ld, headway, rand() As Single
Dim tgavg(12, 500), travg(12, 500), betag(12), betar(12), adjbetag(12, 500), adjbetar(12, 500), sumtgavg(12), sumtravg(12) As Double
Dim randm(12, 500), randc(12, 500) As Double
Randomize
'Clearing the area
Sheets("Sheet2").Range("D20:AB919").ClearContents
Sheets("Sheet2").Range("AE20:AP919").ClearContents
Sheets("Sheet2").Range("AT20:BE919").ClearContents
headway = ThisWorkbook.Sheets("upstream").Cells(80, 2)

'Generating (Pg,Pr) and (Ng,Nr) for all lanegroups
'************************************************************************************************
For sumphase = 1 To 8
   For lg = 1 To 12
      If (ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1) Then
         gr = ThisWorkbook.Sheets("upstream").Cells(42, 1 + sumphase)
         ld = ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg)
         red = Cyclelength - gr
         pg(lg) = gr / Cyclelength
         pr(lg) = red / Cyclelength
         Ng(lg) = Round(pg(lg) * ld * (headway / 60), 0)
         Nr(lg) = Round(pr(lg) * ld * (headway / 60), 0)

      End If
   Next lg
Next sumphase

'Generating the exponential headways for Ng for all lanegroups
'************************************************************************************************
For sumphase = 1 To 8
   ' Generating the tg exponential headways
   For lg = 1 To 12
     If (ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1) And (Ng(lg) > 1) Then
        ReDim rand(Ng(lg))
        gr = ThisWorkbook.Sheets("upstream").Cells(42, 1 + sumphase)
        red = Cyclelength - gr
          For zz = 1 To Ng(lg)
              rand(zz) = Rnd()
              'rand(zz) = ThisWorkbook.Sheets("rand").Cells(2 + zz, lg)
              ld = pg(lg) * ((ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg)) / 3600) * (Cyclelength / gr) ' lambda g
              tgavg(lg, zz) = -Log(rand(zz)) * (1 / ld) ' -ln(U1)t and t = 1/lambda g
```

147

```vba
                sumtgavg(lg) = sumtgavg(lg) + tgavg(lg, zz)
            Next zz
        End If
    Next lg
Next sumphase

' Generating the adjusted exponential headways for all lanegroups
'*********************************************************************************

For sumphase = 1 To 8
    For lg = 1 To 12
        If (ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1) Then
            For zz = 1 To Ng(lg)
                betag(lg) = (60 * headway * pg(lg)) / sumtgavg(lg)
                adjbetag(lg, zz) = betag(lg) * tgavg(lg, zz)
                ThisWorkbook.Sheets("Sheet2").Cells(19 + zz, 3 + lg) = adjbetag(lg, zz)
            Next zz
        End If
    Next lg
Next sumphase

'Generating the exponential headways for Nr for all lane groups
'*********************************************************************************
For sumphase = 1 To 8
    ' Generating the tg exponential headways
    For lg = 1 To 12
        If (ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1) And (Nr(lg) > 1) Then
            ReDim rand(Nr(lg))
            gr = ThisWorkbook.Sheets("upstream").Cells(42, 1 + sumphase)
            red = Cyclelength - gr
            For zz = 1 To Nr(lg)
                rand(zz) = Rnd()
                'rand(zz) = ThisWorkbook.Sheets("rand").Cells(2 + zz, 12 + lg)
                ld = pr(lg) * ((ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg)) / 3600) * (Cyclelength / red) ' lambda g
                travg(lg, zz) = -Log(rand(zz)) * (1 / ld) ' -ln(U1)t and t = 1/lambda g
                sumtravg(lg) = sumtravg(lg) + travg(lg, zz)
            Next zz
        End If
    Next lg
Next sumphase

' Generating the adjusted exponential headways for all lanegroups
'*********************************************************************************

For sumphase = 1 To 8
    For lg = 1 To 12
        If (ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1) Then
            For zz = 1 To Nr(lg)
                betar(lg) = (60 * headway * pr(lg)) / sumtravg(lg)
                adjbetar(lg, zz) = betar(lg) * travg(lg, zz)
                ThisWorkbook.Sheets("Sheet2").Cells(19 + zz, 16 + lg) = adjbetar(lg, zz)
            Next zz
        End If
    Next lg
Next sumphase

'*********************************************** CREATION OF POISSON ARRIVAL CURVE*******************
' Now we have generated the list of Nr and Ng headways,
' Next step is to create the arrival curve from these headways
' By selecting Nr headways for Red interval and Ng Headways for Green Interval

'Decleration

Dim yy, N, pp, rr, gg As Integer
Dim SumH As Double


For lg = 1 To 12
    SumH = 0
    pp = 1
    rr = 1
    gg = 1
    If ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg) > 0 Then
        N = Ng(lg) + Nr(lg)
        If N > 1 Then

            For yy = 1 To N

                ' Now we need to determine whether the headway fall within green or within red
                '*********************************************************************************

Line12:         If (SumH < ThisWorkbook.Sheets("Sheet2").Cells(4 + lg, 3 + pp)) Then
                    If SIGNALFL(lg, pp) = 1 Then
                        If gg <= Ng(lg) Then
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetag(lg, gg)
                            SumH = SumH + adjbetag(lg, gg)
                            gg = gg + 1

                            ' This step ensures that the program switch back to Nr when Ng has been reached
                            '*********************************************************************************
                        ElseIf gg > Ng(lg) Then
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetar(lg, rr)
                            SumH = SumH + adjbetar(lg, rr)
```

```
                                        rr = rr + 1
                                    End If

                            ElseIf SIGNALFL(lg, pp) = 2 Then
                                If rr <= Nr(lg) Then
                                    ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetar(lg, rr)
                                    SumH = SumH + adjbetar(lg, rr)
                                    rr = rr + 1

                            ' This step ensures that the program switch back to Ng when Nr has been reached
                            '*******************************************************************************
                                ElseIf rr > Nr(lg) Then
                                    ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetag(lg, gg)
                                    SumH = SumH + adjbetag(lg, gg)
                                    gg = gg + 1
                                End If
                            End If

                        ' Once the headway fall into the "OTHER" (i.e. Ng headway into red interval/ Nr headway into green) then Sumh is >
                        '*******************************************************************************
                        ElseIf (SumH > ThisWorkbook.Sheets("Sheet2").Cells(4 + lg, 3 + pp)) Then
                                If SIGNALFL(lg, pp) = 1 Then
                                    If gg <= Ng(lg) Then
                                        ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetag(lg, gg)
                                        SumH = SumH + adjbetag(lg, yy)
                                        pp = pp + 1
                                        gg = gg + 1
                                    ElseIf gg > Ng(lg) Then
                                        ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetar(lg, rr)
                                        SumH = SumH + adjbetar(lg, yy)
                                        pp = pp + 1
                                        rr = rr + 1
                                    End If
                                ElseIf SIGNALFL(lg, pp) = 2 Then
                                    If rr <= Nr(lg) Then
                                        ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetar(lg, rr)
                                        SumH = SumH + adjbetar(lg, yy)
                                        pp = pp + 1
                                        rr = rr + 1
                                    ElseIf rr > Nr(lg) Then
                                        ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 30 + lg) = adjbetag(lg, gg)
                                        SumH = SumH + adjbetag(lg, yy)
                                        pp = pp + 1
                                        gg = gg + 1
                                    End If
                                ' This step takes care of the intermediate phases
                                '*******************************************************************************
                                ElseIf SIGNALFL(lg, pp) = 0 Then
                                        pp = pp + 1
                                        GoTo Line12
                                    End If
                            ElseIf ThisWorkbook.Sheets("Sheet2").Cells(4 + lg, 3 + pp) = 0 Then
                                        pp = pp + 1
                                        GoTo Line12
                            End If
                    Next yy
                End If

    End If
Next lg

'Application.Calculation = xlCalculationAutomatic


' Creating second by second arrivals to be used in delay computation later
'*******************************************************************************

Dim ac, dc, Sumac, vehup, vehdown As Double
pp = 1
yy = 1


' Clearing the area

    Sheets("Sheet2").Range("BH20:BS1000").ClearContents


'Creating the cummulative vehicle arrivals
For lg = 1 To 12
    N = Ng(lg) + Nr(lg)
    Sumac = 0
        If N > 0 Then
            For pp = 1 To N
                ThisWorkbook.Sheets("Sheet2").Cells(19 + pp, 45) = pp
                vehup = ThisWorkbook.Sheets("Sheet2").Cells(19 + pp, 30 + lg)
                Sumac = Sumac + vehup
                ThisWorkbook.Sheets("Sheet2").Cells(19 + pp, 45 + lg) = Sumac
            Next pp
        End If
Next lg
```

149

```
      For lg = 1 To 12
         'If lg <> 1 And lg <> 4 And lg <> 7 And lg <> 10 Then
              If ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg) > 0 Then
                      N = Ng(lg) + Nr(lg)
                      Sumac = 0
                      vehup = 0
                      vehdown = 0
                      yy = 1
                      For pp = 1 To (headway * 60)   ' for every second of headway
                          ac = 0
Line22:                      vehup = ThisWorkbook.Sheets("Sheet2").Cells(19 + yy, 45 + lg)
                          vehdown = ThisWorkbook.Sheets("Sheet2").Cells(18 + yy, 45 + lg)
                          If (pp > vehdown) And (pp <= vehup) Then
                            'interpolate the values in between
                            ac = yy - ((vehup - pp) / ((vehup - vehdown)))
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + pp, 59) = pp
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + pp, 59 + lg) = ac
                          ElseIf (pp = (headway * 60)) Then
                            'interpolate the values in between
                            ac = yy - ((vehup - pp) / ((vehup - vehdown)))
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + pp, 59) = pp
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + pp, 59 + lg) = ac
                          ElseIf (pp > vehup) Then
                            If (yy < N) Then
                               yy = yy + 1
                               GoTo Line22
                            End If
                          End If
                      Next pp
              End If
         'End If
      Next lg


      ' Total number of vehicles

      For lg = 1 To 12
         ThisWorkbook.Sheets("upstream").Cells(5, 53 + lg).Value = Ng(lg) + Nr(lg)
      Next lg


      ' Initializing values to be re used

      For sumphase = 1 To 8
         For lg = 1 To 12
            If (ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1) Then
                  For zz = 1 To Ng(lg)
                      sumtgavg(lg) = 0
                  Next zz
            End If
         Next lg
      Next sumphase


      For sumphase = 1 To 8
         For lg = 1 To 12
            If (ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + sumphase) = 1) Then
                  For zz = 1 To Nr(lg)
                      sumtravg(lg) = 0
                  Next zz
            End If
         Next lg
      Next sumphase


      Application.Calculation = xlCalculationAutomatic



      ' Arrival Curves for each lanegroup has been created to be used for TSP and No TSP
      '**********************************************************************************

'For Tsp = 1 To 2  ' [ZRA] TSP = 1 NO TSP = 2 Mar 05-09
For Tsp = 1 To 2  ' [ZRA] Jun 04-09

   Sheets("upstream").Select
   'Set Cycledelay = Range("BB7:BN7")
   Set Cycledelay = Range("BB7:BO7")
   Set btadelay = Range("BB11")

      Sheets("Sheet2").Range("U9:AL409").ClearContents

      i = 1

      For bta = 1 To ThisWorkbook.Sheets("upstream").Cells(39, 13) Step interval
      'For bta = 70 To 75
      'For bta = 71 To 74
      'bta = 76

        ' Departure Curve for bus lanegroup is now created

            depsum = 0
            delay = 0
            pos = 1
```

150

```vba
    For lg = 1 To 12
        qq = 1
        For sumphase = 1 To nophase
            If (ThisWorkbook.Sheets("upstream").Cells(2 + lg, 26) = 1) Then

                mu = ThisWorkbook.Sheets("upstream").Cells(135 + lg, 1 + pos)
                If Tsp = 1 Then 'TSP Time line
                    greentime = ThisWorkbook.Sheets("Timings").Cells(502 + bta, 3 + pos)
                ElseIf Tsp = 2 Then 'Fixed time line
                    greentime = ThisWorkbook.Sheets("upstream").Cells(42, 1 + pos)
                End If

                If ThisWorkbook.Sheets("upstream").Cells(20 + lg, 1 + pos) = 1 Then
                    SIGNALFLAG = 1         ' Signal is green
                Else
                    SIGNALFLAG = 0             ' signal is red
                End If
            If greentime > 0 Then

                If (ThisWorkbook.Sheets("upstream").Cells(13, 1 + lg) > 0) Then

                    'Sheets("upstream").Select

                        For pp = 1 To greentime
                            If SIGNALFLAG = 1 Then   ' THe phase is green
                                dc = mu
                                ac = ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 59 + lg)
                                    If ((depsum + dc) >= ac) Then
                                        depsum = ac
                                        ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 74 + lg) = depsum
                                        delay = delay + (ac - depsum)
                                        qq = qq + 1
                                    ElseIf ((depsum + dc) < ac) Then
                                        depsum = depsum + dc
                                        ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 74 + lg) = depsum
                                        delay = delay + (ac - depsum)
                                        qq = qq + 1
                                    End If
                            ElseIf SIGNALFLAG = 0 Then

                                ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 74 + lg) = depsum
                                ac = ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 59 + lg)
                                delay = delay + (ac - depsum)
                                qq = qq + 1
                            End If
                        Next pp
                End If
            End If

            End If

            cmgr = cmgr + greentime
            pos = pos + 1
                If pos = 9 Then
                    pos = 1
                End If

        Next sumphase
    Next lg

'*****************************************************************************
    busg1 = 0 ' factor to account for bus time of arrival
    busdelay = 0 ' initializing the bus delay
    busdel = 0
    busqueue = 0 ' initializing the INITIAL queue ahead of bus when first detected
    buspresence = 0 ' initializing the bus detection value

    'positioning back

    Sheets("upstream").Range("BB6:BM6").ClearContents
    'Sheets("Sheet2").Range("BW20:CH500").ClearContents


    aa = 0
    bb = 0
    phaa = 0
    pos = 1
    lbdsum = 0
    busdel = 0

For lanegroup = 1 To 12
'For lanegroup = 3 To 3
If lanegroup = 2 Or lanegroup = 8 Or lanegroup = 11 Then
'If lanegroup = 8 Then

    qq = 1
    depsum = 0
    cmgr = 0
    delay = 0

    lanedelay = 0
```

151

```vba
lanebusdelay = 0
busdepart = 0
busquf = 0
busqu = 0




For phase = 1 To nophase
'For phase = 1 To 16   ' define the aggregation interval 160 seconds = 16 phase - 2 cycles (80 sec) of 8 phase each
'For phase = 1 To 88   ' define the aggregation interval 880 seconds = 88 phase - 11 cycles (80 sec) of 8 phase each
   mu = 0
   lambda = 0


   If Tsp = 1 Then  'TSP Time line
      greentime = ThisWorkbook.Sheets("Timings").Cells(502 + bta, 3 + phase)
   ElseIf Tsp = 2 Then 'Fixed time line
      greentime = ThisWorkbook.Sheets("upstream").Cells(42, 1 + pos)
   End If


   If greentime > 0 Then
      phaa = phaa + 1
   End If

'For lanegroup = lndown To lnup
greentime = 0
greentimeres = 0
pointa4 = 0
pointa3 = 0

' Estimating the lambda and mu for the current lanegroup
   If pos > 8 Then
      pos = 0
   End If

   lambda = ThisWorkbook.Sheets("upstream").Cells(116 + lanegroup, 1 + pos)
   mu = ThisWorkbook.Sheets("upstream").Cells(135 + lanegroup, 1 + pos)
   delay = 0

'************************************************************

' Since greentime is recalculated for conditions when queue dissipates, the next lanegroup need an updated greentime
         If Tsp = 1 Then  'TSP Time line
            greentime = ThisWorkbook.Sheets("Timings").Cells(502 + bta, 3 + phase)
         ElseIf Tsp = 2 Then 'Fixed time line
            greentime = ThisWorkbook.Sheets("upstream").Cells(42, 1 + pos)
         End If
'*************************************************************************************************

If greentime > 0 Then
   resflag = 0
   initflag = 0
   initq = 0
   resq = 0

   If ThisWorkbook.Sheets("upstream").Cells(20 + lanegroup, 1 + pos) = 1 Then
      'flag = ThisWorkbook.Sheets("upstream").Cells(20 + lanegroup, 1 + pos)
      SIGNALFLAG = 1        ' Signal is green
   Else
      SIGNALFLAG = 0            ' signal is red
   End If

   ' Bus time of arrival, determination of accumulated green prior to bta, queue ahead of bus
   If lanegroup <> 1 And lanegroup <> 4 And lanegroup <> 7 And lanegroup <> 11 Then   ' Ignoring the left turns
      If ThisWorkbook.Sheets("upstream").Cells(20 + lanegroup, 12) = 1 Then      'determining the lanegroup for TSB Bus

         btt = ThisWorkbook.Sheets("upstream").Cells(12, 32) '[ABDY] Added June 04-09

            'Determine the bus time of arrival phase in first cycle

            If Tsp = 1 Then

               For detbtaphase = 1 To 24

                  lowerbound = ThisWorkbook.Sheets("Timings").Cells(999 + (bta + btt), 2 + detbtaphase) 'ADDED btt on AUG 31, 2009
                  upperbound = ThisWorkbook.Sheets("Timings").Cells(999 + (bta + btt), 3 + detbtaphase) 'ADDED btt on AUG 31, 2009

                  'busarrival = bta + ThisWorkbook.Sheets("upstream").Cells(12, 32)

                  If (bta + btt) > lowerbound And (bta + btt) <= upperbound Then 'ADDED btt on AUG 31, 2009
                  'If busarrival > lowerbound And busarrival <= upperbound Then
                     btaphase = detbtaphase
                     GoSub enddet

                  End If

               Next detbtaphase
            ElseIf Tsp = 2 Then
```

152

```
                    For detbtaphase = 1 To 24
                        If detbtaphase = 1 Then
                            lowerbound = 0
                        ElseIf detbtaphase > 1 And detbtaphase <= 8 Then
                            lowerbound = (ThisWorkbook.Sheets("upstream").Cells(69, detbtaphase))
                        End If

                        upperbound = (ThisWorkbook.Sheets("upstream").Cells(69, 1 + detbtaphase))

                        'busarrival = bta + ThisWorkbook.Sheets("upstream").Cells(12, 32)

                        If (bta + btt) > lowerbound And (bta + btt) <= upperbound Then 'ADDED btt on AUG 31, 2009
                        'If busarrival > lowerbound And busarrival <= upperbound Then
                            btaphase = detbtaphase
                            GoSub enddet
                        End If
                    Next detbtaphase
                End If
            End If
        End If

                '*****************************************************************************

enddet:

        'PRESENCE OF QUEUE IN FIRST CYCLE

        initq = 0
        If phase = 1 And lanegroup < 13 Then
            initq = ThisWorkbook.Sheets("upstream").Cells(94 + lanegroup, 1 + phase)
        ElseIf phase <> 1 Then
            initq = (pointa2(phase, lanegroup) - pointa1(phase, lanegroup))
        End If

        If initq > 0 Then
            initflag = 1
        ElseIf initq <= 0 Then
            initflag = 0
        End If

        '*******************************************************

        'PRESENCE OF RESIDUAL QUEUE

        resq = (initq + (lambda * greentime)) - (mu * greentime)

        If resq > 0 Then
            resflag = 1
            greentimeres = 0
            pointdiss = 0
        ElseIf resq <= 0 And (mu - lambda) > 0 Then
            greentimeres = (initq / (mu - lambda))   ' initq+lambda * greentime = mu * greentime
            pointdiss = 1
            resflag = 0
        End If

        '*******************************************************

        Application.Calculation = xlCalculationManual

        If lanegroup <> 1 And lanegroup <> 4 And lanegroup <> 7 And lanegroup <> 11 And greentime > 0 Then   ' Ignoring the left turns
            If ThisWorkbook.Sheets("upstream").Cells(20 + lanegroup, 12) = 1 Then      'determining the lanegroup for TSB Bus
                btt = ThisWorkbook.Sheets("upstream").Cells(12, 32) '[ABDY] Added June 02-09

                'Now we know the phase bus will arrive, next we will step through to find queue
                If btaphase = 1 And buspresence <> 2 Then
                    buspresence = 1 'flag to identify that bus is now being served
                    busg1 = bta + btt     'time at which the bus arrive in a phase '[ABDY] Modified June 02-09

                    busqueue = (initq + (lambda * busg1)) - (mu * busg1)
                    If busqueue <= 0 Then  ' bus may arrive at a dissipated queue time
                        busqueue = 0
                        'btt = ThisWorkbook.Sheets("upstream").Cells(12, 32) '[ABDY] commented out on June 02-09
                        grem = greentime - (bta + btt)  '[ABDY] Added June 02-09
                        buspresence = 2 '[ABDY] added June 02-09 Bus checked out as there is no queue ahead.
                        busdelay1 = 0   '[ABDY] added June 02-09 There is delay to the bus

                        '[ABDY] commented out this loop as btt is added to bta and no need to determine
                        ' whether btt is within the greentime, as we have added btt to bta already
                                'If grem >= btt Then
                                    'busdelay1 = 0
                                    'buspresence = 2
                                'ElseIf grem < btt Then
                                    'busdelay1 = grem
                                'End If

                    ElseIf busqueue > 0 Then
                        grem = greentime - (bta + btt)
                        '[ABDY] Added on June 02-09
                        'Green time variable is used for both red time and green time
                        'busdelay1 = grem   '[ABDY] commented out on June 02-09
                    End If
```

153

```vb
'[ABDY] May 30-09 Comment out the followign if loop
' If a bus arrives on green with initq then we need this, but we have already got a value for
' busdelay1 and this will initialize the value again, therefore we don't need it.
'determine whether the bus can dissipate in the remaining green time ?
        'If (mu * grem) >= busqueue And busqueue > 0 Then
            'busdelay1 = busqueue / mu  'time to dissipate the queue ahead of bus in remaining green of current phase
            'buspresence = 2 'flag to identify that bus has departed
        'End If

ElseIf btaphase > 1 And btaphase <= 8 And buspresence <> 1 And buspresence <> 2 And btaphase = phase Then
    buspresence = 1
    busg1 = (bta + btt) - lowerbound   '[ABDY] Added the travel time (June -02 - 09)
    busqueue = (lambda * (busg1)) - (mu * busg1)
        If busqueue <= 0 Then  ' bus may arrive at a dissipated queue time
            busqueue = 0
            grem = upperbound - (bta + btt)   '[ABDY] Added June 02-09
            buspresence = 2              '[ABDY] Added June 02-09
            busdelay1 = 0               '[ABDY] Added June 02-09

            '[ABDY] commented out this loop as btt is added to bta and no need to determine
            ' whether btt is within the greentime, as we have added btt to bta already

                    'If grem >= btt Then
                      'busdelay1 = btt
                      'buspresence = 2
                    'ElseIf grem < btt Then
                      'busdelay1 = grem
                    'End If


        ElseIf busqueue > 0 Then
            grem = upperbound - (bta + btt)         '[ABDY] Added June 02-09

            '[ABDY] for TSP cases e.g. bta = 55 and btt = 12 and upperbound = 55, grem = -12
            If grem <= 0 Then
                grem = 0
            ElseIf grem > 0 Then
                grem = grem
            End If

            'busdelay1 = grem                 '[ABDY] June 02-09 bus delay need to be determined based on SIGNALFLAG
            'busdelay2 = bta - lowerbound           '[ABDY] Calculation revised (May 30 - 09)
        End If

        'We don't need this loop June 02-09
        'determine whether the bus can dissipate in the remaining green time
        'If (mu * grem) >= busqueue And busqueue > 0 Then
            'busdelay1 = busqueue / mu
            'buspresence = 2
        'End If
    End If

' at this point we have the queue (busqueue) that bus need to dissipate only [ABDY] June 02-09
  'Transfering it to next phase

        If buspresence = 1 And phase >= btaphase Then  '[ABDY] changed >= from > on June 02 -09
            If SIGNALFLAG = 0 Then   ' PHASE is red just add the red time to busdelay

            '[ABDY] Added this loop on June 02-09
            If phase = btaphase Then
                busdelay1 = grem
                grem = 0
            ElseIf phase > btaphase Then
                busdelay1 = busdelay1 + greentime
            End If

        ElseIf SIGNALFLAG = 1 Then   'phase is green now determine if bus can dissipate or not
            If ((mu * greentime) >= busqueue) Then

                '[ABDY] Jun - 02 - 09
                busdelay1 = busdelay1 + (busqueue / mu)      '[ABDY] Jun-02-09 busdelay1 and time of dissipation
                buspresence = 2                         ' to identify that the bus has dissipated

            ElseIf ((mu * greentime) < busqueue) Then
                busdelay1 = busdelay1 + greentime            ' bus delay1 and greentime of phase
                busqueue = busqueue - (mu * greentime)         ' busqueue is now reduced since the phase is green
            End If
        End If
    End If
  End If
 End If

    Application.Calculation = xlCalculationAutomatic

'*****************************************************************

' ESTIMATION OF DELAY
If phase = 1 Then
    pointa1(phase, lanegroup) = 0
    pointa2(phase, lanegroup) = initq
End If
```

```
            pointa3 = pointa2(phase, lanegroup) + lambda * greentime

        If pointdiss <> 1 Then
            pointa4 = pointa1(phase, lanegroup) + mu * greentime
        ElseIf pointdiss = 1 Then
            pointa4 = pointa2(phase, lanegroup) + lambda * greentime   ' portion of curve after queue dissipates then arrivals are equal to departures
            If phase <> 1 Then
                pointa3res = pointa2(phase, lanegroup) + lambda * greentimeres
                pointa4res = pointa1(phase, lanegroup) + mu * greentimeres

            ElseIf phase = 1 Then
                pointa3res = initq + lambda * greentimeres
                pointa4res = mu * greentimeres
            End If
        End If

        'Transfering values to next phase
        If phase < nophase Then
            phid = phase + 1
            pointa1(phid, lanegroup) = pointa4
            pointa2(phid, lanegroup) = pointa3
        End If


' ******************************************************************************************************************************
' ******************************************************************************************************************************
        ' MD1 Vehicular Delay Estimation
        ' Now we have the poisson arrival curve for every lanegroup
        ' We need to first generate the departure curve and the substract it from the arrival curve to find the delay
        If greentime > 0 Then

            If (ThisWorkbook.Sheets("upstream").Cells(13, 1 + lanegroup) > 0) Then

                'Sheets("upstream").Select

                For pp = 1 To greentime
                    If SIGNALFLAG = 1 Then   ' THe phase is green
                        dc = mu
                        ac = ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 59 + lanegroup)
                        If ((depsum + dc) >= ac) Then
                            depsum = ac
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 74 + lanegroup) = depsum
                            delay = delay + (ac - depsum)
                            qq = qq + 1
                        ElseIf ((depsum + dc) < ac) Then
                            depsum = depsum + dc
                            ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 74 + lanegroup) = depsum
                            delay = delay + (ac - depsum)
                            qq = qq + 1
                        End If
                    ElseIf SIGNALFLAG = 0 Then

                        ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 74 + lanegroup) = depsum
                        ac = ThisWorkbook.Sheets("Sheet2").Cells(19 + pp + cmgr, 59 + lanegroup)
                        delay = delay + (ac - depsum)
                        qq = qq + 1
                    End If
                Next pp
            End If

        End If

    ' Bus delay using MD1 [ABDY] Jun 03-09 Using arrival and Departure Curve

    If (ThisWorkbook.Sheets("upstream").Cells(2 + lanegroup, 26) = 1) Then

            btt = ThisWorkbook.Sheets("upstream").Cells(12, 32) '[ABDY] Added June 04-09
            busac = ThisWorkbook.Sheets("Sheet2").Cells(19 + (bta + btt), 59 + lanegroup)
            busdc = ThisWorkbook.Sheets("Sheet2").Cells(19 + (bta + btt), 74 + lanegroup)
            mubus = ThisWorkbook.Sheets("upstream").Cells(135 + lanegroup, 1 + pos)
            If ((busac - busdc) / mubus) <= 0 Then ' There is no bus queue and no time required for bus to dissipate
                busqu = 0
            ElseIf ((busac - busdc) / mubus) > 0 Then
                busqu = (busac - busdc) / mubus ' time required to dissipate the queue ' The bus need busqu seconds to dissipate
            End If


        If btaphase = phase And busdepart <> 1 Then        '[ABDY] Jun 03-09 The first phase
                If SIGNALFLAG = 1 Then
                    busdel = 0
                    busdepart = 1      ' The bus first phase FLAG
                    busquf = 2          ' this bus has departed in first phase
                    GoSub Endbus        ' this bus has departed in first phase
                ElseIf SIGNALFLAG = 0 Then
                    busdel = upperbound - (bta + btt)
                    busdepart = 1       ' The bus first phase FLAG
                End If
        End If
```

```
              If btaphase < phase And busquf <> 2 Then

                      If SIGNALFLAG = 0 Then   ' Signal is Red then delay / s is 1 sec
                          busdel = busdel + greentime
                      ElseIf SIGNALFLAG = 1 Then   ' Signal is Green then delay / s is 1 mu
                          If ((upperbound - lowerbound) - busqu) >= 0 Then ' Bus can dissipate in the green time
                              busdel = busdel + busqu
                              busquf = 2              ' FLAG that bus has departed
                              busdepart = 1
                              GoSub Endbus
                          ElseIf ((upperbound - lowerbound) - busqu) < 0 Then ' Bus cannot dissipate in the green time
                              busdel = busdel + (upperbound - lowerbound)
                              busqu = busqu - (upperbound - lowerbound)
                          End If
                      End If

              End If

          End If

Endbus:

          ' **********************************************************

          cmgr = cmgr + greentime

' **********************************************************************************************************************************
'**********************************************************************************************************************************


          ' NON GREEN PHASE TIMES
          ElseIf greentime <= 0 And lanegroup <= 16 And phase < nophase Then
              SIGNALFLAG = 0

          'Carry over point 1 and 2 to next cycle
              phid = phase + 1
              pointa1(phid, lanegroup) = pointa1(phase, lanegroup)
              pointa2(phid, lanegroup) = pointa2(phase, lanegroup)
          ElseIf greentime = 0 And lanegroup > 16 Then

          End If

          '************************************

          lanedelay = lanedelay + delay

          If (ThisWorkbook.Sheets("upstream").Cells(2 + lanegroup, 26) = 1) Then
              lanebusdelay = lanebusdelay + busdel
          End If


          pos = pos + 1

          If pos = 9 Then
              pos = 1
          End If

          aa = 0

Next phase


'ThisWorkbook.Sheets("upstream").Cells(7, 66) = busdelay1
   If (ThisWorkbook.Sheets("upstream").Cells(2 + lanegroup, 26) = 1) Then
       'ThisWorkbook.Sheets("upstream").Cells(7, 66) = lanebusdelay
       ThisWorkbook.Sheets("upstream").Cells(7, 66) = busdel   '[ABDY] added Jun 04-09
       ThisWorkbook.Sheets("upstream").Cells(7, 67) = busqu    '[ABDY] added Aug 30-09


   End If

ThisWorkbook.Sheets("upstream").Cells(6, 53 + lanegroup) = lanedelay

   End If 'lane group selections 3 and 9 endif
Next lanegroup

'Writing the values
   Sheets("upstream").Select
   Cycledelay.Select
   Selection.copy
   btadelay.Select
   Selection.PasteSpecial Paste:=xlPasteValuesAndNumberFormats, Operation:= _
      xlNone, SkipBlanks:=False, Transpose:=False

   Set btadelay = btadelay.Offset(1, 0)

   ThisWorkbook.Sheets("upstream").Cells(10 + i, 53).Value = bta
   i = i + 1


Next bta
```

```
        If Tsp = 1 Then
        Sheets("upstream").Select
        Range("BB9:BN9").Select
        Selection.copy
        totdelay.Select
            Selection.PasteSpecial Paste:=xlPasteValuesAndNumberFormats, Operation:= _
                xlNone, SkipBlanks:=False, Transpose:=False

        Set totdelay = totdelay.Offset(1, 0)

        'Sheets("upstream").Range("BA11:BN90").ClearContents

    ElseIf Tsp = 2 Then

        Sheets("upstream").Select
        Range("BB9:BN9").Select
        Selection.copy
        nototdelay.Select
            Selection.PasteSpecial Paste:=xlPasteValuesAndNumberFormats, Operation:= _
                xlNone, SkipBlanks:=False, Transpose:=False


        Set nototdelay = nototdelay.Offset(1, 0)

         'Sheets("upstream").Range("BA11:BN90").ClearContents

    End If

Next Tsp

Set pervol = pervol.Offset(1, 0)

Next percentile

' Returning to default values changed for speeding up the macro

    Application.ScreenUpdating = True


' Estimating the run time
    Finish = Timer
    TotalTime = (Finish - Start)
    MsgBox "Run time " & TotalTime & "sec"
End Sub
```