University of Alberta

Development and Implementation of an Adaptive Transit Signal Priority Strategy in Microscopic Simulation

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Transportation Engineering

Department of Civil and Environmental Engineering

Spring 2014
Edmonton, Alberta

ABSTRACT

Transit Signal Priority (TSP) strategies are widely used to reduce bus travel delay and improve bus service performance. State-of-the-art TSP strategies help buses cross intersections without stopping, either by green extension or red truncation, and enable adaptive TSP plans that reflect real-time traffic conditions. Among all existing adaptive TSP strategies, there are two types of approaches: 1) objective function-based optimization; 2) logic and (or) rule-based optimization. This thesis develops an adaptive TSP strategy via the objective-function approach. The key contributions include an accurate bus delay estimation model, which implements an adaptive TSP strategy into a programming problem, and an adaptive TSP simulation platform, which uses a full-scale signal emulator, ASC/3, in VISSIM. A case study in VISSIM is conducted to evaluate the proposed adaptive TSP strategy versus conventional TSP strategies. Finally, the proposed TSP is compared with previous studies to investigate advantages and disadvantages.

ACKNOWLEDGEMENT

It would not have been possible to finish my master thesis without the help and support of many people. First, I would like to thank my committee members for their guidance. I extend my sincere thanks and respect to my supervisors, Dr. Zhijun (Tony) Qiu and Dr. Amy Kim, who have given me valuable guidance, extensive support and great patience. It has been a great experience for me to work in Dr. Qiu's research group. The excellent research and collaboration environment gave me the opportunity to improve myself every day.

Special thanks go to my research teammates who will also be my lifelong friends. I would like to thank Dr. Pengfei Li. His instruction provides significant support not only on research ideas, but also on research techniques. I would also like to thank Dr. Jie Fang, Ying Luo, Gang Liu, Jing Cao, Elena Yin, Lin Shao, Md Hadiuzzaman and Md Ahsanul Karim, who have always been generous offering their help during graduate studies. Sincere appreciation goes to Rochelle Borchman and Jeffrey King for providing patient help in writing academic papers.

Last but not least, I wish to express appreciation to my family. Only with their support and understanding can I finally finish my graduation study. Thanks for their loving consideration and great confidence in me through all these years.

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LIST OF ABBREVIATIONS

Term	Full Name
APC	Automatic Passenger Count
ATC	Advanced Transportation Controllers
ATSP	Adaptive Transit Signal Priority
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
BRT	Bus Rapid Transit
CBD	Central Business District
CTA	Chicago Transit Authority
CV	Connected Vehicle
DTSP	Dynamic Transit Signal Priority
ETS	Edmonton Transit System
GA	Genetic Algorithm
HCM	Highway Capacity Manual
ITS	Intelligent Transportation System
LOS	Level Of Service
LRT	Light-Rail Transit
MAPE	Mean Absolute Percentage Error
MILP	Mixed Integer Linear Program
MOE	Measures Of Effectiveness
MSE	Mean Squared Error
NEMA	National Electrical Manufacturers Association

NTCIP	National Transportation Communications for ITS Protocol
OSTRAC	Optimized Strategy For Integrated Traffic And Transit Signal Control
PI	Performance Index
PRG	Priority Request Generator
PROMPT	Priority And Informatics In Public Transit
PRS	Priority Request Server
SCOOT	Split Cycle Offset Optimization Technique
SIL	Software-In-The-Loop
SQP	Sequential Quadratic Programming
SS-RTSP	South Snohomish Regional Transit System Priority
TSP	Transit Signal Priority
TTC	Toronto Transit Commission
UTC	Urban Traffic Control
UTOPIA	Urban Traffic Optimization By Integrated Automation
VTA	Santa Clara Valley Transportation Authority

CHAPTER 1. INTRODUCTION

This chapter provides not only the academic and practical background of Transit Signal Priority (TSP), but also the current TSP problem statement and research objective.

1.1. Background

As the world population increases, so too does travel demand, especially in dense areas, such as central business districts, governments and transportation management agencies are becoming increasingly mindful of the potential traffic congestion problems caused by high travel demand. As a countermeasure, these agencies encourage travelers to take public transit as opposed to private automobiles. However, most travelers will not take public transit until it becomes more reliable and efficient. These benefits can be obtained from several advanced transportation technologies, including Transit Signal Priority (TSP).

TSP is a strategy that provides intersection-crossing priority to buses via sensors that detect bus presence and prioritize bus crossing through either green extension or red truncation. For its potential benefits, TSP has recently attracted much research attention. In several studies, TSP reduced transit travel times and increased transit schedule adherence by decreasing intersection delays and stops. It is estimated that, in urban areas, TSP reduces signal-related bus delay by 10-25% of the total bus travel time (Sunkari et al. 1995).

Several Canadian cities have implemented or plan to implement a TSP strategy as one component of an Intelligent Transportation System (ITS) plan to improve public transit service. For example, Toronto began its TSP strategy in 1990. By 2009, approximately 350 of its signalized intersections were equipped and functional with TSP. The City of Edmonton implemented TSP along a major bus corridor in the downtown area.

1.2. TSP Concept and Control Strategies

TSP is an operational strategy that provides priority to buses crossing a signalized intersection. TSP reduces bus delays and stops; hence, improving service reliability and on-time performance.

Generally, there are three categories of TSP control strategies: passive, active and adaptive (Baker et al. 2002). Passive TSP is a prototype control that employs the simplest logic and method. Active TSP is more intuitive than passive TSP, and it is the most widely used control strategy. Adaptive TSP is a newer control strategy designed to overcome some of drawbacks of active TSP. For example, one of the major drawbacks of active TSP is destruction of timing plan and therefore hunting the general traffic delay. However, adaptive TSP is not yet mature enough to be implemented in most places.

1.2.1. Passive TSP

Passive TSP is a kind of fixed signal timing. The offsets and splits are modified in a way that, when a transit bus is scheduled to cross the intersection, the signal light is extended green through pre-determined programming. Passive TSP is not flexible for dynamic traffic or unexpected transit delay. Such strategy works well only when transit operation is predictable and uninterruptable, and the demand is low (Vincent et al. 1978). Fixed signal coordination cannot dynamically change to adapt to external interruption, such as recoverable congestion.

1.2.2. Active TSP

Active TSP is an evolution of passive TSP; it is more intuitive and flexible. Active TSP is based on sensors detecting approaching transit buses and granting appropriate crossing priority. There are two active TSP control tactics: green extension and red truncation; both are basic TSP functions that almost every active TSP system supports.

Usually, active TSP has two primary elements: 1) the Priority Request Generator (PRG) sends a priority request when a transit vehicle, such as Light-Rail Transit (LRT), a bus or a tram, is detected. The PRG location is one way to distinguish different TSP architecture; and 2) the Priority Request Server (PRS) responds to the PRG request, processing it according to certain rules and directing the signal controller to react to or ignore the TSP request. The PRS is always located near the signal controller.

Currently, some signal controller manufacturers, such as Peek Traffic, Econolite and McCain, provide the active TSP system with hardware and software. There are three major types of TSP compatible controllers: NEMA controllers, Type 170 controllers, and Advanced Transportation Controllers (ATC). These controllers are implemented in several North American cities.

On its first day of operation, the MAX Bus Rapid Transit (BRT) project in Salt Lake City, UT showed a 15% (20min) reduction in bus travel time and achieved 97% on-time performance (ITS America 2010). In Silicon Valley, CA, the Santa Clara Valley Transportation Authority (VTA) employs the Bus Rapid Transit (BRT) program on its major transit corridor, which reduces bus delay by 19.4% and 9.2% for southbound and northbound, respectively. In Canada, some metropolises, such as Toronto, Vancouver and Calgary, employ TSP in the transportation network. The Toronto Transit Commission (TTC) buses and streetcars have been provided with priority at signalized intersections since 1990. This TSP strategy benefits Toronto buses with, on average, 5-9 seconds of two-direction delay at each signalized intersection. Up to 40% of transit delay and 20% of transit travel time are saved by granting bus priority (Toronto Transit Commission 2009). In 2000, Calgary Transit initiated a TSP project using GTT's (Global Traffic Technologies) Opticom system. The results show that the number of traffic signal stops was reduced by 32%, while the time spent stopped at traffic signals was reduced by 16%, or about two minutes per round trip (Calgary Transit 2004).

1.2.3. Adaptive TSP

Adaptive TSP provides priority to transit buses, while minimizing the negative impacts to other traffic. This type of TSP will dynamically search an optimal the priority timing plan to both serve the approaching transit bus and cause minimum impact to the general traffic. The optimization process is based on the real-time traffic and transit data. This system efficiently overcomes the shortcomings of active TSP; however, adaptive TSP requires more data, such as traffic volume and bus ridership, to adapt to the prevailing traffic condition. Because of this data requirement and its attainment difficulty and cost, adaptive TSP is not yet widely used. However, transportation researchers endeavour to accomplish the appropriate control algorithm for balancing transit delay and traffic delay.

1.3. Problem Statement

With increasing efforts toward and experiences in the application of adaptive TSP, there is no doubt that transit systems will reap significant, sustainable benefits. However, further research is required for the limitations that exist. Typically there are two sources to these limitations:

- **TSP concept**: common sense dictates that the signal timing at every intersection should be optimized with minimum control delay; however, the whole concept of TSP is to provide extra green time to transit buses. Regardless of which algorithm is used, this negates optimal signal timing; thereby, increasing the control delay. Many researchers and manufacturers make efforts to find an algorithm that can both give appropriate priority to buses and minimize the negative impact to other traffic. However, there are constraints in even the most state-of-the-art adaptive TSP control algorithms:
    - **Simplified bus delay**: in most previous adaptive TSP studies, bus delay is an important Performance Index (PI) indicator; however, as previous bus delay models are derived from cumulative vehicle

curve, they cannot cover all bus delay situations (Christofa et al. 2011; Li et al. 2011). For example, the bus stay and move in queue is not represented in previous bus delay models, causing underestimated bus delay impact.

- **Overflow condition**: in most previous adaptive or dynamic TSP studies, overflow is simplified or omitted, and cycle failure is not considered. However, the overflow condition is a perpetual traffic state parameter—ignoring the overflow condition in TSP control is evidence of a weak model.

- **Data accuracy**: conventional TSP is unable to transfer real time data, such as traffic volume, bus location and bus ridership, to the traffic control system. This lack of data leads to many potential problems; for example, the controller may grant priority to a bus with very low occupancy, while other traffic volume may be high, or the bus may miss the priority green time, which can be caused by inaccurate predicted arrival times and real time bus trajectory tracking. These problems are unavoidable when traditional data collection methods are used. New data collection systems may be the only solution to this shortcoming.

1.4. Research Objective

This research proposes a real-time adaptive TSP strategy using a new objective function with an advanced bus delay model. The proposed adaptive TSP strategy overcomes the limitations of previous studies; thereby, giving a more accurate and better optimized TSP control solution. There are three major goals of this thesis:

1. Develop a new adaptive TSP control strategy based on a novel bus delay estimation model;
2. Implement this adaptive TSP strategy into a mathematical problem; and
3. Develop an adaptive TSP simulation platform using a full-scale signal emulator.

1.5. Thesis Outline

This thesis includes 6 chapters. Chapter 1 provides TSP background as well as the present problem statement and research objectives. Chapter 2 is the literature review, which includes TSP history, classification and research fields. Chapter 3 introduces the proposed adaptive TSP control methodology with the assumptions and constraints. Chapter 4 introduces the detailed procedure of adaptive TSP control strategy implementation. Chapter 5 is the performance evaluation, comparison and results. Chapter 6 gives the conclusion and discusses the future work involved in the proposed adaptive TSP control. Figure 1-1 shows the structure of contents.

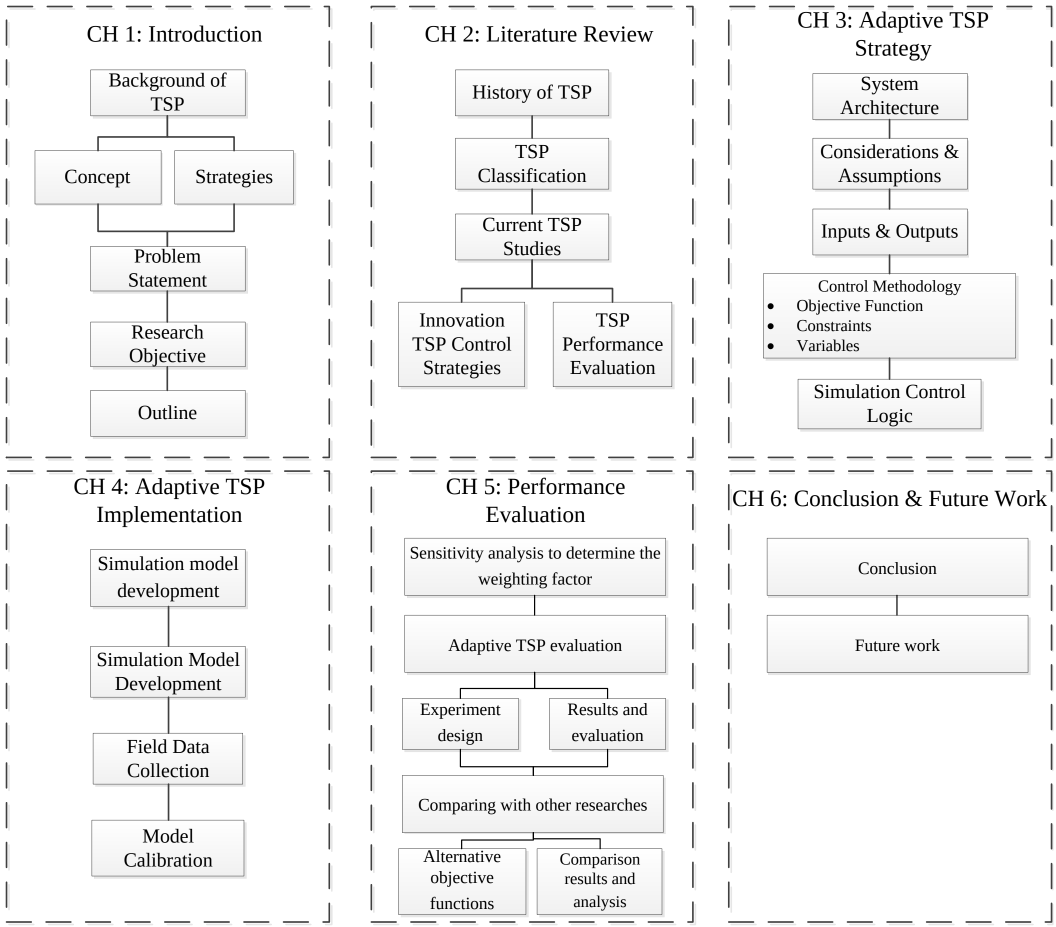


Figure 1-1 Thesis Contents Outline

CHAPTER 2. LITERATURE REVIEW

This chapter gives a review of existing research in the TSP field. The review is split into two major parts: 1) innovative TSP control algorithms; 2) TSP performance evaluation. This chapter also introduces some practical TSP studies, applications and experiences from other cities and areas.

2.1. The History of TSP

The first TSP system was developed in Europe in the 1960s. In the 1970s, the TSP concept was introduced to North America. The purpose of TSP is to help transit buses cross through intersections without stopping. In 1992, the Chicago Transit Authority (CTA) investigated TSP systems in several European countries, including Germany, France, the Netherlands and Switzerland. It was found that transit vehicles in Amsterdam, Netherlands experienced 10-20% travel time reduction compared to the no TSP scenario.

In 1993, Hounsell evaluated a TSP system named PROMPT (Priority and Informatics in Public Transit) in London, England. PROMPT was developed during the implementation and evaluation of real-time public transport priority based on the SCOOT control system (Hounsell et al. 1995). The PROMPT project aimed to develop and implement a new TSP logic according to the prevailing green time and degree of saturation on approaches. This system used inductive loop detectors and AVI technology to monitor the transit vehicle approach.

Another TSP system, implemented in Turing, Italy, was part of a traffic signal control system called UTOPIA (Urban Traffic Optimization by Integrated Automation) (Mauro et al. 1989). UTOPIA is a traffic-responsive Urban Traffic Control (UTC) system based on a hierarchical concept where intersection operations are set up by the central control system. The control system incorporates communications between intersections and a rolling horizon control algorithm so that signal decisions are based on traffic predictions for the next two minutes.

Most recently, several cities in North America, such as North Carolina, Washington, Maryland, Portland, Oregon and Pierce County, have reported successful TSP systems. For example, a 13-18% travel time reduction was reported for express buses along Route MD 2 in Anne Arundel County, Maryland (Maryland State Highway Administration 1993). In Portland, Oregon, a 5-12% bus travel time reduction was reported with no significant travel time increases for other roadway users (Kloos et al. 1995). After an extensive literature review, it is concluded that, aside from improved computing capability and detecting technology, the latest TSP systems have little algorithmic difference from the first TSP system developed in the 1970s.

2.2. TSP classification

Furth and Muller developed a TSP control classification system along three dimensions (Furth et al. 2000):

1. **Active and Passive**: passive TSP is a fixed signal timing that is determined according to the transit schedule. The offsets and splits are modified such that, when a transit bus is scheduled to cross the intersection, the signal light can give it a longer green opportunity. Active TSP is real-time control that can detect approaching transit buses and give them priority. It requires additional equipment, such as special detectors, transmission technologies, TSP-compatible signal controllers, etc. There are two active TSP control policies: green extension and red truncation. When a bus arrival is detected, green extension prolongs the green time past the programmed green phase to allow a bus to travel through the intersection uninterrupted. Conversely, red truncation initiates the green phase to accommodate buses that arrive during a scheduled red phase.
2. **Full and Partial**: full priority control gives zero-delay service to transit buses, regardless of signal timing or impact to other traffic. Partial priority gives several limits to either green extension or red truncation, so that the signal timing suffers the least disruption. Under partial priority, transit buses may fail to cross the intersection.
3. **Conditional and Unconditional**: conditional priority gives priority based on real-time transit information and traffic conditions, the passenger load, schedule adherence and (or) service status. Unconditional priority grants priority to every bus, even if the bus is ahead the schedule.

2.3. Current TSP Control Studies

Generally, current TSP studies contain two research elements: 1) innovative TSP control strategies; and 2) TSP performance evaluation methodologies.

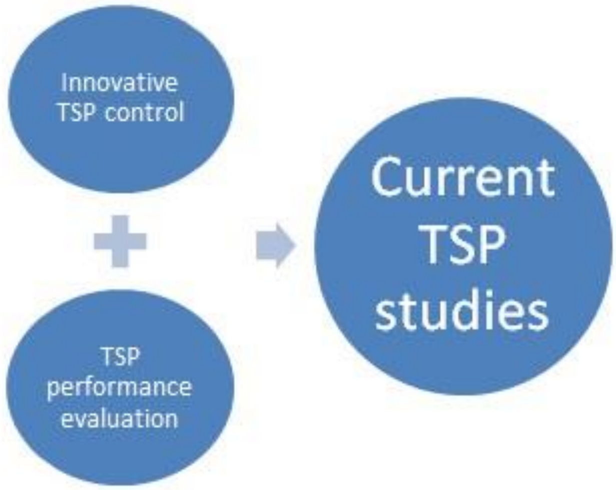


Figure 2-1 Components of Current TSP Studies

2.3.1. Innovative TSP Control Strategies

Innovative TSP control, also called adaptive TSP or dynamic TSP, has two general algorithmic approaches: 1) build the objective function and solve the optimization problem; and 2) pre-define the rules and then the control signals based on those rules. For the optimization approach, most previous studies used PI or delay as the objective function. The rule-based approach has two types of solutions: 1) the logic process, which means that the control is based on predefined logic procedures. These solutions are usually represented by a logic follow chart; and 2) the decision tree, which is used less often than the logic process. A decision tree is established and examined based on the performance of each “branch” of the tree. The categories of TSP control algorithms are shown in the Figure 2-2:

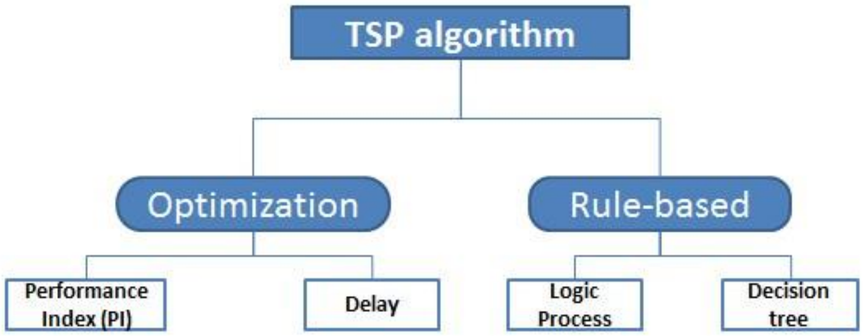


Figure 2-2 Innovative TSP Control Strategy Classification

Optimization-based approach

Delay-based optimization

Most adaptive TSP control algorithms use delay as the objective of their control. The reason is that delay can directly represent the impact of signal control on both traffic and transit. For example, Li (Li 2010) developed an adaptive transit signal priority (ATSP) system in which the ATSP algorithm predicts bus arrivals, traffic queuing conditions, signal status and pedestrian presence to determine TSP strategies. With those four real-time data types, Li designed a mixed integer linear program (MILP) model to minimize a weighted sum of delay at isolated intersections. Equation (1) is that objective function and represents the overall delay, which includes two parts. The first part before the plus sign is the function of overall general traffic delay. The function after summarize represents the total bus weighted delay. It comes from the geometric relationship in diagram of cumulative vehicle versus time.

$$\min d = \sum_{i=1}^{8} \left[\frac{\mu_i}{2}\rho_i (r_{1i}+r_{2i})^2 - r_{2i}\mu_i \min\left(g_{1i}, \rho_i r_{1i}\right)\right] + w_b \frac{R}{t_q} \max\left(t_q - T_{bus}, 0\right) \quad (1)$$

Where,

- d is total system delay;
- g_{ji} is the minimum green time for movement *i* in cycle *j*;
- μ_{i} is saturation flow rate for movement *i*;
- r_{ji} is the red duration time for movement *i* in cycle *j*;
- $\rho_{\mathrm{i}} = \frac{\lambda_{\mathrm{i}}}{\mu_{\mathrm{i}}-\lambda_{\mathrm{i}}}$, λ_{i} is traffic arrival rate for movement *i*;
- R is the red time;
- T_{bus} is bus arrival time;
- t_{q} is queue discharged time; and
- w_{b} is the weighting factor for buses.

Li's ATSP takes into account three cycles for a complete TSP procedure: 1) the previous cycle, during which the bus arrival is detected and predicted; 2) the current cycle, during which the TSP operation is active; and 3) the next cycle, during which the timing plan is recovered. There are three assumptions in Li's model: 1) the impact of ATSP lasts three consecutive cycles; 2) the traffic demand within the three control cycles is stationary; and 3) the TSP request will not be activated at over-congested intersections.

Other studies have also tried to realize adaptive TSP control by minimizing different types of delay. Head et al. developed a decision model for priority control (Head et al. 2006). Their objective was to minimize bus delay. However, they calculated bus delay by bus arrival time minus red time. Thus, their calculation of bus delay only represents red truncation. Other studies use average delay or personal delay as the objective, such as in Zhou et al. (Zhou et al. 2007) and Christofa et al. (Christofa et al. 2011). Zhou et al.'s study gives an objective function calculated by the sum of individual delay over the total traffic delay to obtain the average delay. The individual delay is obtained from difference between the actual time arrival and the ideal arrival time on stop line f or individual vehicles. This model considers a dynamic weighing factor related to ridership and schedule adherence. Christofa's model minimizes the sum of auto delay and bus delay, which are both weighted by occupancy. The auto delay and bus delay are derived from an analytical approach.

PI-based optimization

Intersection delays indicate an optimization problem; however, intersection delay does not solely represent intersection performance. Thus, several researchers began using PI as an alternative objective indicator. Duerr (Duerr 2000) proposed a dynamic TSP control method using the minimum PI. In his implementation, PI is a function of several parts, including bus delay, bus stops, residual queue and overflow impact. This PI represents traffic states other than delay, which is conducive to finding optimal performance. However, Duerr's PI does not directly use signal timing as the decision variable; therefore, it is difficult to obtain the optimal TSP signal plan from the objective function.

Later, Lee et al. (Lee et al. 2008) proposed an innovative TSP control strategy to overcome Duerr's limitation. Their strategy is named OSTRAC (Optimized Strategy for integrated Traffic and Transit signal Control). In this study, OSTRAC implements adaptive TSP control using online data collected via traffic and transit sensors. The PI is calculated as the sum of the weighted average vehicle delay and the weighted average bus delay. The PI is the function of phase duration and sequence. The criterion for the selection of signal timings is the least possible PI under a given timing plan. A Genetic Algorithm (GA) is used to generate the minimum PI and optimal signal timing. Finally, an evaluation was conducted by comparing the performance of OSTRAC to three other control strategies: a pre-timed signal without TSP, a pre-timed signal with conventional TSP and an actuated control with conventional TSP. The results show that OSTRAC consistently and significantly improves efficiency for both traffic and bus operation compared to the other three control strategies.

Rule-based approach

Logic process

Although optimization obtains a TSP signal timing solution, the solution is difficult to implement as a real-time adaptive controller, and its accuracy highly depends on the optimization solver; hence, the logic process, which is used for its simple implementation. Ekeila et al. (Ekeila et al. 2009) proposed a Dynamic Transit Signal Priority (DTSP). This system is comprised of three main components: 1) a virtual detection system; 2) a dynamic arrival prediction model; and 3) a dynamic TSP algorithm. The virtual detection system is achieved via the virtual Automatic Vehicle Location (AVL) system in VISSIM. The dynamic arrival prediction is based on linear models and refined by the Empirical Bayesian estimation and Kalman filtering technologies. As shown in Figure 2-3, the authors defined seven scenarios based on arrival time allocation with the variance boundaries:

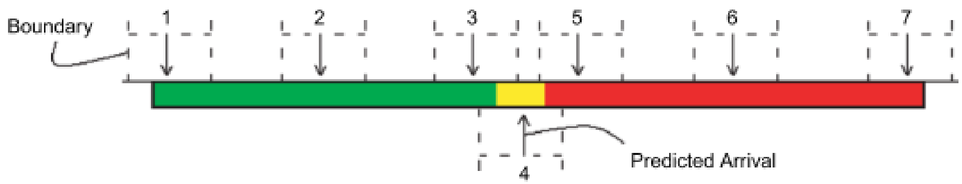


Figure 2-3 Predicted Arrival Time Allocation (Ekeila et al. 2009)

Based on these seven scenarios, the DTSP algorithms evaluate three control plans: 1) green extension; 2) red truncation; and 3) cycle extension. Ekeila et al. also compare the performance of DTSP with the performance of conventional TSP strategies. Two scenarios were evaluated: 1) a hypothetical intersection; and 2) the LRT line. The selected MOEs are the total and average bus delay. Results show that the DTSP algorithm outperforms the conventional TSP in both two cases.

Janos and Furth (Janos et al. 2002) discussed bus priority with highly interruptible traffic signal control. The authors conducted a simulation study of Avenida Ponce de Leon, which is a 6.7-kilometre corridor in San Juan, Puerto Rico. The authors hypothesized that, after TSP operations, it is difficult for signal timing to return to a normal cycle, and that as the frequency of TSP interruptions increases, so too does queue spillback severity. This study demonstrates the feasibility and potential social benefit of highly interruptible traffic signal control with proper transit schedules. The control policy follows a logic chart, as shown in Figure 2-4. VISSIM was used to evaluate the logic control policy against a pre-timed signal control. The results reveal a 10% transit delay reduction and a 1-minute transit travel time reduction under a highly interruptible condition.

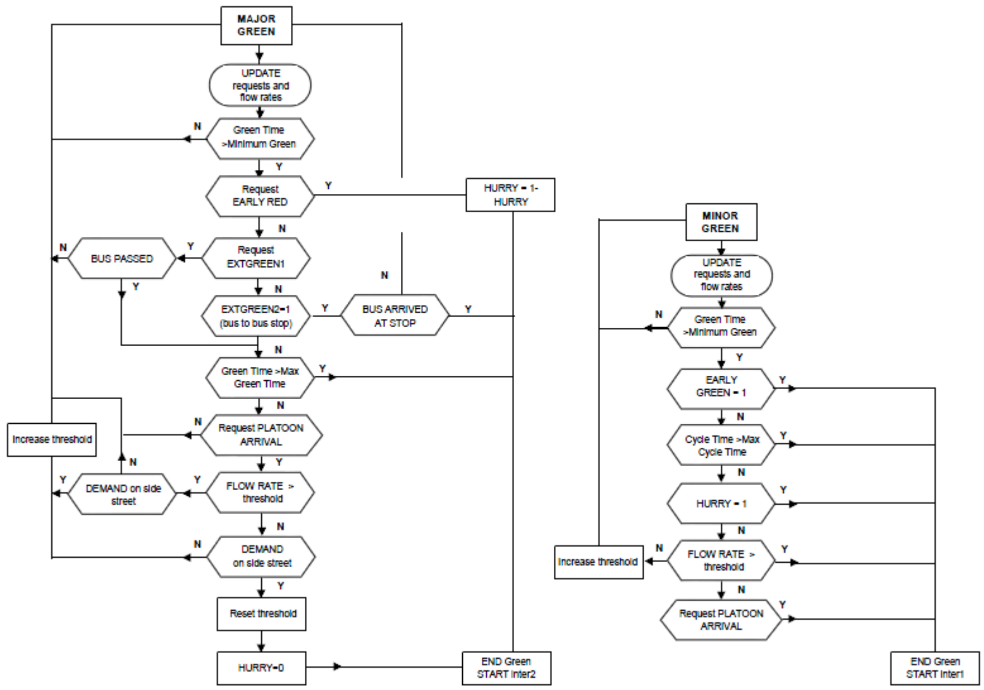


Figure 2-4 Traffic Control Logic (Janos et al. 2002)

Zlatkovic et al. (Zlatkovic et al. 2012) proposed a rule-based algorithm to resolve the issue of multiple TSP requests. The algorithm can be directly implemented using the logic processor in signal controllers. The main postulate of this algorithm is that no signal phases (vehicular or pedestrian) should be skipped within a cycle. The algorithm is designed for unconditional priority, meaning that any transit vehicle can place a TSP call, which will be served according to the rule. This method is quite different from the popular commercial TSP software, which uses priority Request Class Type and Request Class Level, as defined in NTCIP 1211. The algorithm classifies TSP from cycle to cycle according to current intersection operations and conditions. The algorithm provides a more adaptive way to grant multiple TSP calls. The model was also tested in VISSIM with ASC/3 Software-in-the-Loop (SIL) controller emulators. Using customized TSP strategies, the algorithm reduces the Bus Rapid Transit (BRT) delays by more than 30%, with minimal impact to general traffic. This procedure takes full advantage of existing control equipment; thereby, reducing the costs associated with new installations.

Decision Tree

Another type of TSP control algorithm is based on the decision tree. This approach requires an enumeration of all the available options, an evaluation of all the available options and then the selection of the best available option as the solution. This algorithm is a combination of the PI method and a rule-based approach. The decision tree does not need an optimization solver to obtain the solution, and the solution is better than the solution found through the logic process. Ma and Bai developed a service sequence optimizing approach to the issue of multiple bus priority requests (Ma et al. 2008). The approach lists all possible solutions using an enumeration method. All the listed solutions serve as the “branches” of the decision tree. To determine the optimal solution branch, the authors propose as an objective function the average personal delay, as shown in equation (2); three major factors are included: 1) bus delay; 2) schedule delay; and 3) the number of passengers. The proposed decision tree method may render a TSP strategy different than the first-come-first-serve policy.

$$\min D = \sum_{i=1}^{n} Q_i d_{si} / \sum_{i=1}^{n} Q_i \qquad (2)$$

Where,

- D is average personal delay;
- d_{si} is bus delay in phase s;
- Q_i is ridership of bus i;

2.3.2. Summary and Comparison of each Algorithm

Each of the aforementioned TSP control algorithms has advantages and disadvantages. Ideally, algorithms that rely more heavily on mathematics obtain a superior solution and bring more benefit; however, mathematically complex algorithms are difficult to implement. The algorithms that rely more heavily on logic and subjective decisions obtain an inferior solution and bring less benefit; however, mathematically simplistic algorithms are easier to implement. Therefore, there is a trade-off. Table 2-1 lists the advantages and disadvantages of each algorithm.

Table 2-1 Summary of TSP Strategies

Algorithm	Advantage	Disadvantage
Performance Index	1. PI considers different types of performance in the optimization process 2. Optimization using PI can solve the general problem in TSP field. 3. It is easy to use the PI optimization solution method	1. The weighting factor is necessary when combining the different performances and this weighting factor is empirical. 2. The combination of each performance does not have physical meaning. 3. It is difficult to implement in the field.
Delay	1. It can be used to meet different requirements by using different delays as indicators. 2. It is able to combine different delays to obtain the system delay or average personal delay. 3. It is easy to find a common optimization solution method. 4. All types of delay have physical meaning.	1. When combining the different delays, a weighting factor is necessary, and that weighting factor is empirical. 2. When using average delay, the delay must be estimated, which may affect accuracy. 3. It is difficult to implement in the field.
Logic Process	1. Does not use any mathematical model to represent the problem or any algorithm to get the solution. 2. The logic is easy to realize in the field.	1. It is an empirical approach based on a predefined rule; thus, it will not obtain the optimal solution. 2. The rules are subjective. 3. It only can solve a concrete problem case-by-case.
Decision Tree	1. It combines the rule-based approach and the PI method. 2. It is easy to find the sub-optimal solution by comparing the PI in each branch. 3. An optimization solver is not necessary to obtain the solution.	1. It is necessary to enumerate all the option branches in the decision tree. 2. It only can solve a concrete problem case-by-case.

2.4. TSP Performance Evaluation

TSP performance evaluation is important for transit agencies to help determine TSP development strategies. As such, many TSP performance evaluations were conducted in past studies. TSP performance evaluation approaches can be divided into two distinct categories: 1) data-driven (i.e., empirical) analysis; and 2) model-based analysis, as shown in Figure 2-5.

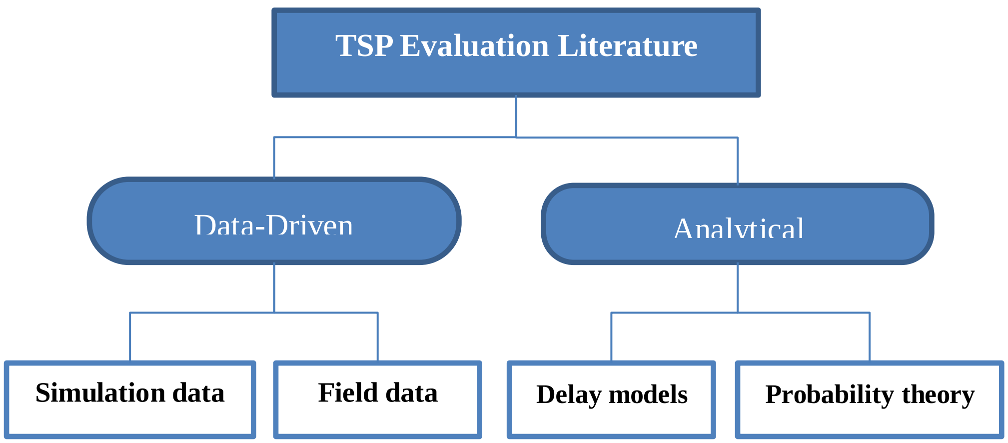


Figure 2-5 TSP Performance Evaluation Study Branches

2.4.1. Data-Driven Evaluation

Ideally, TSP performance data can be obtained via field observations; however, field data collection can be prohibitively expensive. Therefore, in many cases, TSP data must be retrieved via well-calibrated and fine-grained traffic simulators. State-of-the-art traffic simulators have the ability to simulate most traffic conditions and systems, including TSP.

Simulation data

Among the microscopic traffic simulators capable of simulating TSP operations, PTV VISSIM may be the most popular and widely used. Fellendorf (Fellendorf

1994) used VISSIM to model and evaluate actuated signal control strategies, including bus priority operations. Fellendorf hypothesized that simulation-based TSP evaluation is helpful in testing different actuated control strategies and adjusting parameters. Besides VISSIM, other simulation tools are also used in TSP evaluation. For instance, INTEGRATION model was used by Chang et al. (Chang et al. 2003) and Dion et al. (Dion et al. 2004) to conduct an investigation of the potential benefits and service reliability impact of TSP strategies. Muthuswamy et al. (Muthuswamy et al. 2007) evaluated an adaptive TSP algorithm with the WATSim simulator.

Feng et al. (Feng et al. 2003) conducted a TSP performance comparison on the SCOOT (Split Cycle Offset Optimization Technique) traffic control system in Salt Lake City, Utah. The comparison included four elements: signal timing optimization 1) before, and 2) after; and signal timings 3) with TSP, and 4) without TSP. The studied corridor consisted of 9 signalized intersections and 7 bus routes. Different bus headways or frequencies were simulated in VISSIM and the signal timings were either optimized with SYNCHRO 5.0 or self-optimized by SCOOT. The SCOOT system was coupled with VISSIM through interfacing programs, including a VAP module and a communication module, which were developed in C++. The study concluded that with or without TSP, SCOOT outperforms traditional signal timings. Moreover, SCOOT with TSP saves more bus-person delay than SCOOT without TSP. Compared with traditional signal control strategies, SCOOT with TSP reduces bus-person delay by up to 27%, while SCOOT without TSP reduces bus person delay by 5%.

Field data

Field-data-based evaluation is another approach belonging to data-driven analysis. Zheng et al. (Zheng et al. 2009) evaluated the TSP system in Washington using field data as well as simulation data. In this study, field data, which was collected for the South Snohomish Regional Transit System Priority (SS-RTSP) in Washington, included transit operation data without TSP for one week and with TSP for another week. Three buses were selected as the test vehicles and multiple MOEs, including transit travel time, average person delay, etc., were used to evaluate the TSP strategies. More analysis was conducted in VISSIM. The evaluation results show that TSP reduces bus travel time by 2.5-5.0%. However, the SS-RTSP cannot always guarantee the travel delay reduction.

Kimpel et al. (Kimpel et al. 2005) conducted an analysis based on TriMet Bus Dispatch System data in Portland, Oregon. Portland's TSP system uses conditional TSP policies. The selected study routes suffered multiple operational problems, such as inadequate scheduling or ineffective management. The study covered 24 comparable scenarios, including 6 bi-directional segments and 3 time periods. The mean value and variance of each MOE was used to represent the performance. Three main measurements were analyzed: 1) bus running time; 2) on-time performance; and 3) passenger waiting time. Over all, the study did not find a significant improvement to running time nor on-time performance. Moreover, it was found that both headway mean and headway variance increased after TSP deployment, meaning that the performance worsened after TSP implementation. As such, the authors concluded that TSP cannot consistently improve bus performance for individual vehicles. A regression approach was also developed to connect the bus travel time to other variables, including actual travel time, scheduled travel time, stops, lift operations, service years, delay at origin terminal, period (TSP and no TSP) and time period. The authors tried to find the coefficient for each variable using a linear regression method. Eventually, R^2 equaled 0.971, which meant that the linear relationship was good.

2.4.2. Analytical Model-Based Evaluation

This type of TSP evaluation focuses on how to represent and predict TSP system MOEs using analytical models. Liu et al. (Liu et al. 2008) proposed an analytical TSP model based on the deterministic queuing theory. In this study, only the uniform delay and the residual queue delay were taken into account, while the random delay was considered insignificant and subsequently ignored. Two basic TSP strategies were evaluated: 1) early green; and 2) green extension. The cumulative vehicle count curves were used to develop the delay models. 2 other assumptions were made: 1) the vehicle arrival rate is constant; and 2) the saturation flow rate is constant. Control delay was modeled for two TSP strategies to estimate the average personal delay on both prioritized and non-prioritized approaches. The shadows in Figure 2-6 represent the possible changes to delay due to TSP operations. The authors also derived the relationship between TSP and average personal delay.

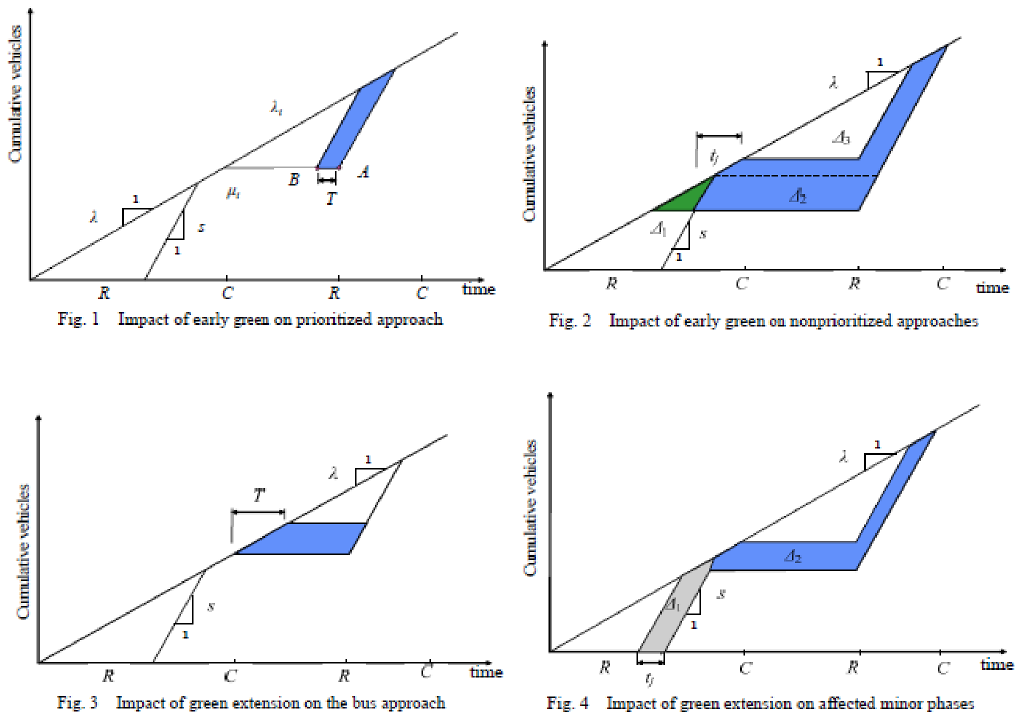


Figure 2-6 Impact of TSP in Different Scenarios and Approaches (Liu et al. 2008)

In Liu et al.'s model, simplifications, such as using D/D/1 queue model to represent control delays and ignorance of site-specific geometry, render the model questionable. Also the study did not consider some special features for buses at intersections, such as queue jumping or dedicated transit phase.

Abdy et al. (Abdy et al. 2011) proposed an analytical model to overcome the major limitations of Liu et al.'s model. In Abdy et al.'s study, four issues regarding Liu's model are addressed: 1) the impact brought by the TSP operation should cover both the current cycle and the following recovery cycle, rather than just one cycle; therefore the additional delay brought by TSP should also include the two cycles; 2) the average vehicle delay should be divided by the number of vehicles arriving over the two cycles; 3) it is possible that the TSP operation causes temporary oversaturation at non-prioritized approaches and (or) possible queue spillback; and 4) the evaluation should consider the frequency of TSP requests. In total, 16 functions were created and their combinations used to reflect delay in different scenarios.

Skabardonis and Christofa (Skabardonis et al. 2011) proposed another analytical approach to evaluate TSP impact on traffic operations. This study facilitated the prediction of TSP impacts from a planning and operational point of view without microscopic simulation. The authors used the probability theory to estimate vehicle delay. They regarded the delay as an expectation of two conditions: 1) with TSP; and 2) without TSP. The equation is:

$$d = \mathrm{E}(d|\mathrm{bus})\mathrm{P}(\mathrm{bus}) + \mathrm{E}(d|\mathrm{No\ bus})\mathrm{P}(\mathrm{No\ bus}) \quad (3)$$

Where,

- d is the average delay per vehicle;
- E is the expectation value; and
- P is the probability;

After the delay was calculated, TSP performance was represented by the Level of Service (LOS) defined in the Highway Capacity Manual (HCM). In this model, only the common traffic conditions, such as degree of saturation, signal timing, bus frequency and TSP settings, were taken into account. Therefore, it is a high-level model.

2.4.3. Summary

There are two approaches to TSP performance evaluation: 1) data-driven; and 2) analytical-model-based. Data-driven-based approaches are reliable, credible and better represent a real-world scenario; however, conducting and collecting field observations can be costly and laborious. Conversely, analytical-model-based approaches have several advantages: 1) they easily calculate or estimate delay impact; 2) there is no requirement for data quality and quantity; 3) there is no need to build a simulation model; 4) the results are comparable, as the analytical model is consistent across evaluations; However, the analytical model need to be verified via several studies before it can be accepted and used by other users. Both approaches are used in many studies. Which approach to use depends on the evaluation objective and study data supply.

CHAPTER 3. ADAPTIVE TSP STRATEGY DEVELOPMENT

This chapter introduces the proposed adaptive TSP strategy. The chapter includes an introduction of the system architecture, the objective function of the control algorithm and the simulation platform.

3.1. System Architecture

Unlike conventional TSP strategies, the proposed adaptive TSP control strategy is based on real-time traffic data and signal timing plan. The adaptive TSP system has three embedded processes: 1) the PRG sends the priority request to the PRS whenever a bus reaches the check-in detector; simultaneously, the traffic detection system and signal timing system sends real-time data to the PRS; 2) the PRS activates an optimization module to calculate a TSP timing plan; and 3) the PRS commands the controller to run the optimized timing plan.

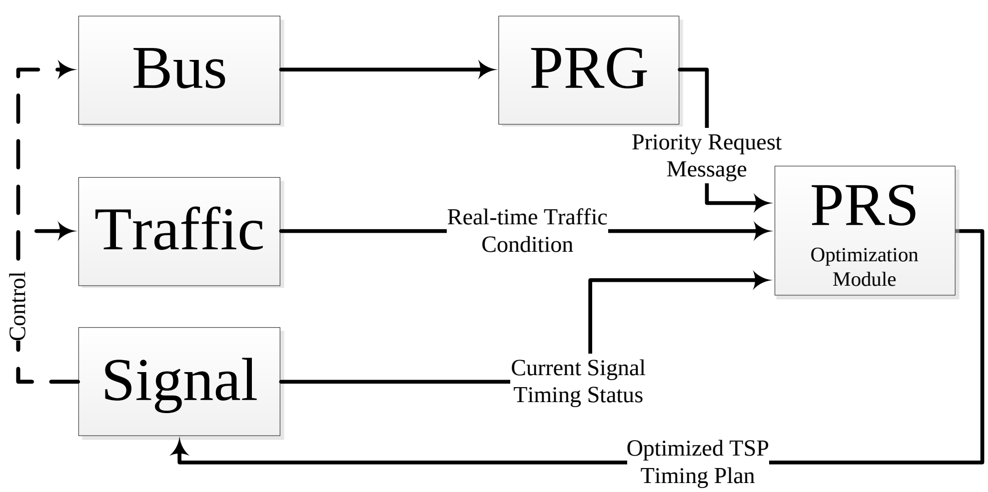


Figure 3-1 Adaptive TSP Control Strategy Architecture

Figure 3-1 shows the conceptual architecture of the proposed adaptive TSP strategy. There are three major objects that provide real-time data or status updates: 1) bus objects contain bus-specific data, such as the bus arrival time and bus speed; 2) traffic objects contain traffic-specific data, such as traffic volume and turning volume; and 3) signal control objects provide the current timing plan as a background timing plan; the system then sends an optimized TSP timing plan to the signal controller.

3.2. Considerations & Assumptions

Roadway situations are complex: it is impossible consider all cases in a control model; therefore, some considerations must be made:

1. The phase plan follows the National Electrical Manufacturers Association (NEMA) standard. The controller that used in this research is ASC/3, which is a popular traffic controller following the NEMA standard. The default phase mapping in the NEMA standard is shown in Figure 3-2.
2. There are no bus stops between the check-in detector and the stop line, because stops between a check-in detector and a stop line would have a huge effect on the bus delay estimation.
3. There is no phase rotation and each phase will serve only one time in each cycle. Phase rotation or multi-service for one phase in one cycle breaks the NEMA timing plan.

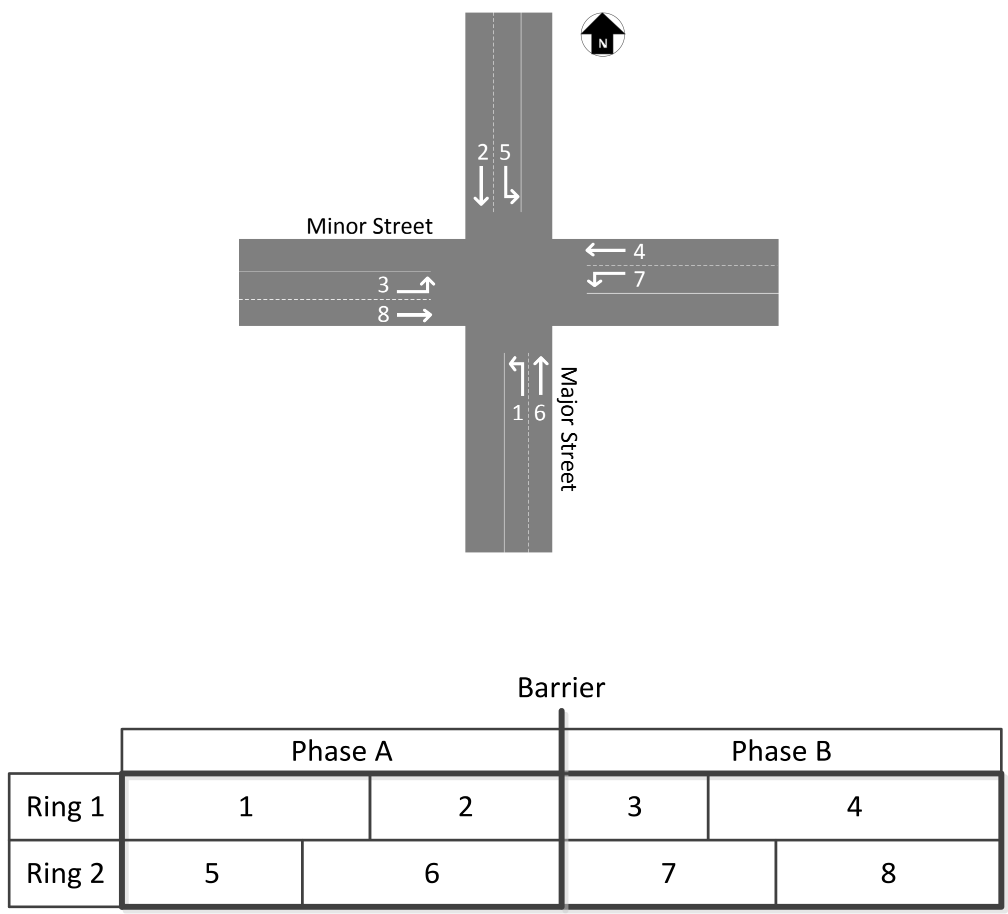


Figure 3-2 Phases, Ring and Barrier Diagram of NEMA Standard

It is unrealistic to take all traffic dynamics into account for control design; therefore, some assumptions must be made to reasonably simplify the problem:

1. There are no residual queues in the beginning of TSP control start;
2. There is no phase re-service;
3. Slow buses do not generate moving bottlenecks;
4. There are no bus stops between the check-in detector and a stop line;
5. All buses will cross the intersection within two cycles;
6. There is fixed cycle length at the subject intersection;

7. There is uniformity of traffic arrival and driver behaviors in each traffic state; and
8. There is no significant acceleration and deceleration process.

3.3. Inputs & Outputs

The proposed optimization model takes three categories of inputs: 1) traffic conditions; 2) transit status; and 3) signal timing parameters. Traffic conditions, including intersection traffic movement count, capacity flow, arrival flow, capacity speed and jam density, are derived from traffic detectors. Transit status includes the actual bus arrival time and bus arrival speed. Signal timing parameters include the signal controller settings, such as the cycle length and current phase splits.

The model generates the optimal phase splits as outputs. These splits offer the best performance for the combination of bus delay and traffic delay.

3.4. Model Formulation

3.4.1. Objective Function

The present TSP system objective is to reduce bus delay at intersections, while maintaining an acceptable level of service to other traffic on all approaches. To represent this, we designed the objective function, as shown in Equation (4). The first item in Equation (4) refers to the weighted maximum control delay, d_a, among all approaches, and the second item refers to the weighted total bus delay, $\beta\sum_N d_b$. Using the maximum control delay on one approach instead of the average control delay at intersections can avoid a situation where, if a bus is approaching the major-minor intersections on the mainline, then using the average control delay at intersections may make the solver favor the mainline traffic too much and increase the control delay on non-TSP approaches to an unacceptable level of service.

$$D = \alpha \max\left(d_{a,i}\right) + \beta \sum_{N} d_b \quad (4)$$

Where,

- D, average weighted delay, s/veh;
- d_a, average traffic delay, s/veh;
- d_b, bus delay, s;
- α , β , weighting factor;

Control Delay Estimation: d_a

The control delay estimation is based on the models recommended by the HCM 2010. The uniform delay is expressed as:

$$UD = \frac{1}{2} C \frac{\left(1 - g/C\right)^2}{1 - \left(g/C\right)\min(X,1)} \quad (5)$$

Where

- UD : The uniform delay;
- C: Cycle length;
- g: Effective green time;
- v: Flow rate;
- X : v/c ratio or degree of saturation;

Following Webster's delay model (F.V.Webster 1958), the random delay is expressed as:

$$RD = \frac{1}{2v}\left(\frac{X^2}{1-X}\right) \quad (6)$$

Where

- RD : Random delay;

And he suggests the sum of the uniform delay and the random delay should be expressed as:

$$d_a = 0.9(UD + RD) \quad (7)$$

Once the volume to capacity ratio (*X*) is larger than 1, overflow occurs; therefore, an additional item besides the uniform delay, which called overflow delay, needs be added:

$$OD = \frac{T}{2}(X-1) \quad (8)$$

Where

- OD : Overflow delay;
- T : Analysis period;

Under the overflow condition, uniform delay is expressed as:

$$UD_0 = \frac{1}{2}C(1 - g/C) \quad (9)$$

The average delay becomes:

$$d_a = UD_0 + OD \quad (10)$$

Where:

- d_a : the average traffic delay;

Bus Delay Estimation: d_b

Bus delay is estimated through the relationship between projected trajectory, queuing profile and signal timing. According to shockwave theories, there are three shockwaves formed under uncongested traffic conditions due to the cyclic changes of traffic signals (Stephanopoulos et al. 1979): queue formation (v_1), queue discharge (v_2) and queue clearance (v_3).

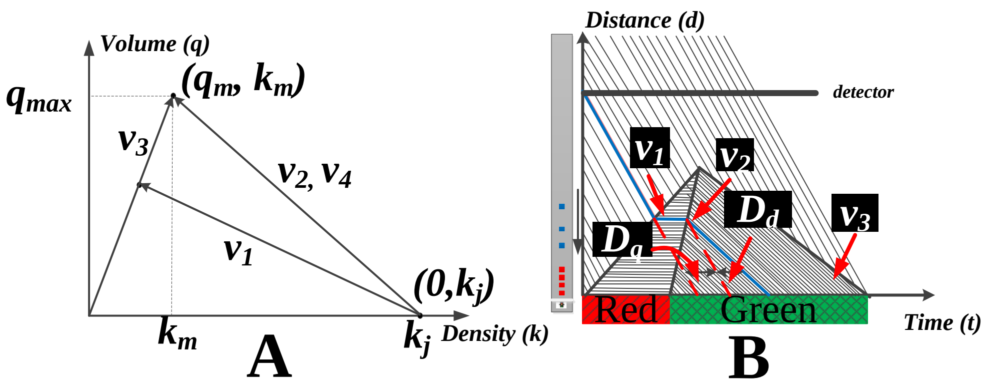


Figure 3-3 Shockwaves at signalized intersection

As shown in Figure 3-3, these three shockwaves form two triangle shapes within each cycle. The shockwave speed for these three states can be calculated as:

$$v_1 = \left|\frac{0 - q_a}{k_j - k_a}\right|; v_2 = \left|\frac{q_m - 0}{k_m - k_j}\right|; v_3 = \left|\frac{q_m - q_a}{k_m - k_a}\right| \qquad (11)$$

Where,

- q_a, k_a, arriving traffic volume and density;
- k_j, jam density;
- q_m, k_m, capacity volume and density;

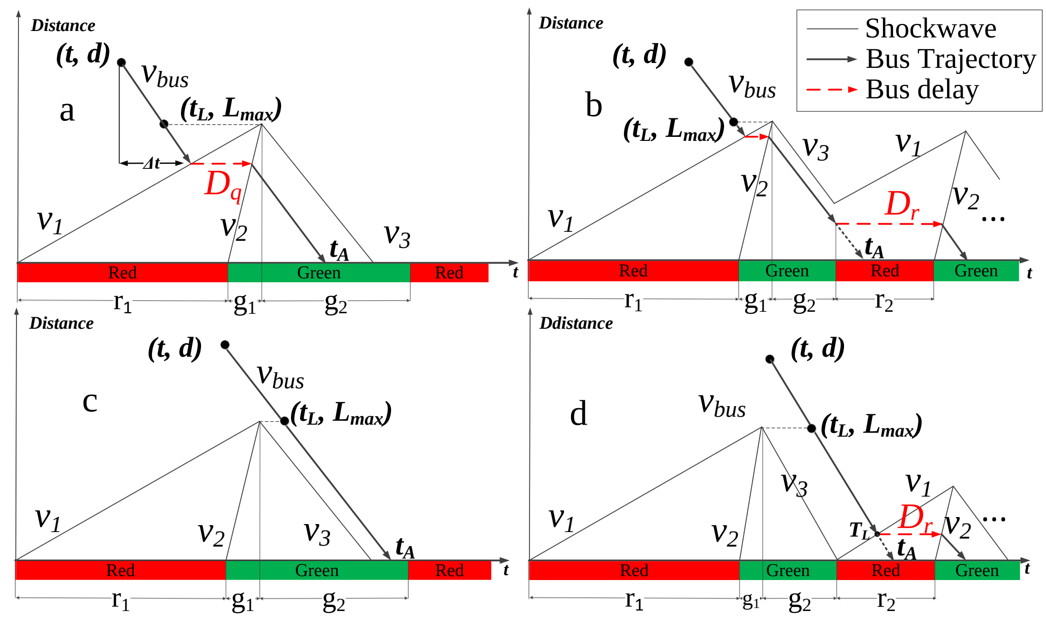


Figure 3-4 Four Bus Delay Scenarios for Estimation.

Depending on when the bus reaches the detector, four possible scenarios could occur, as shown in Figure 3-4. Three types of bus delays could possibly be generated: 1) the bus queuing delay (D_q), which is caused by the bus joining and waiting in the queue; 2) the bus waiting delay (experienced red) (D_r), which is generated when buses cannot cross an intersection within one cycle and have to wait for the next cycle; and 3) the bus moving delay (D_d), which is generated when the bus speed is higher than the capacity speed, in which case buses have to slow down and join the moving queue. In summary, the bus delay can be expressed as:

$$d_b = \theta_1 D_q + \theta_2 D_r + \lambda D_d \qquad (12)$$

θ and λ are parameters that can take values of 0 or 1. λ is equal to 1 only if the traffic is under a high-speed-limit condition ($v_{bus}>v_m$). θ is determined by when the bus reaches the location of maximum queue length (t_L) and when the bus arrives at the stop line (t_A). θ's value can be expressed as:

1) If ($t_L < r_1 + g_1$),

   Then θ_1=1 otherwise θ_1=0;

2) If ($t_A < r_1 + g_1 + g_2$),

   Then θ_2=0 otherwise θ_2=1;

t_L and t_A can be calculated by following equations:

The moment when the bus reaches the maximum queue length can be calculated as:

$$t_L = t + \frac{\left(d - L_{\max}\right)}{v_{bus}} \tag{13}$$

$L_{\max}$, which represents the maximum queue length, can be derived as:

$$v_1\left(r + g_1\right) = v_2 g_1 \Rightarrow g_1 = \frac{v_1 r}{v_2 - v_1} \Rightarrow L_{\max} = \frac{v_1 v_2 r}{v_2 - v_1} \tag{14}$$

Regard the difference between the time when a bus is discovered (t) and the time when it joins the queue as Δt; then, calculate the predicted time when the bus arrives at the stop line by following Equation (15) and (16):

$$d = v_1\left(t + \Delta t\right) + v_{bus}\Delta t \Rightarrow \Delta t = \frac{d - v_1 t}{\left(v_1 + v_{bus}\right)} \tag{15}$$

$$t_A = \begin{cases} t + D_q + \dfrac{d}{v_{bus}}, v_{bus} \le v_m \\ t + \Delta t + D_q + \dfrac{v_1\left(t + \Delta t\right)}{v_m}, v_{bus} > v_m \end{cases} \tag{16}$$

If $t_L < r_1 + g_1$ (Figure 3-4.a and Figure 3-4.b), then the bus will join the queue and create a queuing delay, D_q, which can be calculated as:

$$D_q = \frac{v_1(t+\Delta t)}{v_2} + r_1 - (t+\Delta t) = r_1 - \left(\frac{v_2 - v_1}{v_2}\right)\left(\frac{v_{bus}t + d}{v_1 + v_{bus}}\right) \tag{17}$$

The bus waiting delay (experienced red), D_r, is calculated as:

$$d = (T_L - r_1 - g_1 - g_2)v_1 + (T_L - t)v_{bus} \Rightarrow T_L = \frac{d + (r_1 + g_1 + g_2)v_1 + v_{bus}t}{v_1 + v_{bus}} \tag{18}$$

$$D_r = \begin{cases} r_2 + \dfrac{(t_A - r_1 - g_1 - g_2 - r_2)v_{bus}}{v_2} \ (t_L < r_1 + g_1) \\ \dfrac{(T_L - r_1 - g_1 - g_2)v_1}{v_2} + r_1 + g_1 + g_2 + r_2 - T_L \ (t_L > r_1 + g_1) \end{cases} \tag{19}$$

In high-speed-limit traffic conditions, a bus tends to drive at a higher speed, v_{bus}. However once the bus joins the queue, the bus will have to follow the capacity speed v_m, which is lower than v_{bus}, generating the moving bus delay, D_d, as illustrated in Figure 3-5:

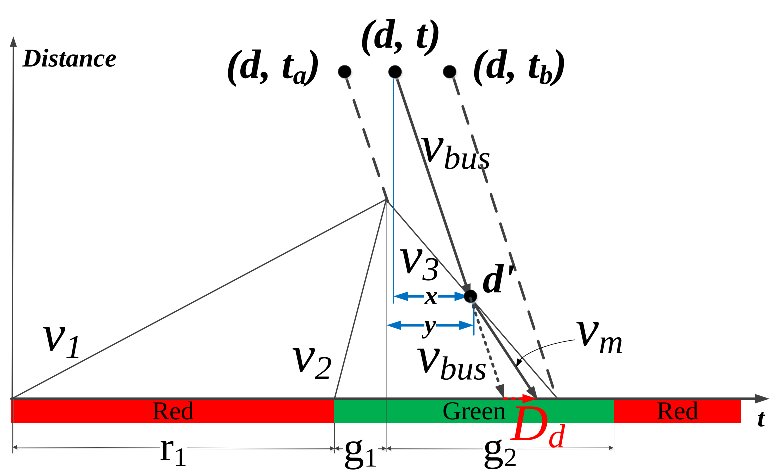


Figure 3-5 Illustration of Additional Delay under High-Speed Condition

D_d can be calculated as:

$$D_d = \begin{cases} \dfrac{v_1(t+\Delta t)}{v_m} - \dfrac{v_1(t+\Delta t)}{v_{bus}}, & t_L < r_1 + g_1 \\ \dfrac{d - v_{bus}x}{v_m} - \dfrac{d - v_{bus}x}{v_{bus}}, & t_L > r_1 + g_1 \end{cases} \tag{20}$$

$$x = \frac{d - L_{\max} + v_3(t - r_1 - g_1)}{v_{bus} - v_3} \tag{21}$$

All symbols in Equations (11) through (21) are defined in Figure 3-4 and Figure 3-5.

The proposed bus delay estimation method needs more justification to show the advantages over existing bus delay estimation methods before. Existing bus delay estimation methods can be basically classified into two types: 1) define bus delay as the difference between the time when a bus places a TSP call and the time when the bus reaches the stop line. The major issue in this method is that, when a bus sends a TSP request, there is distance between the advance detector and the stop line; 2) estimate bus delay using the cumulative vehicle count curve; however, this method only applies to a special scenario where there are bus-only lanes.

Using microscopic simulation, VISSIM, a comparison study was conducted to compare the proposed bus delay estimation method against the two existing bus delay estimation methods. A signalized intersection, with eight phases, was simulated. An advance bus detector was set around 200 meters back from the stop line. The red duration of bus service was set at 48 seconds and the cycle length was set at 100 seconds.

Figure 3-6 shows the comparison of the three methods. Although each of these methods is correlated with the observed samples, the new bus delay model better matches the ground truth. If a bus has to wait another cycle to cross the intersection, then the waiting delay includes two parts: 1) the experienced red and 2) the moving delay when the queue is being cleared. Therefore, for those buses that could not cross the intersection within one cycle, the later they are discovered, the more delay they will experience.

The effectiveness of the three methods were further evaluated using the Mean Absolute Percentage Error (MAPE) and the Mean Squared Error (MSE). As the MAPE has a major drawback of a possible zero denominator if the sample has no observed bus delay, we ignored some zero samples in the MAPE analysis. As shown in

Table 3-1, the proposed method has the lowest MSE and MAPE: it can be concluded that the proposed method is more effective in estimating bus delay than the existing methods.

Table 3-1 Comparison of Bus Delay Estimations

Indicator	Definition	Time difference method	Cumulative curve method	New method
MSE	$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)^2$	366.069	19.95	9.24
MAPE	$\text{MAPE} = \frac{100\%}{n}\sum_{i=1}^{n}\left\lvert\frac{\hat{Y}_i - Y_i}{\hat{Y}_i}\right\rvert$	38.1%	18.9%	17.9%

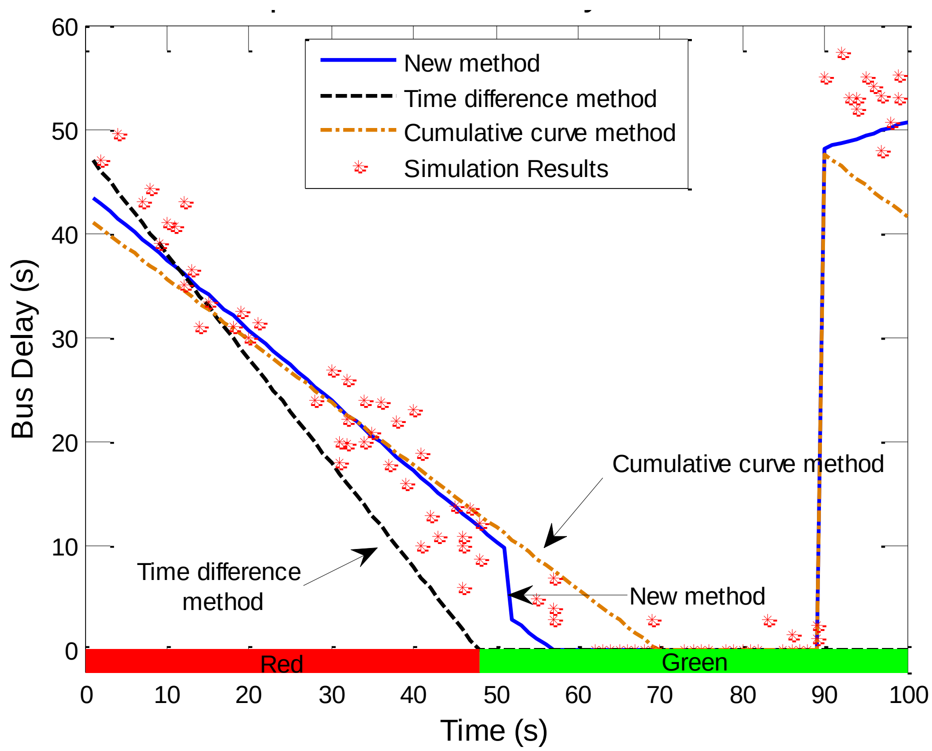


Figure 3-6 Comparison of Bus Delay Estimation Models

3.5. Constraints

Green Duration Constraint

The decision variables are green durations. The constraints are composed of the physical structure of signal controllers and actual traffic conditions. In North America, the commonly accepted constraints are composed of three parts: 1) maximum and minimum greens; 2) pedestrian settings; and 3) cycle length and NEMA dual ring structure. The green duration constraints have been extensively defined in other literature (Head et al. 2006). Green duration constraints can be expressed as:

$$\max\left(\lambda\left(g_{walk}+g_{pedclearance}\right),g_i^{\min}\right)\le g_i\le\max\left(\lambda\left(g_{walk}+g_{pedclearance}\right),g_i^{\max}\right)\quad(i=1,2,3,\ldots,8) \tag{22}$$

Where:

- g_i : green duration time;
- $g_i^{\min}$: minimum green;
- $g_i^{\max}$: the maximum green;
- g_{walk} : walk time;
- $g_{pedclearance}$: pedestrian clearance; and
- λ : flag variable (0: no pedestrian call; 1: pedestrian call);

Cycle Length Constraint

In the standard ring structure, the total green time in each ring should be equal to the cycle length:

$$\begin{aligned}&\sum_{i=1}^{4}\left(g_i+y+ar\right)=C;\\&\sum_{j=5}^{8}\left(g_j+y+ar\right)=C;\end{aligned} \tag{23}$$

Where,

- C , cycle length, s;
- g , green phase duration time, s;
- y , yellow time, s;
- ar , all red time, s;

Barrier Constraint

The barrier constraint restricts ring 1 and 2; the same side of the barrier should have the same duration:

$$\begin{cases} g_1 + g_2 = g_5 + g_6 \\ g_3 + g_4 = g_7 + g_8 \end{cases} \tag{24}$$

Where:

- C: Cycle length;
- g_i: Green duration of phase i;
- y: Yellow time; and
- ar: All-red time;

3.6. Variables

Objective function is formulized as:

$$\min D = w_a \cdot d_a\left(S_T, T\right) + \sum w_b \cdot d_b\left(S_b, T\right) \tag{25}$$

Where:

- S_T, Traffic status
- S_b, Traffic status
- T, Signal timing plan

The target is minimizing the overall intersection delay, so that the TSP can reduce bus delay, as well as reduce negative impacts to other traffic. The input of the objective function is the signal timing plan, which is also the output. Several control variables are needed, such as S_T, which represents the traffic status, and S_b, which represents the bus status. Both S_T and S_b contain several components. T represents the signal timing plan, which is to be optimized.

Table 3-2 Notation of the Variable

Status	**Control Variable**	**Symbol**
Traffic (S_T)	Traffic turning volume	v
	Arrival volume	q_a
	Capacity volume	q_m
	Capacity speed	V_m
	Jam density	k_j
	Saturation flow	s
Bus (S_b)	Bus detection time	t
	Bus arrival speed	v_{bus}
Signal Timing (T)	Current timing plan	x_0
	Cycle length	C

3.7. Optimization Formulation

The objective function in Equation (4) is quadratic and all constraints are linear. To obtain the optimal real-time TSP plan, a Matlab sequential quadratic programming (SQP) solver, an iterative optimizing method, was used. The necessary optimization inputs were retrieved through VISSIM COM interface and the optimal TSP plans were downloaded to the ASC/3 controller using multiple NTCIP messages. The optimization problem was formulated as:

$$\min_{\mathbf{g}} \quad D = \alpha_i \max\left(d_{a,i}(\mathbf{g})\right) + \sum\nolimits_N \beta d_b(\mathbf{g})$$

$$\text{subject to: } \begin{cases} g_i - \max\left(\lambda\left(g_{walk} + g_{pedclearance}\right), g_i^{\max}\right) \le 0 \\ -g_i + \min\left(\lambda\left(g_{walk} + g_{pedclearance}\right), g_i^{\min}\right) \le 0 \\ \sum_{i=1}^{4}\left(g_i + y + ar\right) - C = 0 \\ \sum_{j=5}^{8}\left(g_i + y + ar\right) - C = 0 \\ g_1 + g_2 - g_5 - g_6 = 0 \\ g_3 + g_4 - g_7 - g_8 = 0 \end{cases} \tag{26}$$

The control delay and bus delay are calculated using Equation (5) through (21). The weights are determined according to the sensitivity analysis. In practice, users may develop solvers or use alternative solvers to reach the optimal TSP plan.

3.8. Simulation Platform Architecture

The simulation platform architecture is illustrated in Figure 3-7. VISSIM, with the ASC/3 module, a full-scale signal emulator, was used as the traffic simulator. For signal timing optimization, real-time traffic and bus data was sent and received via COM interfaces. When a bus was detected by the advance detector, the "Mediator" module collected all necessary traffic data via VISSIM and signal timing data via the NTCIP standards. Once such information was collected, it was sent to the "Optimizer" module to obtain the optimal signal timing to minimize the PI. The Optimizer updated the quadratic problem, obtained the optimal TSP plans and sent that new TSP timing back to the Mediator via the .NET framework. Finally, the Mediator module sent the optimal TSP plans back to the simulator through a series of NTCIP messages. Specifically, the current timing plan was saved in a different split plan in ASC/3, and then replaced with the new optimal TSP signal timing. Once TSP timing plan expired (i.e., buses check out or the maximum timer is reached), the Mediator recovered the original signal timings. If there are multiple TSP requests, the Optimizer recalculates the optimal TSP timing and updates the signal timing accordingly. As a result, a granted TSP may be cancelled within the same cycle if the buses on other approaches appear to have a higher TSP need. During TSP operations, the cycle length and offset are not changed; therefore, the coordination on the mainline can be maintained.

For this study, new TSP timings did not change the phasing sequence or render skipped phases; however, these more aggressive adaptive TSP strategies will be studied in the future.

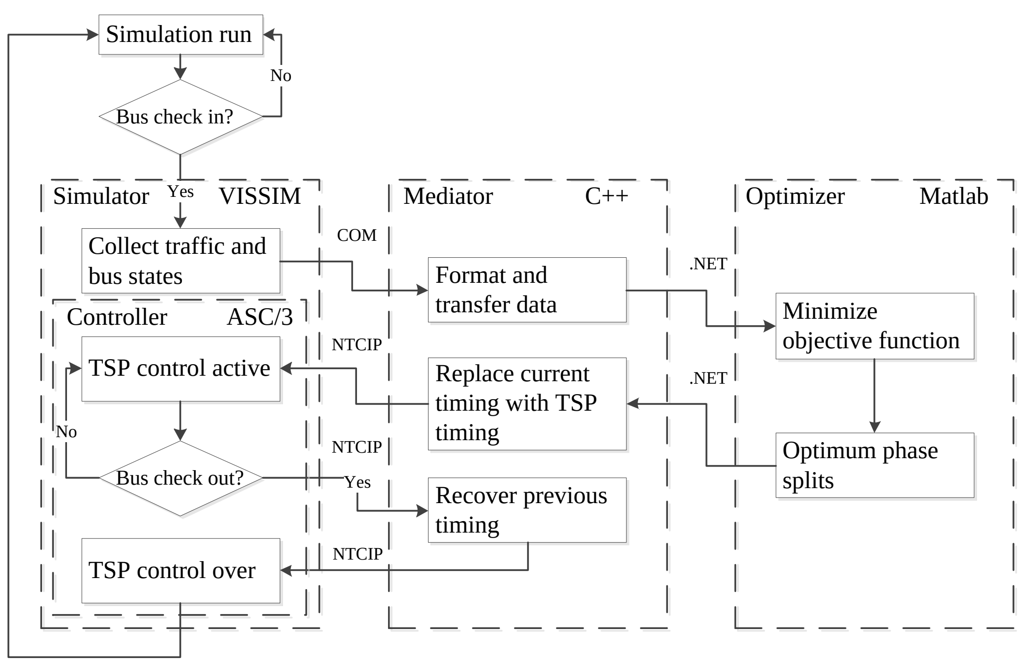


Figure 3-7 Architecture of the Proposed Adaptive TSP Systems

CHAPTER 4. ADAPTIVE TSP IMPLEMENTATION

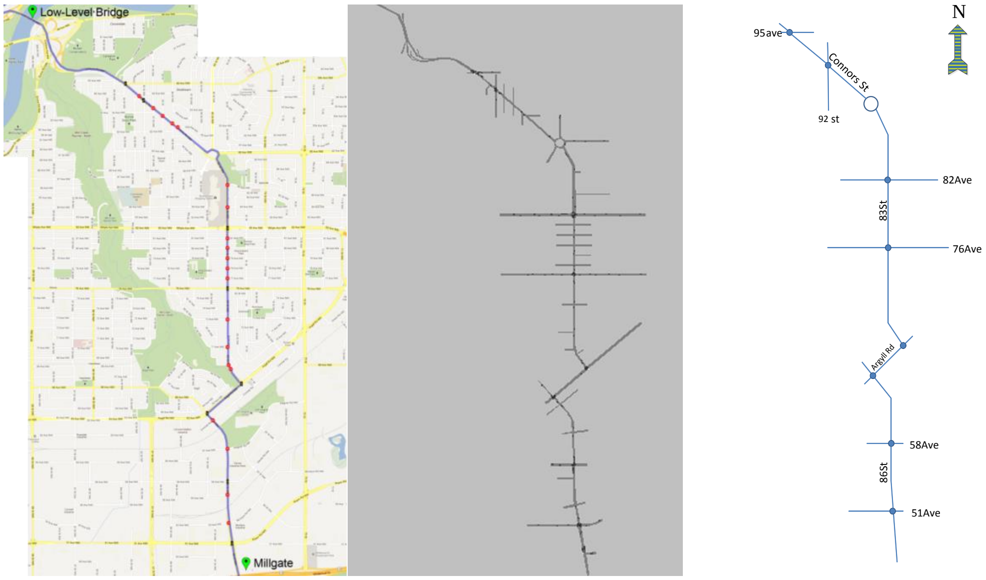
This chapter introduces the simulation-based adaptive TSP implementation platform. The simulation model was developed in VISSIM and calibrated with field traffic data. The chapter also introduces how TSP implementation was accomplished: C++ programming to connect the simulation and the optimization solver.

4.1. Simulation Model Development

The TSP evaluation study was conducted using a microscopic simulation tool, VISSIM, with an ASC/3 module. The ASC/3 model is able to simulate signal control exactly the same as in the field. In the ASC/3 model, there is a TSP function that contains strategies: green extension and red truncation. For model calibration and validation in VISSIM, field data collection is a necessary step of TSP modeling.

4.1.1. Study Scope

The study area is a southeast transit corridor in Edmonton, Alberta, Canada. The corridor starts at the Millgate Transit Centre and runs to the downtown core, stretching along 86th Street, Argyll Road, 83rd Street, Connors Road, and the Low-Level Bridge. Most parts of the transit corridor and major intersections are modeled in VISSIM. Figure 4-1 shows the layout of study corridor.



(A) (B) (C)

Figure 4-1 the Scope of Work and the Layout of the Simulation Model
(A: Corridor Map; B: Simulation Network; C: Simplified Network)

4.1.2. VISSIM Modeling

The traffic network was built in simulation using VISSIM 5.4 containing ASC/3, a full-scale signal controller. The modeling work consisted of several steps: 1) drawing roadway networks; 2) inputting traffic volumes; 3) configuring traffic signal; 4) setting up transit routes; and 5) defining driving behaviors. The layout of the roadway network was retrieved from Google Maps. Traffic volumes were obtained from data sets provided by City of Edmonton.

4.1.3. Configuring Signal Controllers in VISSIM

The signal control was simulated in VISSIM using the ASC/3 signal emulator. The ASC/3 software is one of the most popular firmware for actuated signal controllers in North America. It is compliant with NEMA controllers and can offer signal coordination, pre-emption, transit signal priority and more. The ASC/3 control module in VISSIM is a fully functional controller emulator and can realize VISSIM's "software-in-the-loop" function.

Three key configurations are needed to realize the TSP function in VISSIM: 1) mapping the bus detectors in VISSIM; 2) configuring the detectors in VISSIM to detect TSP requests; and 3) developing the priority message transformation via NTCIP in ASC/3. To distinguish the TSP-enabled buses from the general traffic and regular buses, a new vehicle type was defined in simulation: 'TBus'. When this type of bus reaches the virtual detector, the detector sends the request to activate the TSP strategy. To serve the bus, the timing plan switches to the TSP plan. After the bus checks out, the timing plan recovers to normal timing. All the timing related processes are finished by C++ programming using the NTCIP protocol.

4.1.4. Modeling Public Transit (PT) Transit & Stations in VISSIM

VISSIM is able to effectively simulate transit operation. There are two key configurations related to transit simulation: 1) route and 2) schedule. Route and schedule data were provided by City of Edmonton. The route and schedule was selected from the September 2012 sign-up, when the passenger demand is the highest. There are 25 bus lines operating within the study network. This study focused on TSP performance during the PM peak of weekdays; therefore, only the weekday bus schedule was simulated in VISSIM.

In VISSIM, it is also possible to model the side-street transit stations and bus bays. The bus stops were located according to the Google Maps.

4.1.5. Simulation Period

The PM peak period was selected for simulation because it has the highest volume of ridership. The PM peak is from 15:30 to 17:30. However, in simulation, it is necessary to input some vehicles before evaluation. This is the warm-up time, which is 10 minutes. Cool down time is also necessary, which is also 10 minutes.

4.2. Data Collection

To build a valid VISSIM model, various data is necessary. The data, including traffic data, transit data and signal data, was provided by the City of Edmonton. Other geometric and necessary data was collected from public websites, such as Google Maps.

4.2.1. Traffic Volumes and Turning Movement Counts at Intersections

The traffic volumes and turning movement counts were provided by the City of Edmonton. The turning movement counts were collected at eight signalized intersections and one roundabout along the study corridor, as shown in Table 4-1.

Table 4-1 Turning Movements Data

Intersection No.	Location	Data Missing	Interval	Collection Date
1	51 Avenue and 86 Street	No	5min	09/15/2010
2	58 Avenue and 86 Street	No	5min	09/15/2010
3	63 Avenue and 86 Street	No	5min	09/16/2010
4	Argyll Road and 83 Street	No	5min	09/16/2010
5	76 Avenue and 83 Street	No	5min	02/15/2011
6	82 Avenue and 83 Street	No	5min	04/19/2011
7	90 Avenue and 83 Street	No	5min	06/09/2009
8	Connors Road and 92 Street	No	5min	05/27/2009
9	95 Avenue and Connors Road	No	5min	05/30/2011

Although the turning movement counts were not collected on same date, they represent the real-world traffic pattern. It is necessary to convert the data to the same time period by traffic balancing. The raw data contains not only turning movement counts, but also vehicle types. Therefore, the average heavy vehicle rate can be calculated and modeled in VISSIM. Pedestrian counts are also included in the raw data.

Figure 4-2 gives the hourly turning movement and the lane assignment at each intersection along the southeast corridor.

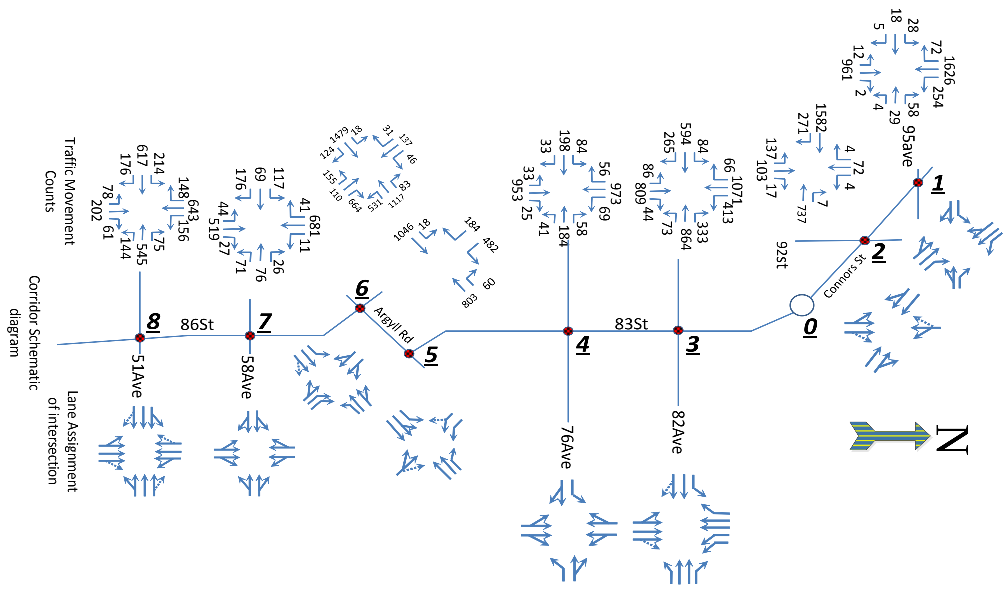


Figure 4-2 the Turning Movement Count and Lane Assignment at Intersection along the Study Corridor

4.2.2. Transit Schedule

The transit schedule was provided by ETS. The last fall schedule, which was released in September 2012, was selected for its consistency with the time of field observations. All of the bus lines traveling along the study transit corridor are listed in Table 4-2.

Table 4-2 Bus Routes on Study Corridor

Route No.	Route/Path	Route No.	Route/Path
6	Millgate--86st--51ave—South gate	**8**	Millgate--86st—Argyll Rd--83st--Connors RD--Downtown
15	Millgate--86st--Argyll Rd--83st--Connors RD--Downtown	**33**	Millgate--51ave—Meadows
61	Millgate--86st --Argyll Rd --83st-- Connors RD --Downtown	**64**	Millgate--86st --Argyll Rd --83st-- Connors RD --Downtown
65	Millgate--86st --Argyll Rd --83st-- Connors RD --Downtown	**66**	Millgate--86st --Argyll Rd --83st-- Connors RD --Downtown
68	Millgate--86st --Argyll Rd --83st-- Connors RD --Downtown	**69**	Millgate--86st --Argyll Rd --83st-- Connors RD --Downtown
72	Mill Woods-- 51ave-- Millgate--86st --Argyll Rd --83st-- Connors RD – Downtown	**73**	Millgate-- 51ave Southgate
81	Millgate-- 86st--66ave--Downtown	**84**	Millgate—51ave--Capilano
87	Millgate-- 86st--66ave--Downtown	**321**	Millgate--51ave--76ave--83st--roundabout--82ave --Bonnie Doon
80	87st&58ave—58ave--83St&Davies Rd--76ave&81st --90ave&81st	**83**	Meadows--GirardRd&76ave—Downtown
151	Dowtwon--92st&93ave --89st&76ave --78st&76ave	**4**	Bonnie Doon--Capilano
94	Bonnie Doon--Capilano	**82**	75st&82ave --82ave --83st--Connors Rd Downtown
85	83st&90ave-- 85st--90ave--Capilano	**86**	79st&90ave--Downtown
112	Downtown-- Connors Rd --95ave – Capilano		

Only 9 lines travel the whole transit corridor. Those lines are No. 8, No. 15, No. 61, No. 64, No. 65, No. 66, No. 68, No. 69, No. 72. Only No. 8 and No. 15 operate all the time, while the other routes are express only for peak hours.

4.2.3. Signal Timing

The signal controllers were configured as actuated with virtual loop detectors in VISSIM. The phasing sequence depends on the real condition. The signal plans are represented following standard NEMA 8-phases diagram. Intersection (Int.) 4, Int.7 and Int.8 have a standard four-phase plan without protected left-turn phases. The remaining intersections contain protected left-turn phases. Coordinated Phase 2 and Phase 6 are the reference phases. Yellow time and all-red time were set according to the respective real signal timing. The final signal timing plan is shown in Table 4-3.

Table 4-3 Signal Timing at Each Intersection

No	Intersection	Cycle	Offset	Timing Plan
1	95ave& Connors Rd	115	12	Φ_2 76s, Φ_4 22s / Φ_5 15s, Φ_6 61s, Φ_8 22s
2	92st& Connors Rd	120	41	Φ_2 35s, Φ_4 75s / Φ_6 35s, Φ_8 75s
3	82ave& 83st	140	68	Φ_2 69s, Φ_3 7s, Φ_4 46s / Φ_5 25s, Φ_6 44s, Φ_8 53s
4	76ave& 83st	130	36	Φ_2 75s, Φ_4 45s / Φ_6 75s, Φ_8 45s
5	Argyll& 83st	130	20	Φ_2 26s, Φ_3 42s, Φ_4 48s / Φ_6 26s, Φ_8 90s
6	Argyll& 86st	130	79	Φ_1 8s, Φ_2 19s, Φ_4 85s / Φ_6 27s, Φ_7 27s, Φ_8 58s
7	58ave& 86st	130	96	Φ_2 80s, Φ_4 30s / Φ_6 80s, Φ_8 30s
8	51ave&86st	140	55	Φ_2 55s, Φ_4 75s / Φ_6 55s, Φ_8 75s

4.3. VISSIM Model Calibration

VISSIM calibration aims to ensure that the estimation performance is accurate and reliable. There are no universal rules for micro-simulation calibration; thus, it is often conducted based on discretion according to the goals and available data. One popular method to calibrate VISSIM models is to compare certain major model outputs with the field observations and ensure that the difference is within an acceptable range. In this study, two simulation outputs were selected as the calibrating objectives:

1. Link traffic volumes along the bus corridor should be matched. Comparing the simulation volume and field volume, the coefficient of determination

(R-square) value should larger than 0.9, which is justified as an acceptable range.

2. Match bus travel time for entire corridor and the relative difference from the field observations should be within 10%, which is justified as an acceptable range.

One objective of calibration is to match traffic volumes in simulation with the observed traffic volumes. Based on the existing traffic volumes at major intersections, the mid-block traffic volumes between major intersections can be calculated. In simulation, vehicle counters are placed at each segment between two signalized intersections. In addition, the simulation output is a mean value through 10 times of run. Thus, the variation caused by random factors can be eliminated. To ensure the traffic volume trend is consistent with real-world measurements, 5-minute interval volumes should compared station by station. The aggregated hourly results of traffic volume calibration are shown in Table 4-4. Only one value of relative error, the third segment on northbound, exceeds the criterion. Traffic volume trend results are shown in Figure 4-4.

Table 4-4 Traffic Volume Calibration Results

Segment No. (Figure 4-2)	Southbound (vph)			Northbound (vph)		
	Simulation	Field	|ERR|%	Simulation	Field	|ERR|%
1-2	1108	1217	8.98%	551	586	5.97%
2-0	976	1025	4.71%	529	561	5.57%
0-3	837	850	1.54%	676	787	14.15%
3-4	701	660	6.27%	742	765	2.99%
4-5	462	485	4.65%	741	759	2.36%
5-6	982	1010	2.72%	1568	1529	2.55%
6-7	514	524	1.94%	500	525	4.64%
7-8	566	567	0.19%	543	569	4.46%

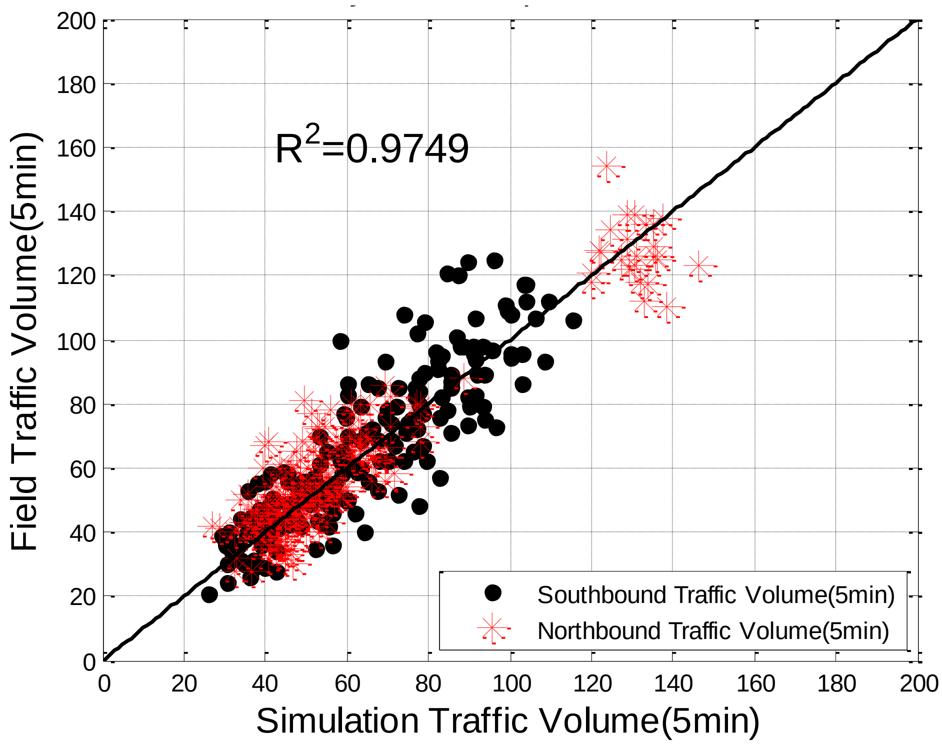


Figure 4-3 R-square Value of Entire Southeast Corridor

The coefficient of determination, R^2, analysis was conducted to investigate the relationship between simulation output and field observation. R^2 indicates how well data points fit a proposed line or curve. On the graph, the actual traffic volumes are represented on the y-axis and simulated traffic volumes are represented on the x-axis: if the actual traffic volumes exactly match the simulated volumes, then all data points would be on a 45 degree line and R^2 value for the dataset would equal 1. However, the farther away from the 45 degree line those data points are, the greater the discrepancies between actual and simulated traffic volumes, and hence, the lower the R^2 value of the dataset.

The expression for R^2 is:

$$R^2 = 1 - \frac{\sum_i (v_i - f_i)^2}{\sum_i (v_i - \frac{1}{n}\sum_{i=1}^{n} v_i)^2} \quad (27)$$

Where:

v_i : the 5-minute traffic volumes from the VISSIM simulation

f_i : the 5-minute empirical traffic volumes

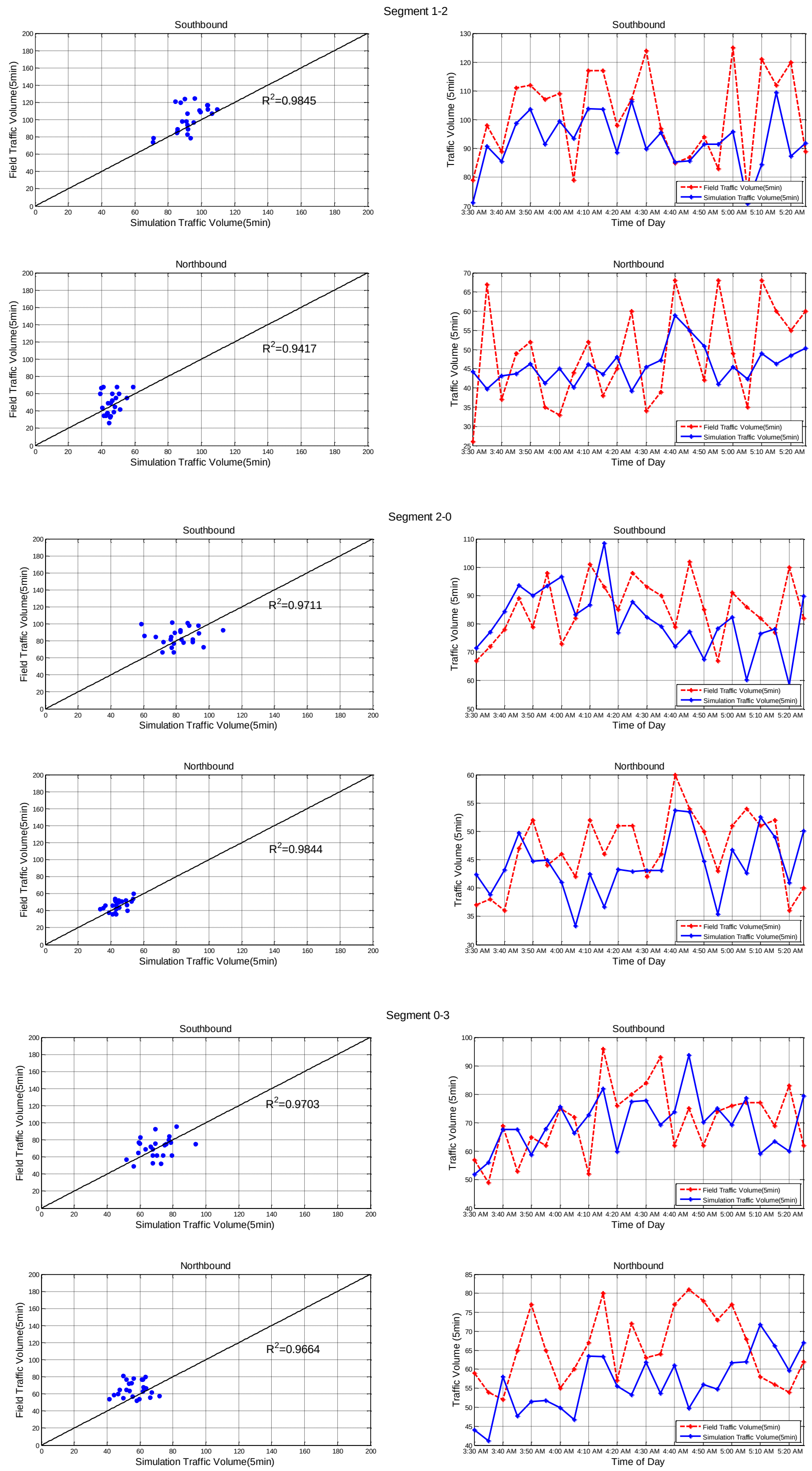


Figure 4-4a Calibration Results for each Segment along the Corridor

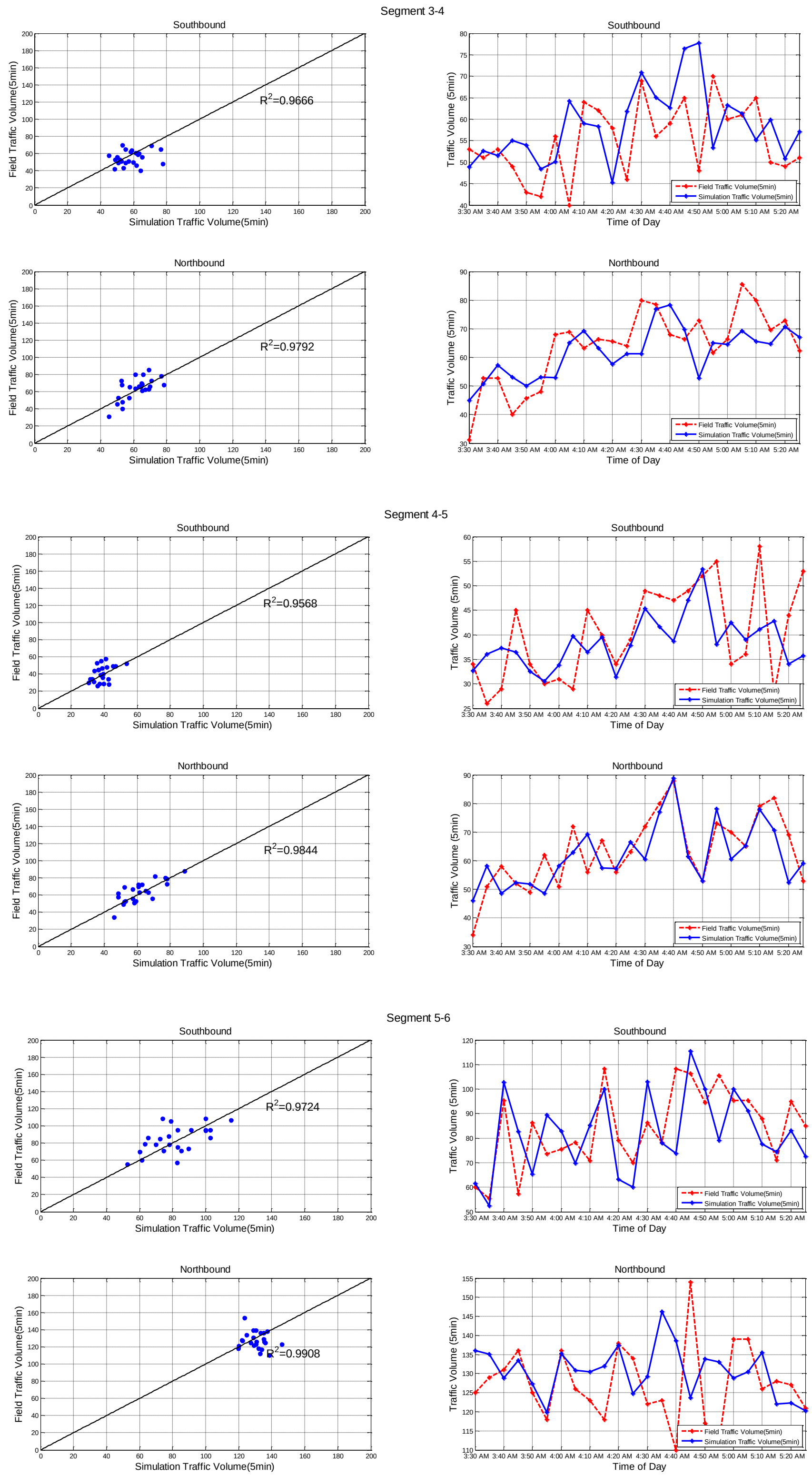


Figure 4-4b Calibration Results for each Segment along the Corridor

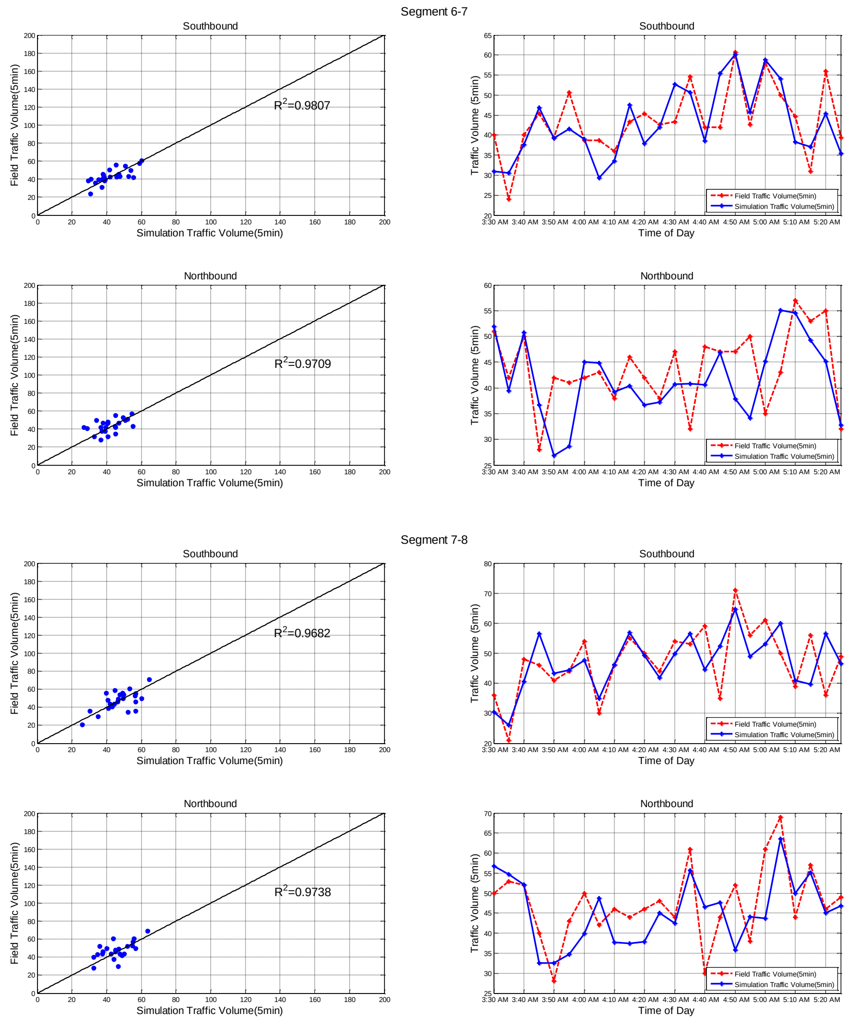
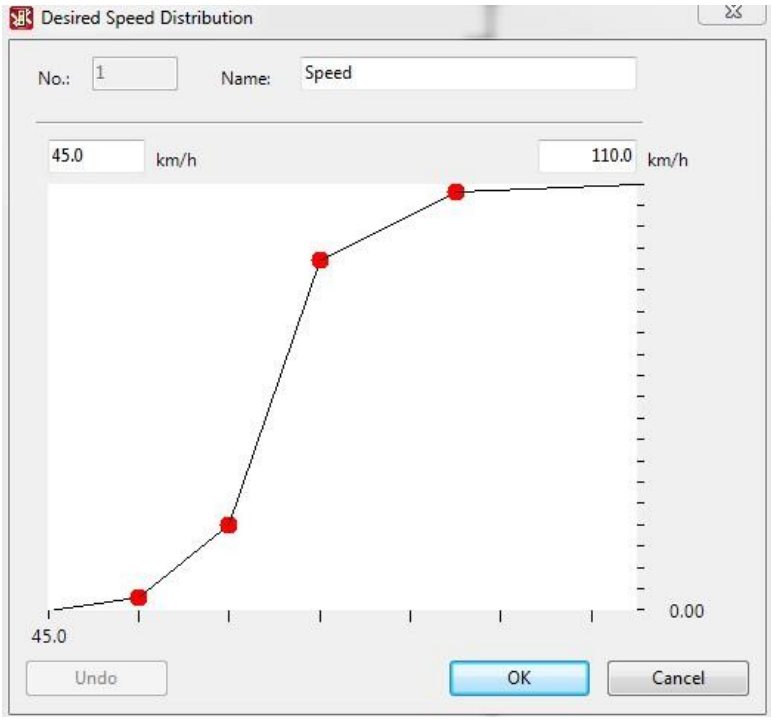


Figure 4-4c Calibration Results for each Segment along the Corridor

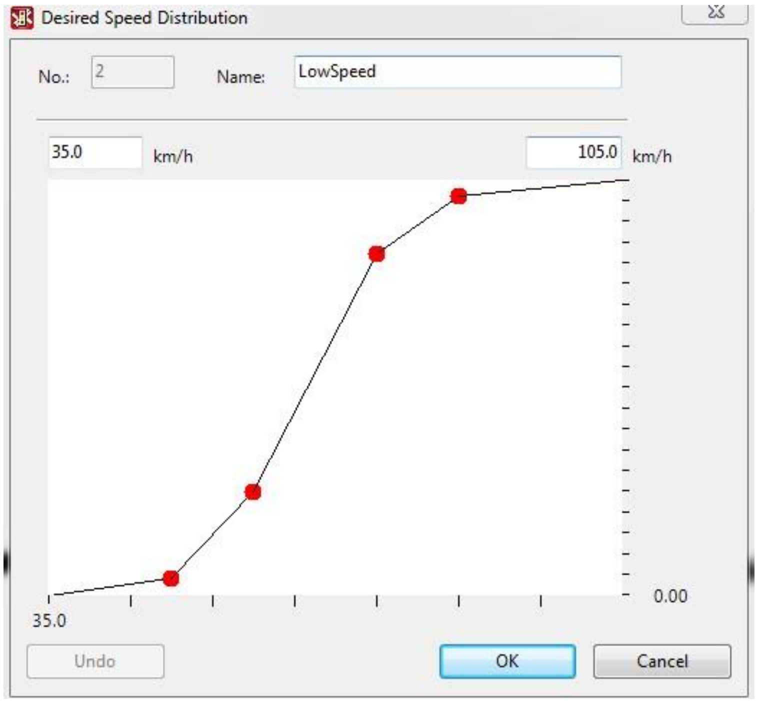
Transit travel time calibration is to match the transit operation status along the study corridor with the field data. The transit travel time is calibrated through adjusting the desired bus speed. Desired speed is an important parameter for on-road vehicle operation and achievable travel speed. If there is not an obstacle ahead, vehicles will travel at the desired speed, which follows a pre-defined distribution. Stochastic distributions of desired speeds can be defined for each vehicle type. The desired speed for general vehicles is defined by the City of Edmonton through multi-year observations. The speed profile covers the 60 km/h speed limit, which is applied along the study corridor. There are two distributions regarding two different scenarios.

- For signalized intersections with spacing greater than 400 metres (m) or where the expected free flow speed is greater than 65 km/h, the speed profile is 45-0, 55-0.03, 65-0.20, 75-0.82, 90-0.98, and 110-1.0.
- For signalized intersections with spacing less than 400 m, the speed profile is 35-0, 50-0.04, 60-0.25, 75-0.82, 85-0.96, and 105-1.0.

The desired speed distribution for general vehicles is shown in Figure 4-5. In transit travel time calibration only desired bus speed will be adjusted. The buses with higher speed usually have less travel time.



A



B

Figure 4-5 Desired Travel Speed of General Vehicle in Southeast Corridor (A: Long Spacing Intersections Segment; B: Short Spacing Intersections Segment)

Table 4-5 gives the total travel time once the transit bus driver crosses the entire corridor. The total travel time for a regular bus in simulation is almost 20 min to finish the entire corridor. In the field it takes almost same amount of travel time for both northbound and southbound buses.

Table 4-5 Corridor Travel Time Calibration Results

Mode	Direction	Travel Time (s)		
		Simulation (s)	Field (s)	|ERR| (%)
Transit	Northbound	1068.6	1178	9.28%
	Southbound	1089.7	1105	1.38%

4.4. Implement adaptive TSP into VISSIM

Chapter 3 discussed the logic of simulating adaptive TSP in VISSIM. There are three major parts: 1) simulator; 2) mediator; and 3) optimizer. Among these three parts, the mediator plays the most important role in the system. The C++ program, which is the main body of the mediator, drives the simulation run step by step via the COM interface. On each step, the simulation reports the bus detection status of the whole corridor to C++, and C++ examines whether a bus needs priority. As long as a bus is detected, the program will retrieve the necessary traffic data through the COM interface from VISSIM and the signal timings via NTCIP from ASC/3 (American Association of State Highway and Transportation Officials et al. 2008). After all the information is ready, the program requests the optimizer, Matlab, to solve optimization problem using sequential quadratic programming (SQP). C++ and Matlab are connected through the .NET framework. After the calculation is done, C++ will replace the current timing with the optimized one in the ASC/3 controller. After the TSP request expires or the bus checks out, C++ will recover the original timing to ASC/3. In this study there were a total of 8 controllers along the corridor. To make the TSP processes independent of each other, the program used separate threads to process the TSP strategies. Figure 4-6 shows the entire procedure on one intersection. All other signal controllers have the same procedure, but are controlled by other threads.

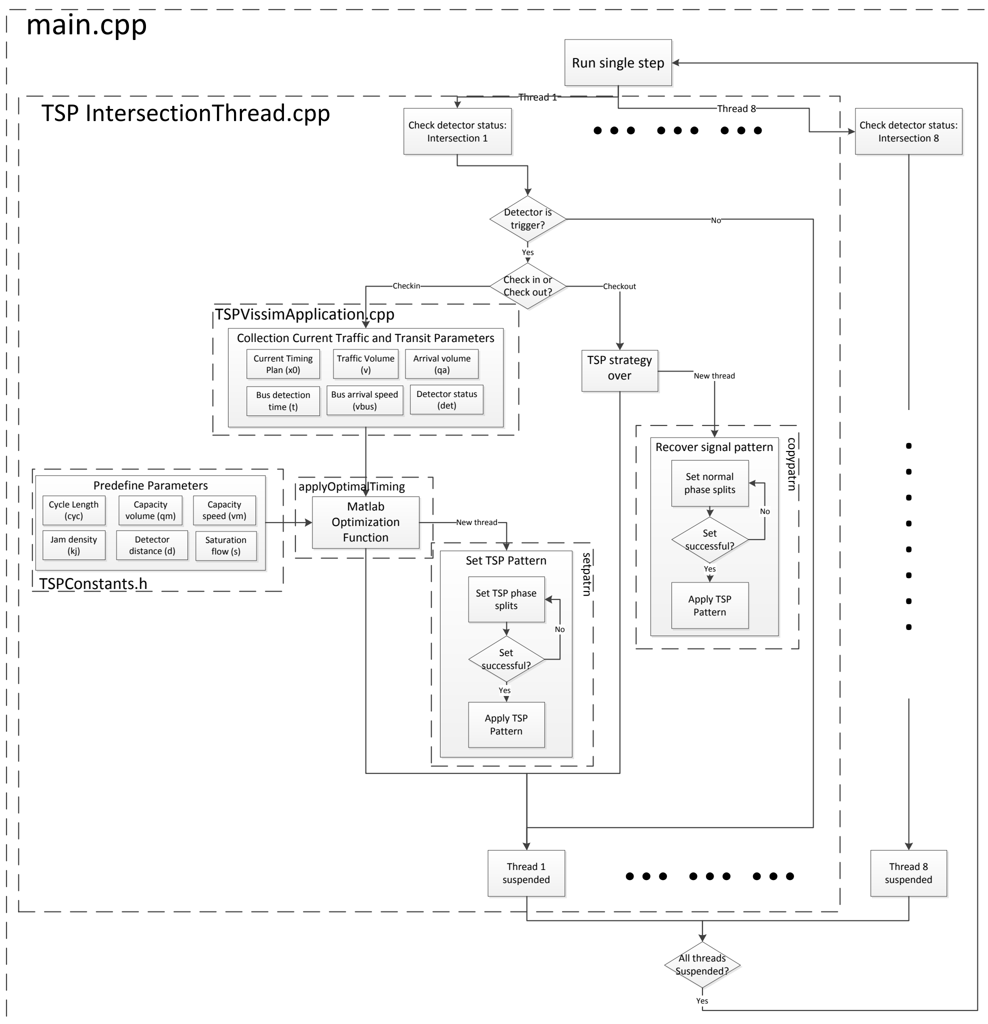


Figure 4-6 Programming flow chart of TSP strategy in VISSIM

If there are multiple TSP requests, the program recalculates the optimal TSP timing and updates the signal timing accordingly. As a result, a granted TSP may be replaced with a new TSP plan, considering the needs of multiple TSP requests. Once a TSP request is granted and finished, the controller recovers the original signal timing and inhibits TSP requests for 1 cycle to recover the impact on signal control of using priority strategy. During TSP operations, the cycle length and offset are not changed; therefore, the coordination on the mainline can be maintained.

CHAPTER 5. PERFORMANCE EVALUATION

This chapter evaluates the proposed adaptive TSP performance. Before evaluation, a sensitivity analysis was conducted to determine the best weighting factor. This chapter also provides a comparison study among non-TSP, conventional TSP and adaptive TSP scenarios.

5.1. Sensitivity Analysis to Determine the Weighting Factor

In this case study, the first step was to find a suitable value for the weighting factors α and β. The reasonable approach was to conduct a sensitivity test and analyze the relationship between the performance and weighting factor α and β. The value of β/α determines the performance of the objection function. To investigate how the factors perform, a numerical study was conducted. The test range of β/α was from 10-100 with 10 intervals. Set $\beta/\alpha = 1$ as the reference point, because here a bus can be regarded the same as a general vehicle.

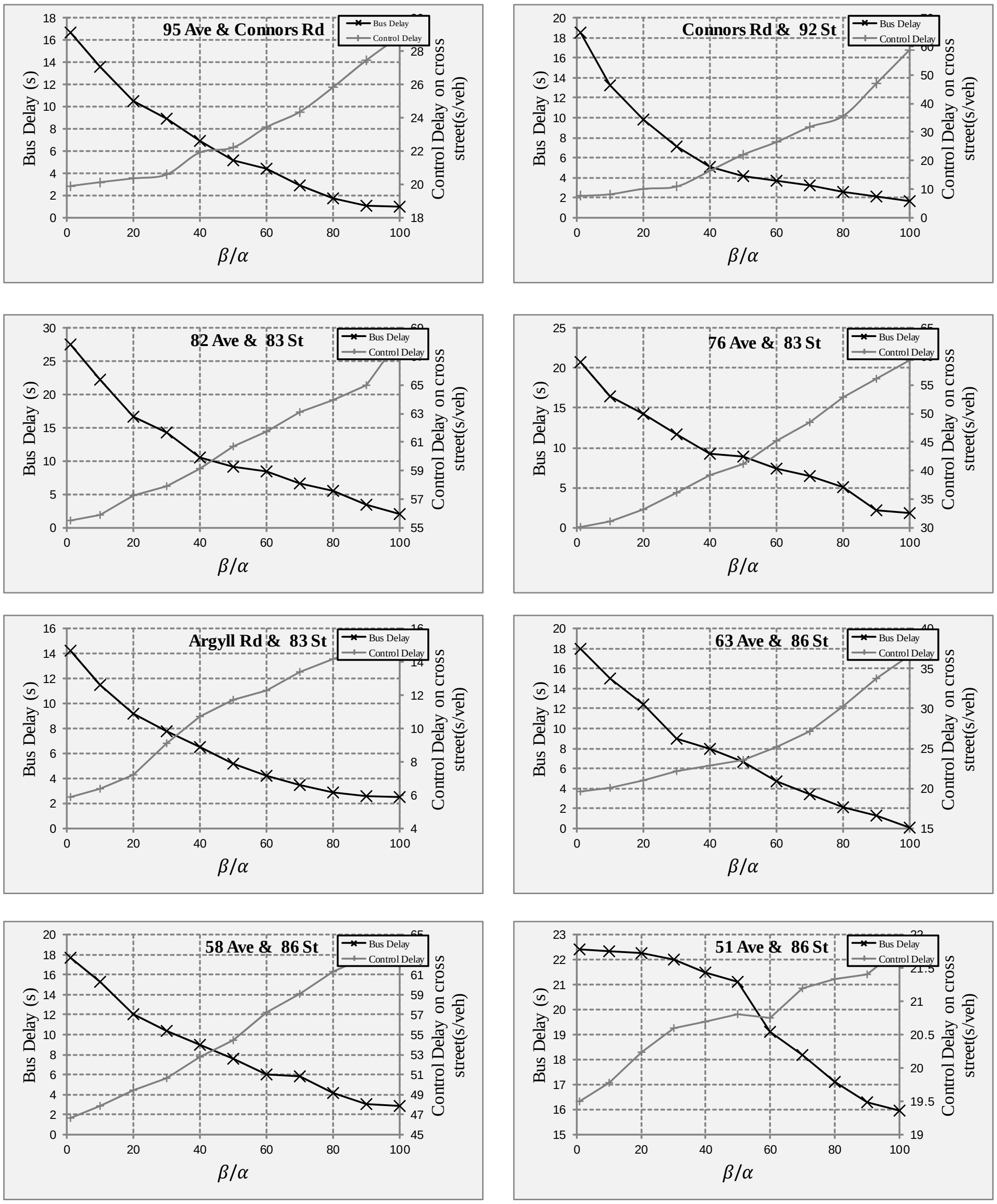


Figure 5-1 Sensitivity Analysis of the Weighting Factor

Figure 5-1 shows the relationship between the β/α, bus delay and control delay for each intersection. As the β/α increases, the bus delay decreases because of a higher weighting given to the bus. However, at the same time, the control delay increases, and at increasing rates. Therefore, the best value of β/α belongs to the location where the marginal bus delay and traffic control delay are equal.

It can be observed that, the best values are different for each intersection. Therefore, the different *β/α* values should be determined and used at each specific intersection. However, the range of the value should remain approximately 40 to 80.

5.2. Adaptive TSP Evaluation

5.2.1. Experiment Design

The main purpose of the experiment was to test the performance of the proposed adaptive TSP control strategy and compare it with other conventional TSP strategies. To test the adaptive TSP performance, a reference scenario was configured. This was the baseline scenario without any TSP control. Besides baseline, two types of TSP control strategies were considered as the objects. The three control scenarios are:

1. Baseline: actuated control at signalized intersections without any TSP control strategy.
2. Active TSP: actuated control at signalized intersections, with active TSP strategy. The TSP can grant the priority to transit buses via green extension or red truncation.
3. Adaptive TSP: actuated control at signalized intersections, with the proposed adaptive TSP strategy. The TSP will generate the optimized TSP plan to ensure benefit for both transit buses and general vehicles.

In this experiment, 2 peak hours were simulated. In each test scenario, the simulation ran 10 times with different random seeds to obtain the mean of the performance as the final result. The conventional active TSP strategy has a typical setting of 10-second maximum green extension and 5-second guaranteed green on other phases.

Four Measures of Effectiveness (MOEs) were considered and analysed:

1. Total bus travel time along the corridor;
2. Bus delay at each intersection;
3. Control delay and Level of Service (LOS) at each intersection; and
4. General traffic travel time along the corridor.

These four MOEs determine TSP performance and benefit. The first two MOEs are related to transit buses and investigate how many seconds TSP can save bus travel time and bus delay. These are major benefits obtained from a TSP control strategy. The last two MOEs are related to general vehicles and represent the impact of TSP control on general vehicles.

5.2.2. Evaluation Results and Comparison

The results are shown in Table 5-1, Table 5-2, Table 5-3 and Table 5-4. Comparing the non-TSP scenario to the TSP scenario, both active and adaptive TSP bring significant bus travel time savings. The t-test was used to investigate the significance of improvement gained by the proposed adaptive TSP. A t-test is any statistical hypothesis test in which the test statistic follows the Student *t* distribution if the null hypothesis is supported. It can be used to determine whether the mean of two sets of data are significantly different from one another, and is most commonly applied when the test statistic follows a normal distribution if the value of a scaling term in the test statistic is known. In the t-test, one assumption is that the sample of the results follows the normal distribution at a 95% confidence level.

Total bus travel time

Total bus travel time represents the bus travel time along the entire corridor. Only the buses driving through the entire corridor are counted as the object. The results are the average value of the multiple runs. And the t-value represents the significance of the mean value of travel time improvement. Comparing the non-TSP scenario to the TSP scenario, both active and adaptive TSP bring significant bus travel time savings, as shown in Table 5-1. The mean value of the total travel time shows adaptive TSP will save about 40-80 seconds compared to the baseline. And the active TSP can save 60-90 seconds along the whole corridor compared to the baseline. The active TSP has more saving on bus travel time than adaptive TSP.

Table 5-1 Total Bus Travel Times on the Southeast Corridor

Control Type	Southbound		Northbound	
	Average total travel time (s)	Time saving	Average total travel time (s)	Time saving
Baseline	1089.7	N/A	1086.6	N/A
Active	999.7	90	1024.4	62.2
t value	4.33		2.35	
t critical value	1.78		1.78	
Significant improvement?	Yes		Yes	
Adaptive	1010.5	79.2	1046.6	40
t value	5.89		1.83	
t critical value	1.78		1.78	
Significant improvement?	Yes		Yes	

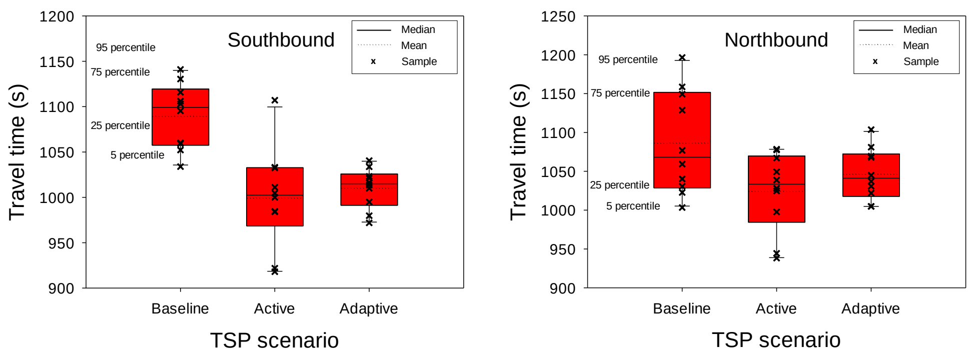


Figure 5-2 Total Bus Travel Time Comparison

Figure 5-2 shows a box plot to visually represent the travel time sample in the set. Each box gives the mean and median value and the 25 and 75 percentile value in the set. From the figure, it is easy to see that the buses under adaptive TSP control scenario have the shorter bus travel time versus the baseline. The significance of the mean value difference between baseline and adaptive TSP shows that it can be regarded as a significant improvement of average travel time. Although the adaptive TSP doesn't show better performance on saving travel time than active TSP, it will take consideration on the traffic control delay on minor street so that the TSP will not affect general traffic too much. Trading off the transit priority and general traffic delay is the major objective of developing adaptive TSP strategies.

Bus delay at intersection

The bus delay at intersections is defined as the delay between a bus approaching the intersection and a bus crossing the stop line. The delay from simulation includes the bus waiting delay, accelerate/decelerate delay, and low-speed moving delay. The delay counts were taken at each intersection for both directions on mainline. The comparison results are shown in Table 5-2.

Table 5-2 Bus Delay at Individual Intersection

No.	1	2	3	4	5	6	7	8
Intersection	**95 Ave & Connors Rd**	**Connors Rd & 92 St**	**82 Ave & 83 St**	**76 Ave & 83 St**	**Argyll Rd & 83 St**	**63 Ave & 86 St**	**58 Ave & 86 St**	**51 Ave & 86 St**
	Delay/Bus (sec)							
Direction	SB	SB	SB	SB	SB	SB	SB	SB
Baseline	11	7.3	15.8	10.4	6.2	25.4	6.4	25
Active	6.7	2.5	8.3	5.2	3.6	17.8	3	15.7
Saving	4.3	4.8	7.5	5.2	2.6	7.6	3.4	9.3
t value	3.11	5.96	4.29	3.31	3.06	1.94	3.81	3.82
t critical value (two tail)	2.1							
Confidence Level	95%							
p value	5.94E-03	2.13E-05	4.33E-04	3.82E-03	6.70E-03	6.71E-02	1.27E-03	1.23E-03
Significant improvement?	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Adaptive	8	4.7	9.3	7.2	6.2	20.4	5.3	18.1
Saving	3	2.6	6.5	3.2	0	5	1.1	6.9
t value	2.03	4.22	3.47	1.5	0.02	1.54	1.06	2.71
t critical value	2.1							

(two tail)								
Confidence Level	95%							
p value	5.90E-03	8.90E-04	5.00E-03	1.51E-01	9.80E-01	1.40E-01	3.10E-01	1.80E-02
Significant improvement?	No	Yes	Yes	No	No	No	No	Yes
	Delay/Bus (sec)							
Direction	NB	NB	NB	NB	NB	NB	NB	NB
Baseline	19.8	7.8	19.7	7.4	5.4	13.4	6.9	36.7
Active	10.8	2.1	13	6.9	3.7	4.1	5.4	23.7
Saving	9	5.7	6.7	0.5	1.7	9.3	1.5	13
t value	5.02	8.54	2.19	0.21	0.35	1.63	1.74	2.61
t critical value (two tail)	2.1							
Confidence Level	95%							
p value	8.76E-05	9.49E-08	4.18E-02	8.34E-01	7.24E-01	1.20E-01	9.74E-02	1.77E-02
Significant improvement?	Yes	Yes	Yes	No	No	No	No	Yes
Adaptive	12	3.2	14.1	4.2	3.1	13.5	4	25.6
Saving	7.8	4.6	5.6	3.2	2.3	-0.1	2.9	11.1
t value	4.83	5.92	2.28	1.77	2.76	0.38	3.93	2.78
t critical value (one tail)	2.1							
Confidence Level	95%							
p value	2.60E-04	1.00E-04	3.60E-02	9.70E-02	1.50E-02	7.10E-01	1.70E-03	1.60E-02
Significant improvement?	Yes	Yes	Yes	No	Yes	No	Yes	Yes

In Table 5-2, it can be found that in most of intersections for both directions, the active TSP scenario suffers the least bus delay. Then the adaptive TSP ranks as second, and baseline suffers the most delay. It can be concluded that the active strategy saves more bus delay than adaptive TSP, because active TSP grants priority to bus regardless of the traffic condition. It also can be concluded that there are similar reductions on bus delay caused by both active and adaptive TSP at most of intersections. That means, in terms of bus delay, active and adaptive TSP provide almost the same benefit to the bus.

Int. 5 and Int. 6 are special because the corridor turns right at Int. 5 and turns left at Int. 6 for southbound, and reverse for northbound. Therefore, here the results may have a different pattern (bus delay and control delay).

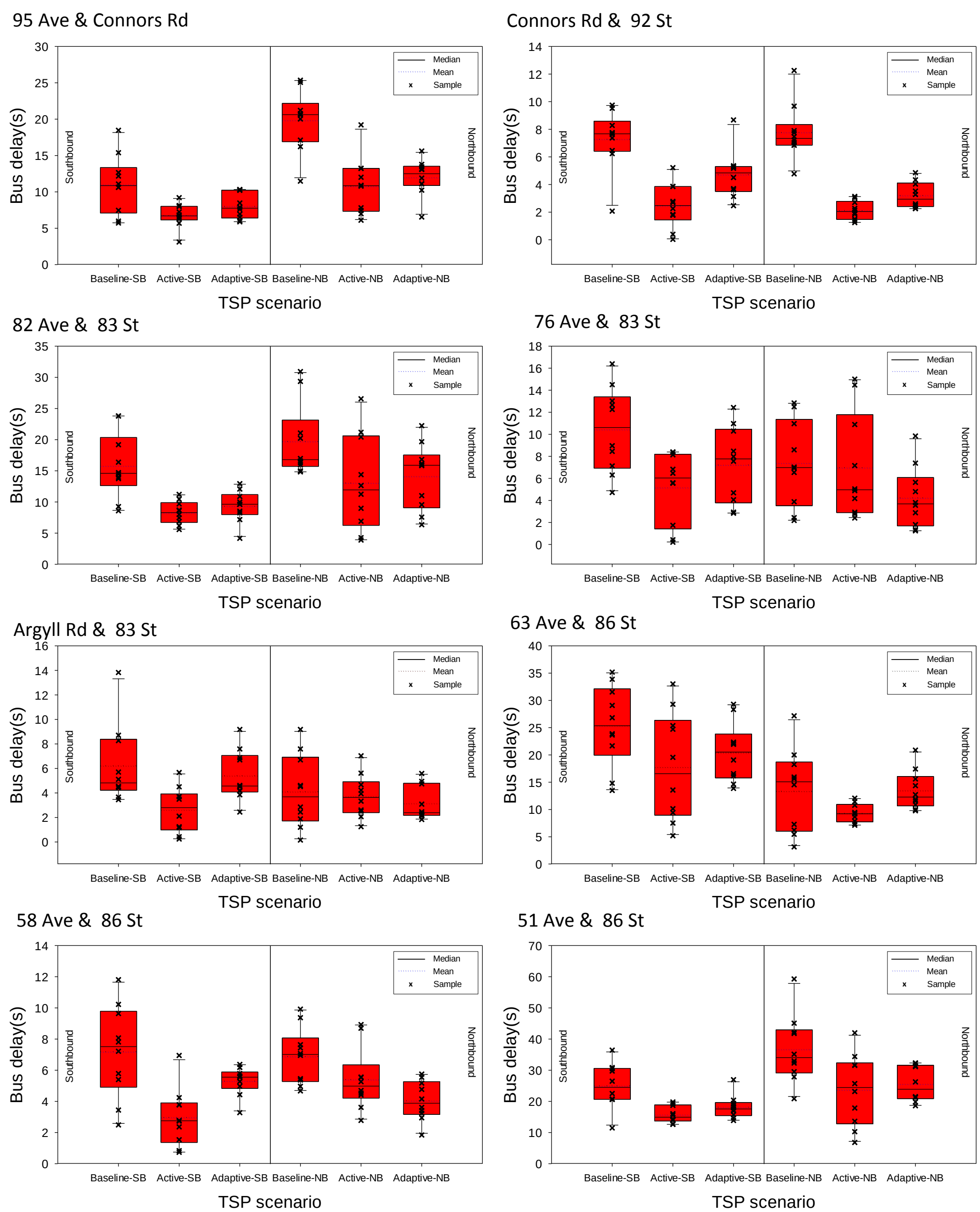


Figure 5-3 Bus Delay Comparison between Active and Adaptive TSP at Intersections

Control delay and LOS at the intersection

The intersection Level of Service (LOS) and control delay for both mainline and side-streets are shown in Table 5-3. The LOS is determined by the control delay and the control delays are split into main-street (on corridor) and side-street (cross corridor).

Table 5-3 Intersection Level of Service and Control Delay

No.	1				2				3			
Intersection	95 Ave & Connors Rd				Connors Rd & 92 St				82 Ave & 83 St			
	Average Vehicle Control Delay(seconds/vehicle)											
	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street
Baseline	A	8.6	C	24	B	11.4	C	34.2	C	27.7	E	58.7
Active	A	7.7	C	28.8	A	9.2	D	42.7	C	24.3	E	76.2
Saving		0.9		-4.8		2.2		-8.5		3.4		-17.5
t value		0.5		1.67		1.46		2.21		0.83		3.18
t critical value (two tail)	2.1											
Confidence Level	95%											
p value		0.62		0.11		0.16		0.04		0.41		0.01
Significant change?		No		No		No		Yes		No		Yes
Adaptive	A	8.4	C	23.4	B	10.2	C	32.9	C	25	E	52.5
Saving		0.2		0.6		1.2		1.3		2.7		6.2
t value		0.19		0.04		1.04		0.039		0.67		0.63
t critical value (two tail)	2.1											
Confidence Level	95%											
p value		0.84		0.96		0.31		0.97		0.51		0.53
Significant change?		No		No		No		No		No		No
No.	4				5				6			
Intersection	76 Ave & 83 St				Argyll Rd & 83 St				63 Ave & 86 St			
	Average Vehicle Control Delay(seconds/vehicle)											
	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street
Baseline	A	7.2	D	43.1	B	11.7	A	7.9	C	25.6	C	33.6
Active	A	3.4	D	49	B	10.3	A	8.5	C	20.8	D	45
Saving		3.85		-5.9		1.4		-0.6		4.8		-11.4
t value		1.95		1.04		0.79		0.49		1.39		2.26
t critical value (two tail)	2.1											
Confidence Level	95%											
p value		0.07		0.31		0.43		0.63		0.18		0.04
Significant change?		No		No		No		No		No		Yes

Adaptive	A	6.4	D	41.5	B	10.4	A	7.2	C	23.3	C	27.5
Saving		0.8		1.6		1.3		0.7		2.3		6.1
t value		0.03		0.208		1.13		0.84		1.63		1.41
t critical value (two tail)	2.1											
Confidence Level	95%											
p value		0.97		0.83		0.27		0.411		0.123		0.177
Significant change?		No		No		No		No		No		No

No.	7				8			
Intersection	58 Ave & 86 St				51 Ave & 86 St			
	Average Vehicle Control Delay(seconds/vehicle)							
	LOS	Main Line	LOS	Cross Street	LOS	Main Line	LOS	Cross Street
Baseline	A	3.9	E	60.5	C	21.8	C	20.2
Active	A	2.6	E	72.8	B	19.0	C	25.5
Saving		1.3		-12.3		2.8		-5.3
t value		2.67		1.79		0.94		1.18
t critical value (two tail)	2.1							
Confidence Level	95%							
p value		0.02		0.09		0.36		0.25
Significant change?		No		No		No		No
Adaptive	A	5.2	E	52.7	B	19.6	C	21.9
Saving		-1.3		7.8		2.2		-1.7
t value		0.74		1.42		0.51		0.8
t critical value (two tail)	2.1							
Confidence Level	95%							
p value		0.47		0.173		0.61		0.432
Significant change?		No		No		No		No

It was found that, compared to the baseline scenario, active TSP increases control delay at some intersections. Active TSP significantly increases traffic delay on side-streets. Adaptive TSP can help neutralize this problem. As a trade-off between the bus priority and general traffic delay, adaptive TSP will consider both aspects so that bus gets less benefit under adaptive than active TSP. However, the major objective of adaptive TSP is to consider both granting TSP priority and minimizing general traffic impact.

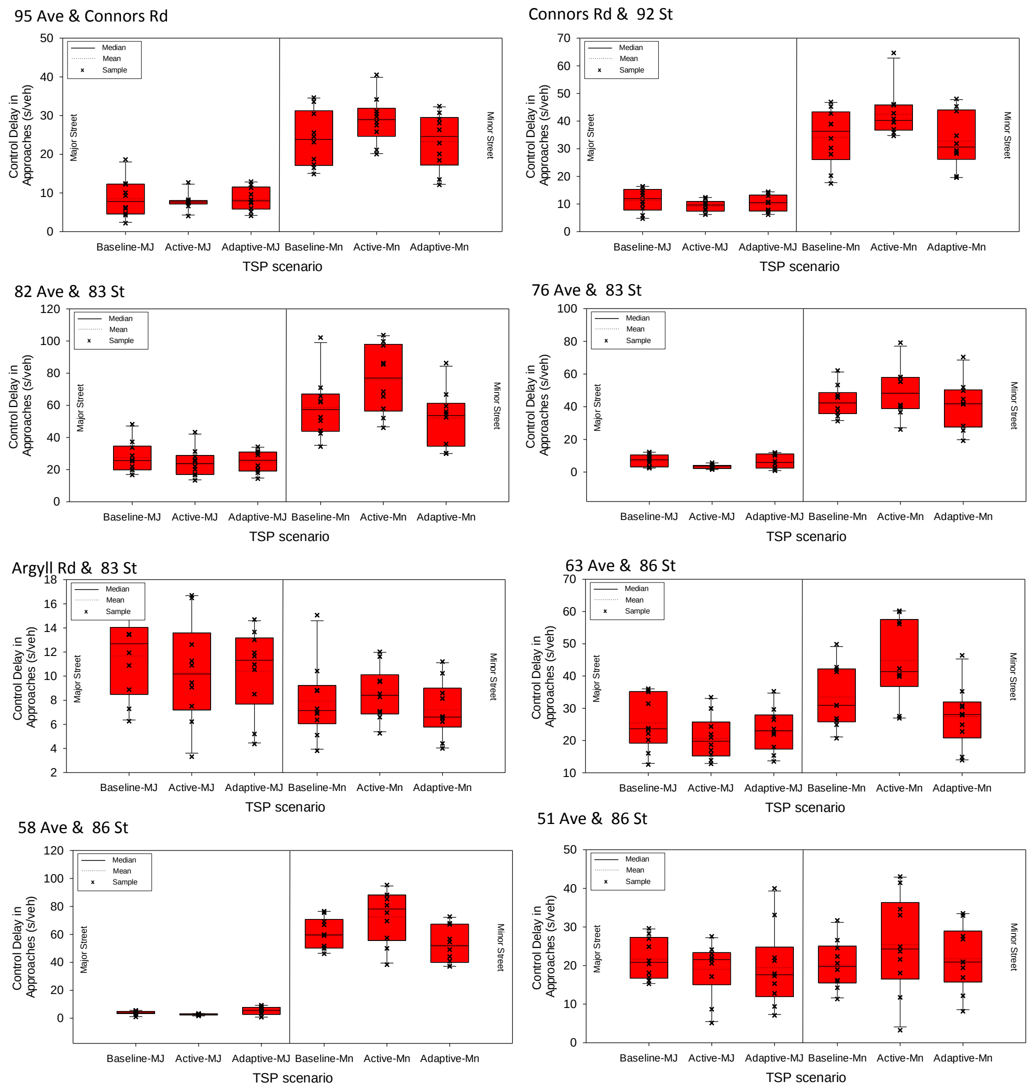


Figure 5-4 Intersection Control Delay

General traffic travel time

Table 5-4 shows the general traffic travel time under three scenarios. The general traffic travel time section is the same one as the bus travel time section.

Table 5-4 General Traffic Travel Time along the Corridor

Control Type	Southbound		Northbound	
	Average total travel time (s)	Time saving	Average total travel time (s)	Time saving
Baseline	496.8	N/A	530.4	N/A
Active	488.3	8.5	534.2	-3.8
Adaptive	494.3	2.5	522.5	7.9
t value	0.91		0.57	
t critical value	1.78		1.78	
Significant improvement?	No		No	

From Table 5-4 it can be found that the TSP has no significant impact to general traffic travel time. When TSP is activated, general traffic on bus approaches can even obtain some benefit; although, most of vehicles still drive under the normal signal timing plan. On average, the mean value does not show a significant change.

5.3. Comparison with Other Researches

The objective of this section is to investigate the differences between the new proposed adaptive TSP control algorithm and previous studies. It is important to see the benefit of the new algorithm and how it outperforms previous studies. The selected previous studies follow the optimization approach, but have different objective functions. Two alternative objective functions were selected for review to represent various optimization targets. The proposed study duplicated the TSP control algorithm of previous studies and implemented it in micro-simulation using the same performance MOEs.

5.3.1. Alternative Objective Function

Bus delay only

One of the previous studies considers only bus delay as the objective function. Generally, this objective function is used to solve the problem of multiple bus priority requests. It was first proposed by Head et al. (Head et al. 2006) and He et al. (He et al. 2011) who used a heuristic solution to solve the objective function. The objective function involved the bus delay of one or more buses approaching the intersection, and granted as much as priority to the transit bus as possible. Thus the traffic delay was ignored during the optimization.

Control delay & bus delay

The objective function with both control delay and bus delay is a more popular way to formulate the optimization problem. This kind of objective function not only correctly represents the preliminary TSP problem, which is the trade-off between reducing bus delay and increasing traffic delay, but also it is easy to formulate in both mathematical functions and programming. One of the pioneer studies was done by Li (Li et al. 2011). He proposed an adaptive TSP control strategy combining the traffic control delay and bus delay. His control delay was derived from the queue theory and the bus delay was estimated from cumulative vehicle counts. Although his control strategy was reasonable and reliable, the bus delay estimation from cumulative curve may not have been accurate enough.

5.4. Comparison results and analysis

Total bus travel time

Table 5-5 Total Bus Travel Times on the Southeast Corridor

Control Type	Southbound		Northbound	
	Average total travel time (s)	Time saving (vs. baseline)	Average total travel time (s)	Time saving (vs. baseline)
Baseline	1089.7	N/A	1086.6	N/A
New Bus Delay model and control delay	1010.5	79.2	1046.6	43.1
Bus delay only	988.4	101.3	994.7	95
Cumulative Curve Bus delay and Control Delay	1036.5	53.2	1040.7	49

Table 5-5 shows the total bus travel time along the whole corridor under different adaptive TSP scenario. From the table, it can be found that if the objective function only considers bus delay, the travel time will be the least. This TSP system will provide as much as priority to the bus regardless of other traffic at the intersection. However, the travel time saving is only up to about 50 seconds more than the proposed adaptive TSP functions. On the other hand, the cumulative bus delay method shows similar travel time saving as the new bus delay method.

Bus delay at intersection

Table 5-6 Bus Delay at Individual Intersection

No.	1	2	3	4	5	6	7	8
Intersection	**95 Ave & Connors Rd**	**Connors Rd & 92St**	**82Ave &83St**	**76Ave &83St**	**Argyll Rd & 83St**	**63 Ave &86St**	**58Ave &86St**	**51Ave &86St**
	Delay/Bus (sec)							
Direction	SB	SB	SB	SB	SB	SB	SB	SB
Baseline	11	7.3	15.8	10.4	6.2	25.4	6.4	25
New Bus Delay model and control delay	8	4.7	9.3	7.2	6.2	20.4	5.3	18.1
Saving (vs. baseline)	3	2.6	6.5	3.2	0	5	1.1	6.9
Bus delay only	8.1	5.2	8.2	5.4	6	20.7	3.7	19
Saving (vs. baseline)	2.9	2.1	7.6	5	0.2	4.7	2.7	6
Cumulative Curve Bus delay and Control Delay	8.6	6.5	12.5	7.8	6.2	17	4	20.4
Saving (vs. baseline)	2.4	0.8	3.3	2.6	0	8.4	2.4	4.6
	Delay/Bus (sec)							
Direction	NB	NB	NB	NB	NB	NB	NB	NB
Baseline	19.8	7.8	19.7	7.4	5.4	13.4	6.9	36.7
New Bus Delay model and control delay	12	3.2	14.1	4.2	3.1	13.5	4	25.6
Saving (vs. baseline)	7.8	4.6	5.6	3.2	2.3	-0.1	2.9	11.1
Bus delay only	11.2	4.6	13.3	3.8	3.1	12.9	3.1	22.1
Saving (vs. baseline)	8.6	3.2	6.4	3.6	2.3	0.5	3.8	14.6
Cumulative Curve Bus delay and Control Delay	15.1	4.5	17.8	7.4	5.6	19.8	4.7	33.9
Saving (vs. baseline)	4.7	3.3	1.9	0	-0.2	-6.4	2.2	2.8

The bus delay at intersections shows the same trend as bus travel time. The objective function with travel time only performs best among the three candidates. The other two objective functions give the same performance as one another. Each objective functions saves bus delay at most intersections.

Control delay and LOS at the intersection

Table 5-7 Intersection Level of Service and Control Delay

No.	1				2				3			
Intersection	95 Ave & Connors Rd				Connors Rd & 92 St				82 Ave & 83 St			
	Average Vehicle Control Delay(seconds/vehicle)											
	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street
Baseline	A	8.6	C	24	B	11.45	C	34.2	C	27.7	E	58.7
New Bus Delay model and control delay	A	8.45	C	23.4	B	10.2	C	32.95	C	25	D	52.5
Saving (vs. baseline)		0.15		0.6		1.25		1.25		2.7		6.2
Bus delay only	A	8.55	C	25.05	A	9.4	D	39.25	C	23.5	E	69.9
Saving(vs. baseline)		0.05		-1.05		2.05		-5.05		4.2		-11.2
Cumulative Curve Bus delay and Control Delay	A	9	C	23.25	B	10.82	D	35.55	C	25.1	E	64.25
Saving(vs. baseline)		-0.4		0.75		0.63		-1.35		2.6		-5.55

No.	4				5				6			
Intersection	76 Ave & 83 St				Argyll Rd & 83 St				63 Ave & 86 St			
	Average Vehicle Control Delay(seconds/vehicle)											
	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street	LOS	Main Line	LOS	Side Street
Baseline	A	7.25	D	43.1	B	11.7	A	7.95	C	25.6	C	33.6
New Bus Delay model and control delay	A	6.4	D	41.5	B	10.45	A	7.2	C	23.35	C	27.55
Saving(vs. baseline)		0.85		1.6		1.25		0.75		2.25		6.05
Bus delay only	A	5.95	D	48.25	B	10.6	A	7.1	C	26.8	C	33.5
Saving(vs. baseline)		1.3		-5.15		1.1		0.85		-1.2		0.1
Cumulative Curve Bus delay and Control Delay	A	7.15	D	44.3	B	10.45	B	12	D	48.85	D	45.25
Saving(vs. baseline)		0.1		-1.2		1.25		-4.05		-23.25		-11.65

No.	7				8			
Intersection	58 Ave & 86 St				51 Ave & 86 St			
	Average Vehicle Control Delay(seconds/vehicle)							
	LOS	Main Line	LOS	Cross Street	LOS	Main Line	LOS	Cross Street
Baseline	A	3.9	E	60.55	C	21.85	C	20.25
New Bus Delay model and control delay	A	5.25	D	52.75	B	19.65	C	21.95
Saving(vs. baseline)		-1.35		7.8		2.2		-1.7
Bus delay only	A	4.45	E	63	B	17.25	D	38.25
Saving(vs. baseline)		-0.55		-2.45		4.6		-18
Cumulative Curve Bus delay and	A	5.3	E	61.1	B	18.6	C	22.3

Control Delay									
Saving(vs. baseline)		-1.4		-0.55		3.25		-2.05	

The control delay at intersections is demonstrated in Table 5-7, which shows that the objective function with the proposed bus delay model gives the least negative impact among the three compared objective functions, especially at cross streets. The objective function with only bus delay is always higher than baseline, which means the TSP affected traffic mobility on minor streets. The cumulative curve bus delay method negatively impacts minor streets.

General traffic travel time

Table 5-8 General Traffic Travel Time along the Corridor

Control Type	Southbound		Northbound	
	Average total travel time (s)	Time saving (vs. baseline)	Average total travel time (s)	Time saving (vs. baseline)
Baseline	496.8	N/A	530.4	N/A
New Bus Delay model and control delay	494.3	2.5	522.5	7.5
Bus delay only	483.8	13	525	5.4
Cumulative Curve Bus delay and Control Delay	496.4	0.4	528.7	1.3

Table 5-8 shows that TSP will not affect the general traffic travel time no matter which TSP control strategy is used.

CHAPTER 6. CONCLUSION AND FUTURE WORK

This chapter gives an overall summary and discusses the limitations of the research. This chapter also proposes future work that can potentially improve the proposed adaptive TSP performance.

6.1. Research Summary

Conventional active TSP systems fully provide priority to buses on major lines; however, the observable weakness is that other traffic suffers significant delays. Most adaptive TSP strategies make efforts to solve this problem. This study proposed one solution, a new adaptive control algorithm, to balance the trade-off between decreasing bus delay and increasing general vehicle delay.

Chapter 2 gave a review of research related to field of TSP control. The review consisted of two parts: 1) the innovative TSP control strategy; and 2) TSP performance evaluation. In the first part, there are two major approaches to realize adaptive or dynamic TSP control: 1) the objective function-based approach; and 2) the rule-based approach. The objective function-based approach is more popular, because it converts the control problem to an optimization problem, increasing the approach's universality and compatibility. In the second part, the simulation and analytical evaluation were reviewed to demonstrate TSP performance.

Chapter 3 developed a new mathematical model for bus delay estimation. Compared with previous bus delay models, the new model contains additional delay parts, which can be happen in the intersection. Through combining the bus delay model and intersection control delay model for general vehicles, an objective function was formulized as a quadratic programming problem. Then Matlab, which has a full function of SQP, was used as the solver.

Chapter 4 summarized the implementation of adaptive TSP in a micro-simulation platform. The adaptive TSP was implemented in a well-calibrated simulation model for a TSP corridor in the City of Edmonton. The TSP implementation was achieved through C++ programming. The communication through NTCIP between the ASC/3 controller and C++ API was the key for realizing TSP control in simulation. Chapter 4 also provides the details about developing and calibrating the proposed model with field data.

Chapter 5 provides the evaluation and comparison study and results. From the simulation-based evaluation, there are two major conclusions:

- Both active and adaptive TSP save bus travel time along the corridor and bus delay at intersections. In most of intersections, active TSP saves more delay than adaptive TSP. However, there is a limit on the savings and the savings are not always statistically significance at each intersection.
- Adaptive TSP never shows significant impact on general vehicles, while active TSP shows negative impact on minor streets at some intersections.
- TSP control does not show an impact on the general traffic driving along the corridor. The individual vehicle is seldom affected by TSP unless it is approaching the intersection with a prioritized bus.

6.2. Limitations of the Research

The research has several limitations:

1. The determination of weighting factor. Although sensitivity analysis is the most popular way to determine the best-fit weighting factor, it is still too empirical to be completely convincing. The value of the weighting factors lacks universality, as it is determined case-by-case. Thus, the value should be changed case-by-case.
2. The proposed strategy does not consider that a bus may be running ahead of schedule. Ideally, for passengers on the bus, minimizing travel time is the first objective. However, in reality, transit operations need to maintain the bus on-time performance. Therefore, the ahead-schedule buses should not get priority.
3. The detection system uses fixed point detectors for bus check-in and check-out. The detectors can only detect when the bus approaching and exiting the intersection. The detectors cannot track the bus behavior between the check-in detector and the check-out detector, which affects the optimized strategy application. Also, detector location could be a factor of TSP performance and detector location was not considered in this study.

6.3. Future work

The proposed TSP control strategy can be further updated by studying the new data sources and alternative optimization algorithms. New data sources, such as

Connected Vehicle (CV) technology and GPS, can provide more accurate transit trajectory data than a signal loop. Also, trajectory data can support real-time estimation on transit delay and perform continuous optimization to make the TSP control more adaptable.

Alternative optimization algorithms could provide improved solutions. The research currently uses SQP to obtain the optimal solution within an acceptable calculation time period. Heuristic programming has been used and proven effective in other TSP control strategies. However, the computational costs limit its application for real-time control. If it is possible to improve its computational efficiency, heuristic programming may be a better algorithm for optimizing the proposed TSP plan.

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