DEVELOPMENT AND APPLICATIONS OF ADAPTIVE TRANSIT SIGNAL PRIORITY SYSTEMS

LI, Meng

DEVELOPMENT AND APPLICATIONS OF ADAPTIVE TRANSIT SIGNAL PRIORITY SYSTEMS

Doctoral Dissertation

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Engineering

by:

LI, Meng

Academic Advisor:

Prof. Hideki NAKAMURA

Department of Civil Engineering
Nagoya University
JAPAN
February, 2010

ACKNOLEGEMENT

It is a great pleasure to thank all those who make this thesis possible. I am so honored to receive so many great helps and supports.

I owe my deepest gratitude to my academic advisor Prof. Hideki Nakamura. Without him, I would not even have the chance to pursue my doctoral degree in Nagoya University. When the first time I contacted him for my application, he showed significant understanding and quickly put together a time table for me. Such immediate response and careful considerations impressed me so much. Thus I quickly made my mind to follow him to pursue my doctoral degree, which is an important milestone of my life. For my short stay at Nagoya University, I learned a lot from his invaluable suggestions and insightful guidance on my research, his working spirit and attitudes. I am so grateful for his support and his care on not only my study and my dissertation but also my daily life and my family.

I would like to express my sincere appreciation to my doctoral committee members, Prof. Masao Kuwahara, Prof. Takayuki Morikawa, as well as Assoc. Prof. Toshiyuki Yamamoto, and Assoc. Prof. Hirokazu Kato. They provided significant suggestions and comments on my research, my presentation, and my thesis. I'm also grateful for their patience on listening to my long presentations and for their warm discussions to improve my work.

This thesis would not be possible without the support from my family, particularly my parents Qiutao Li, Shuwen Shi, my wife Xiaonan Mu, my sister Ning Li, and my parents-in-law Xinting Mu and Weiyang Zhu. Among my family, my parents have the biggest desire and expectation on me to get a doctoral degree. They have constantly and kindly pressured me on getting the degree since I was at Tsinghua University, at University of California, Berkeley, and then at Nagoya University. Without such supports and expectations from my family, I would not be able to overcome all the difficulties along the way in such a short period of time.

My deep appreciations also go to my colleagues at California PATH, UC Berkeley, particularly Director Alexander Skabardonis, Mr. Wei-Bin Zhang, Mr. James Misener, Dr. Steven Shladover, Dr. Kun Zhou, Mr. Guoyuan Wu, Dr. Liping Zhang, Dr. Yue Li, and Dr. Jingquan Li. It is Prof. Alexander Skabardonis who introduced me to my advisor Prof. Hideki Nakamura and started all this study. I am so grateful for my manager Mr. Wei-Bin Zhang who led me to the research field and taught me how to grow from a team member to a team leader. He also showed significant patients and supports to allow me working part-time for his projects while I am away from California PATH. I am also thankful for my colleagues' help and understanding on my work for this period of time.

Many thanks from me to my friends in Nagoya University in Nakamura's Interchange lab. Mr. Wael Alhajyaseen and I had so much fun and smile in the constant and endless talking on research, daily and future life, family and love, politics and religions. Assist. Prof. Miho Asano provided me constructive comments and suggestion to solid my research. She and Mr. Masato Kobayashi also kindly helped me translate my thesis abstract into Japanese. My appreciation also goes to Dr. Keshuang Tang for discussions and suggestions on my research and my life in Nagoya and to Mr. Fumiyasu Shiraki as my tutor. I would like to specially thank Mr. Xiaolu Huang and other students who collected valuable video and traffic signal timing data from Nagoya City. Without such data, I cannot complete my thesis in a solid way.

I am heartily thankful my advisor at Tsinghua University, Prof. Huapu Lu, who inspired me to pursue my doctor degree in Japan and gave me many valuable suggestions for my future. I am also grateful for my friend, Assist. Prof. Yafeng Yin. He showed me how to write an academic paper and how to conduct academic research.

Lastly, I offer my regards and blessings to all of those who helped and supported me in any respect during the completion of the thesis.

ABSTRACT

As the world population kept growing and more cars enter the transportation system, both of our urban streets and highways, particularly in the metropolitan areas, are getting more and more congested. On the other hand, these metropolitan areas have also reached the limit to build more road facilities. However, the supply of transportation infrastructure is still far behind the continuous increments on users' demands.

Multi-modal transportation, particularly public transportation, has been recognized as the key to the future sustainable transportation system. With an improved and attractive public transit services, more travelers will utilize transit freeing up space on our streets, diminishing our dependence on fossil fuels, and improving air quality.

Although prevailing active TSP systems are efficient in granting priority to buses, they might incur noticeable delays to the minor-phase traffic, which has raised concerns among traffic engineers and thus has impeded the wide-scale acceptance and deployment of TSP systems. Given the existing development of adaptive TSP (ATSP) only focused on rarely deployed adaptive signal control systems, ***this study attempts to develop adaptive TSP systems specifically for the state-of-practice traffic signal control systems, i.e. fixed-time and actuated control systems.***

The first ATSP model developed in ***Chapter 3*** utilizes global positioning system (GPS) based automatic vehicle location (AVL) system to continuously monitor bus movements. The resulting historical and online bus data are used by a bus arrival time predictor to predict bus arrival times to signalized intersections. Given the bus arrival information together with real-time traffic and signal status data obtained from the closed-loop signal control system, a delay-based ATSP optimization model aims to minimize the objective of weighted delays through manipulating the green splits of signal phases for two consecutive cycles at one intersection. The model objective is the weighted bus delay together with total traffic delays in the period of two control cycles. A set of system constraints were set up to protect the safety requirements, to maintain the logic of dual-ring actuated signal control, and to make the best use of the dynamic information from bus AVL systems, signal controllers, traffic loop sensors, and pedestrian push buttons. The numerical case studies were conducted for a medium-congested scenario and a highly-congested scenario. In both of the two scenarios, the proposed model demonstrated a significant delay reduction (up to 100%) for transit vehicles while the impacts on other vehicular traffic varied from 4.4% to 13.2%. The weighting factor on bus delay is sensitive with the impacts on other traffic, particularly in the highly-congested scenario. At the end, a field operational test has been conducted along a two-mile-long signalized arterial which

consists of seven signalized intersections. The results show a promising performance in the field environment. At the most congested intersection, the bus delays and traffic delay along bus phase have been reduced by 43% and 16%, respectively, while the traffic delay on minor phases was increased by 10%. All the changes were statistically significant.

Chapter 4 expands the discrete ATSP model to a centralized ATSP system for transit vehicles. As the "brain" of the system, the PRG adopts a three-scheme conditional priority control strategy. Scheme I, which applies to late transit vehicles, features a timing optimization model. With the randomness of transit vehicles' running time in mind, the mixed-integer quadratic programming (MIQP) model could minimize the expected delay for transit vehicles while with only limited impacts on other traffic. A case study, based on San Diego Trolley system, demonstrates that an enormous intersection delay saving is as much as 89.5%, or 25.3 sec/train for late trains after applying the proposed scheme I strategy, meanwhile the impact on other traffic in the priority cycle is only 4.4 second per vehicle. For scheme II and III when no priority is needed, traffic delay savings are 32.5% and 52.0%, respectively. A simulation model coded in PARAMICS not only confirms the benefits of the proposed model but also validates the practicality of the centralized ATPS system.

Chapter 5 summarized the findings and experiences from the previous two ATSP models and developed an integrated delay-based model for a centralized ATSP system. In this chapter, the optimization model not only considers the bus delay and all vehicular traffic delay but also considers pedestrian delay as an important factor of traffic signal operation. System constraints were set up to guarantee the safety of operation and the logic of traffic signal control. The proposed model has been evaluated by a numerical case study. The case study was based on Key Route Bus System in Nagoya, Japan. The test site consists of three signalized intersections. Two typical bus trip trajectories were collected by GPS devices and applied by the proposed system. The testing results for the two types of trips were promising. The bus delays were reduced by 86% and 46%, respectively. The average vehicular delay on bus phase was reduced by about 26% while vehicular delay on non-bus phase was increased by about 13%. The average pedestrian delay was reduced by about 3%. Overall, the average person delay was reduced by about 10%. Finally, a sensitivity analysis was conducted for the weighting factor on bus delay. The weighting factors from 20 to 100 were testified. For the test site, the weighting factors below 100 do not make much difference on the system performance for all the eight MOEs except for BSD. When bus arrival time at signalized intersection #1 is between -5 to 25 on the local clock, the bus signal delay can be further reduced by 20 seconds after raising the weighting factor from 20 to 100. But for average vehicular delay, average pedestrian traffic delay, average person delay, the changes are less than 1 second. Therefore, it is reasonable to select a relatively high weighting factor such as 100 to save more bus delay without introducing significant delay to other traffic. With weighting factor for bus delay is 100, the average bus delay for all bus arrivals can be reduced by about 47 seconds and 61%, meanwhile the average traffic delay on non-bus phase has been increased by 7 seconds per vehicle and 13%. The delays for vehicular traffic along bus phase and for pedestrian traffic decreased by 9% and 3%, respectively. Overall, the average person delay has been reduced by 3 seconds per person and 9%.

At the end, ***Chapter 6*** concludes the findings of the study. ***The methodologies and analysis results from this study make the concept and implementation of adaptive TSP possible for the state-of-practice traffic signal control systems, i.e. fixed-time and actuated control systems*** The study provides transportation authorities with three cost-effective ways to achieve ATSP upon the widely deployed traffic signal control systems. More specifically, it provides quantitative models to explicitly balance the benefits and impacts of ATSP. According to the results from the numerical case studies, microscopic traffic simulations, and the field operational tests, the developed model demonstrated significant benefits on bus movement while minimizing the impacts to other vehicular traffic and pedestrian traffic. Last, a comparison of the TSP developments in Japan and in the Untied States is presented. The dissertation ends with the potential future directions as a continuous of this research subject.

Table of Contents

List of Tables

List of Figures

Chapter 1

INTRODUCTION

1.1 Background

As the world population kept growing and more cars enter the transportation system, both of our urban streets and highways, particularly in the metropolitan areas, are getting more and more congested. On the other hand, these metropolitan areas have also reached the limit to build more road facilities. However, the supply of transportation infrastructure is still far behind the continuous increments on users' demands.

Moreover, the continuous and strong growth on transportation demands has created the ever-worst congestion together with the ever-serious concerns on energy shortage. Over the next 25 years, world demand for liquid fuels and other petroleum is expected to increase more rapidly in the transportation sector than in any other end-use sector, as shown in **Figure 1-1**. The transportation share of total liquids consumption increases from 52 percent in 2005 to 58 percent in 2030 in the IEO2008 reference case.

Multi-modal transportation, particularly public transportation, has been recognized as the key to the future sustainable transportation system. With an improved and attractive public transit services, more travelers will utilize transit freeing up space on our streets, diminishing our dependence on fossil fuels, and improving air quality.

Buses have been serving as the backbone of public transportation in most cities in the world. Despite the importance and efficiency of buses, little attention has been paid to them until the recent worldwide effort of BRT which is aimed to improve bus services throughout the world. BRT, as defined by the U.S. Federal Transit Administration (FTA): "a rapid mode of transportation that can provide the quality of rail transit and the flexibility of buses", has shown promising in reducing bus travel time, improving schedule adherence, increasing bus ridership, and reducing overall transit system cost.

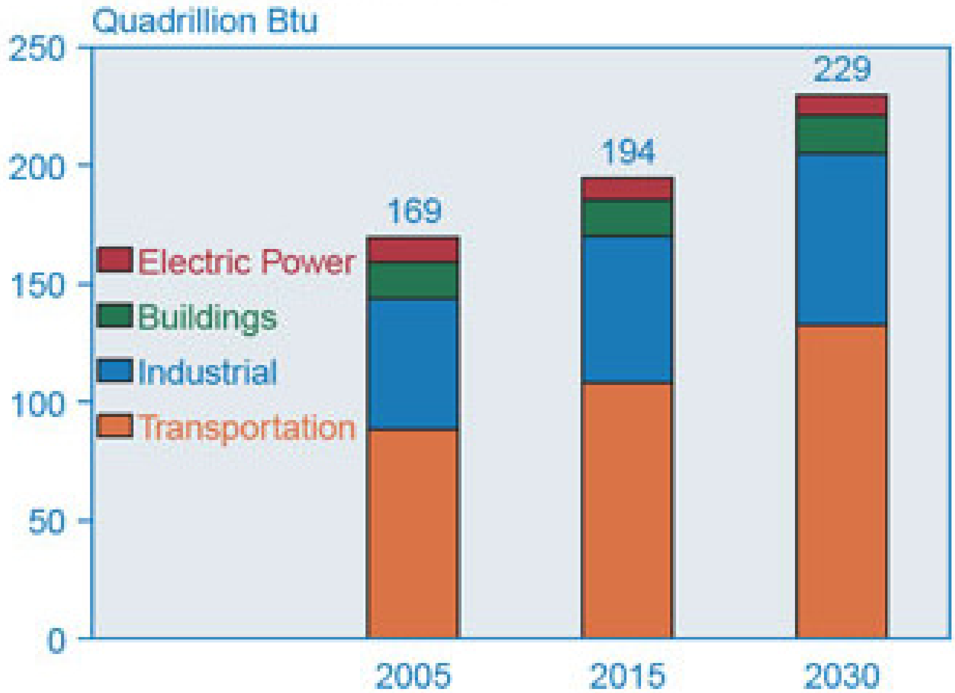


Figure 1-1 World liquids consumption by end-use sector, 2005-2030
(Source: Energy Information Administration (EIA) 2005)

1.2 TSP Concept

Transit signal priority (TSP) is an operational strategy that facilitates in-service transit vehicles going through signalized intersections. It can reduce transit delay at intersections and improve its on-time performance or schedule adherence, thereby increasing the quality of transit service. Comparing with other public transit services, particularly subway systems, TSP is a cost-effective method to enhance regional mobility.

TSP is an important component of BRT. Past studies have shown that time spent waiting at red lights accounts for 8 to 12 percent of buses route time, it is also found that waiting at traffic lights accounts for five times more delay in route speed than travelling in traffic itself. TSP, simply, is an operational strategy to reducing delay for transit vehicles at signalized intersections by temporarily adjusting the traffic signal timing to benefit transit vehicles. Although the concept of TSP is somewhat identical with pre-emption in that both of them are intended to provide prioritized right-of-way at signalized intersections to some specified vehicles, it is notable that signal priority differs from signal preemption in that the latter requires "immediate" and "absolute" attention and needs to "interrupt" the normal signal operation process, on the other hand, TSP "modifies" the normal process to better accommodate transit vehicles and therefore is much conditional and subject to more strict constraints.

The concept of TSP has been adopted and implemented to the field in Europe in the 1960s and in the United States since the early 1970s. Early deployment of TSP has mainly concentrated in large cities of Europe, where the important role of public transportation in providing sustainable mobility is recognized at the highest level. In the United Kingdom, for example, the importance of public transportation, especially bus, has been addressed in the White Paper "A New Deal for Transport" published in 1998 by the government of United Kingdom. The document notes in particular that "the White Paper emphasizes the importance of bus priority measures in reducing journey times and making buses more reliable".

The implementation of TSP has been investigated as a viable way of improving transit service as well as reducing operational cost, however, deployment has been relatively slow on account of various factors, among which the concern that bus signal priority may compromise other non-transit vehicles is the critical. Most of the American traffic signal control systems are closed-loop systems that are traffic responsive and provide benefits to overall traffic flow than transit vehicles. Integration of TSP with the existing signal control systems involves not only significant hardware and software modification but also development of promising priority control algorithms. Although relevant transportation polices in favor of transit vehicle operation has not been made in the world, tremendous efforts have been made recently by both local and national transportation agencies with regard to investigation, implementation, and evaluation of TSP systems..

1.3 TSP Control Strategies and State of the Practices

TSP control strategies may be categorized into three types: passive, active, and adaptive (ITS America, 2004). It also roughly represents the evolution of TSP and its level of sophistication over years.

1.3.1 Passive Priority

Passive priority strategy represents the initial efforts of the development of TSP concept. Such strategies are to design signal timings to favor transit vehicles along signalized arterials, particularly for the heavy transit vehicles. Passive priority systems are often applied to fixed-timing signal control systems and do not require transit vehicle detection. Such strategies only work well when transit operations are predictable and frequent, and traffic demand is low (Vincent et al. 1978; Courage et al. 1977). It is due to the signal coordination with considerations of low speed transit vehicles would generate significant impacts on other traffic flows no matter whether the transit vehicles present or not. Even there is no mixed flow traffic with transit vehicles, such as the trolley system in downtown San Diego, CA (Celniker et al. 1991), there is still significant impacts on the cross-street traffic flows. Such significant negative impacts with and without transit vehicle arrivals make the passive priority systems fading away from the current practices.

1.3.2 Active Priority

Active priority systems address the critical shortcoming of passive priority systems and adopt selective vehicle detections to detect approaching transit vehicles and adjust signal timings in a predefined manner to provide, e.g., early green, green extension or special transit phase to them. The majority of the TSP deployments in the world so far are active systems (e.g., Fehon et al. 2004; Kimpel et al. 2004). **Figure 1-2** and **Figure 1-3** illustrate two popular detection technologies for the active TSP systems.

The Opticom™ system from 3M is probably the most widely implemented traffic priority control system that enables signal priority operation to both emergency and transit vehicles. The system, as shown in **Figure 1-2**, works by an emitter in the vehicle that, when activated, sends an optical flashing signal at a certain rate (flashes per second), and at an exact duration, that is detected at the signal. The electronic impulse then interrupts the signal sequences and turns the signal to green in the direction of emergency or transit vehicle.

The concept to using existing inductive loop in the roadway to identify emergency or transit vehicles was introduced in Traffic Detector Handbook (1990). An additional transponder, as shown in **Figure 1-3**, which is usually mounted on the underside of the vehicle, is designed to continuously transmit a unique code that identifies the vehicle. In most cases, the loop detector is designed not only to sense presence of a transit vehicle, but in some cases, serves as Automatic Vehicle Identification (AVI) sensor. These sensors embedded in the pavement receive a radio-frequency code from the transponder when bus traveling over the detection area and transmit the signal to the sensor unit installed within the traffic signal controller. For the distributed system, local signal controllers have the authority to grant signal priority upon the detection of a transit vehicle; for the centralized system, the sensor unit transmits the vehicle ID to the signal priority manager computer for tracking and schedule comparison, the computer makes decision on whether or not give the bus priority according to the preset priority strategies based on bus schedule and/or headway.

Figure 1-2 Opticom^{TM} signal preemption/priority system
(Source: http://www.3m.com/us)

All these deployments have demonstrated positive effects on improving transit service quality. In the literature, Ling and Shalaby (2003) applied an artificial intelligence method to optimize green phase durations in order to reduce transit headway deviations. They also conducted a simulation study to demonstrate the model performance on reducing transit headway deviations with limited impact on other traffic. Janos and Furth (2002) proposed a rule-based TSP system for the transit system in San Juan, Puerto Rico that has an extremely high serving frequency. Nichols and Bullock (2004) has discussed the use of global positioning system (GPS) technology for estimating an upper bound on the potential benefits of active TSP system.

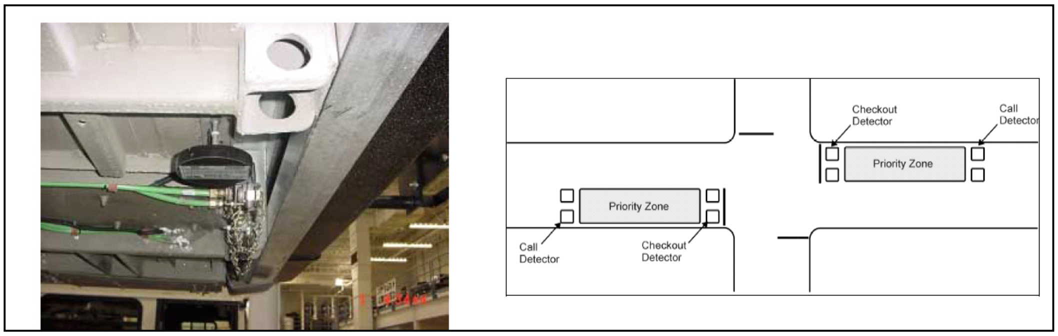


Figure 1-3 Inductive loop with on-board transponder

1.3.3 Adaptive Priority

Adaptive priority systems provide priority to transit vehicles while at the same time trying to minimize negative impacts to other traffic. A typical adaptive TSP system may consist of three important components: 1) a continuous detection that can detect an approaching transit vehicle continuously, so that its arrival time can be predicted and updated in a real-time manner; 2) communication links among transit vehicle, priority request system and signal controllers to share transit vehicle's arrival time, real-time traffic and pedestrian condition, signal status and real-time signal timing strategy; 3) a signal control algorithm that adjusts the timing to provide priority while explicitly considering the impacts to the rest of the traffic and ensuring traffic and pedestrian safety. The signal control algorithm should gracefully make a trade-off between transit delay and traffic delay and adaptive to the movement of the transit vehicle and the prevailing traffic condition.

1.4 Role of Pedestrian in Traffic Signal Control

Vehicle delay is perhaps the most important parameter used by transportation professionals to evaluate the performance of signalized intersections. HCM (2000) uses the average control delay experienced by vehicles at intersection approaches as a base for determining the level of service. Pedestrian traffic has not been given the same priority as vehicular traffic. However, at many urban areas where large volume of pedestrian exists, it is more rational and reasonable to evaluate the level of service of roadways from a multi-modal perspective. A key goal of multi-modal transportation systems is to minimize delays for all roadway users, including motorized traffic, bicyclists and pedestrians. However, Webster's (1958) and other numerous methods for signal optimization focus on reducing vehicle delays without considering pedestrian flows and delays. Long signal cycle durations from optimizing vehicle flows and signal coordination for vehicles, have negative effects on pedestrian movements and may impose large delays on pedestrians

(Bayley 1966). Furthermore, long cycles may cause a safety hazard for pedestrians, thus one of the most effective measures to improve pedestrian safety and compliance is by making signals as comfortable as possible, and this is done by minimizing pedestrian waiting time (Garder 1989). Therefore, investigating the rationality of considering pedestrian delays in the optimization of signal control and providing guidelines for the conditions where such a policy should be implemented is very useful and significant.

Few studies have been done to investigate the balance between pedestrian and motorized traffic delays at isolated intersection or the network level. Noland (1996) analyzed the signal timing solutions regarding pedestrians and motorized traffic at isolated intersections with high pedestrian demand. The relative cost of time was used to analyze the performance of signal control, however the difference between optimized signal parameters considering pedestrian and vehicle delays and those considering vehicle delays only was not shown. Furthermore, general guidelines about the conditions where such control policy is advantageous and reasonable for implementation were missing.

Ishaque, et al. (2005 and 2007) analyzed the trade-offs in pedestrian and vehicle delays in a hypothetical network by considering relative values of time for pedestrians and vehicles. They found that shorter cycle lengths are beneficial for pedestrians. Moreover, the existing policies that are most advantageous to vehicles might be disadvantageous to pedestrians, which do not make the network optimally perform for all road users. Although, they assumed that pedestrian delay is composed only from control delay. Actually with high demands, pedestrians experience significant delays while discharging at the edge of the crosswalk and while crossing the street due to the interaction between opposing pedestrian flows. Furthermore, a discussion about the optimized signal parameters considering pedestrian and vehicle delays was not presented.

Few studies addressed the issue of bi-directional pedestrian flow and its impact on crossing time and speed at signalized crosswalks and the resultant delays. HCM (2000) does not consider the effects of pedestrian demand and crosswalk width on pedestrian crossing time. However when pedestrian demand increases at both sides of the crosswalk, crossing time increases due to the interaction between conflicting pedestrian flows.

Urbanik, et al. (2000) investigated the effects of different pedestrian phasing schemes based on various left-turning control types and split phasing on pedestrian delays. Wang, et al. (2009) introduced a set of models for calculating pedestrian delays at signalized intersections. The models take into considerations of various signal phasing and pedestrian treatment scenarios, especially under two-stage crossing situation. They found that specially designated signal phasing and pedestrian treatments are able to reduce pedestrian delays without affecting vehicle delays significantly. However, in their analysis, no optimization model was developed and no consideration was given to the experienced delay by pedestrians while discharging or crossing at the crosswalk.

Teknomo (2006) proposed a microscopic pedestrian simulation model as a tool to evaluate quantitatively the impacts of a proposed control policy before its implementation on pedestrian behavior at signalized intersections. The developed model was used to demonstrate the effect of bi-directional flow at signalized crosswalks. It was found that at high pedestrian demand with roughly equal flow from each side of the crosswalk, the average crossing speed might drop up to one third compared to the uni-directional flow, which will result in large experienced delays while crossing.

Golani et al. (2007) proposed a model for estimating crossing time considering start-up lost time, average walking speed, and pedestrian headways as a function of the subject and opposite pedestrian platoons separately. They found that the size of the opposite pedestrian platoon can cause a significant increase in the crossing time of the subject pedestrian platoon especially at high demands. The proposed model relates the impact of bi-directional flow to the headway between pedestrians when they finish crossing. Therefore, it is difficult to see how the interaction is happening and what the resulting speed drop or deceleration is.

Alhajyaseen, et al. (2009a; 2009b) developed a theoretical methodology to model total pedestrian crossing time. Pedestrian platoon crossing time is modeled by utilizing the aerodynamic drag force theory to estimate the reduction in crossing speed due to an opposite pedestrian flow. The proposed model was successfully validated from empirical data. In the final formulation, the reduction in crossing speed is estimated as a function of pedestrian demands at both sides of the crosswalk, signal timing parameters and crosswalk geometry. It was found that at high pedestrian demand, a significant reduction in the crossing speed and increasing in the crossing time occurs due to the interaction between the bi-directional flows. Therefore, it was concluded that the interactions between opposing pedestrian flows are significant and should be considered in evaluating pedestrian flow at signalized crosswalks.

1.5 TSP Practices in Japan

There are very few literatures about the TSP applications in Japan. Actually, transportation planners and engineers in Japan have designed and deployed the bus rapid transit (BRT) systems in Nagoya City as early as the late 1970s and the early 1980s. The curb guided bus technology was also introduced to a BRT system in Nagoya City in 2001

(Takeshita et al. 2009). However, neither of the two BRT systems have equipped with TSP systems. An important reason is the very long cycle length together with high service frequency during the peak hour.

A few studies about TSP have been conducted by Japanese researchers and transportation engineers. In 1999, Sakakibara et al. developed a real-time signal control system and named as management by origin-destination related adaptation for traffic optimization (MODERATO). A public transportation priority systems (PTPS) was proposed and applied the infrared beacons to detect buses. Two simple priority treatments were designed: early green and green extension. No quantitative method was proposed to consider the impacts of the TSP operation. Nandani et al. (2008) developed an improved bus signal priority model to consider bus queuing delay at or close to traffic signals when triggering TSP requests. It provides a more accurate travel time prediction model for active TSP systems and can potentially further reduce the delay for transit vehicles. The research on how to quantitatively balance the benefits and impacts of TSP systems are still very rare in Japan.

There is only one Japanese TSP application which was briefly referenced. In April 1996, Sapporo City started an operation of a Public Transportation Priority System (PTPS) along a 5.7 kilometer (km) section of Route 36 (ITS developed by Japanese Police 1999). The details of the implemented PTPS systems were not presented together with the testing results. But according to the term PTPS, it should be an application of the MODERATO system. An evaluation on the effectiveness of the system on weekdays was conducted during the month of May 1996 for the time period between 7:30 AM and 9:00 AM. Bus travel times in the section were reduced by 6.1 percent, while ridership increased 9.9 percent. A 7.1 percent reduction in the number of stops busses made at signals was also reported. Such improvement resulted in a 20.8 percent reduction in stopped time.

1.6 Problem Statement

With more and more experiences from the TSP applications all over the world, it is no doubt that TSP can be very significant to help transit systems be the key component in the future sustainable transportation system. However, many research and development efforts are still needed for the large deployment of TSP systems.

Ever since the emergence of the concept of TSP, researchers and traffic engineers have been seeking for best solutions to prioritize transit vehicles while minimizing impacts to other vehicles. A common understanding is that the more frequent priority requests and services at traffic signals the severer interruptions it loads onto normal signal operations.

The shortcomings of existing TSP control strategies are obvious from this point of view as their performance, to different level, relies on the means of transit vehicle detection. Opticom^{TM}, Inductive loop, and RF tag/receiver are point or zone detection systems which sense the presence of transit vehicles at fixed locations or within a limited area. The detection range influences TSP operations. Short detection range would result in late calls that have limited lead time for Early Green treatment and could miss the potential Green extension treatment. Large detection range, on the other hand, would lead to less predictability in transit's arrival at the intersection due to the uncertainties of bus movements after detection and consequently less efficient TSP operations. Most importantly, there is no optimal detection range that is suitable for any traffic conditions. Under current TSP strategy, the priority operation is initiated simultaneously upon the detection of a bus regardless of its necessity, which may lead to either false priority calls or insufficient time in signal cycle to grant enough priority service.

False calls are those priority requests that are granted but actually not needed or those failed to discharge the bus during the prioritized interval. In the former case, the bus solicits not necessary Early Green service when it can actually traverse through the intersection within normal phase interval, which brings no benefits to buses but disrupts non-transit vehicles. The latter refers to the priority requests for Green Extension treatment but failed to discharge the bus within the maximum extension period, which often occurs in the case bus detectors are located too far from the intersection. In addition current TSP systems usually deploy simple methods to shorten non-transit phases to provide Early Green treatments regardless of the real time traffic demand, for example, shorten each phase by a fixed and predetermined ratio, and consequently impact the general purpose traffic.

Automatic vehicle location (AVL) based TSP system has the potential to overcome the shortcomings. It usually consists of three subsystems including global positioning system (GPS) based bus location system, a centralized control station, and communication links among bus, control station, and the bus management center. The historical and real time bus movement data from GPS can be used to estimate bus location as well as predict bus arrival time to bus stops and intersections. The prediction of transit's arrival at the intersection can help select the optimal time point to trigger the traffic signal controller for priority service.

The addition of real-time traffic information (density, volume) will also be of significant importance in improving priority control algorithms. A few of adaptive traffic signal control algorithms have been improved by the manufacturers to embed TSP functions. Two of the most promising adaptive prioritization algorithms are SCOOT (Split

Cycle Offset Optimization Technique) version 3.1 and OPAC (Optimized Policies for Adaptive Control). The SCOOT kernel software allows for buses to be detected either by selective vehicle detectors (i.e., bus loops and bus-bone transponders) or AVL systems, Where SCOOT is given a bus identifier as part of the bus detection, it can match this detection with a previous detection of the same bus. This is generally possible with an AVL system; it is also possible in principle with selective vehicle detection systems, but because of data transmission restrictions, the bus identifier may not be transmitted to SCOOT and only a single bit indicates the presence of a bus. The signal timings are optimized to benefit the buses by providing either green extension or recall to an associated phase. Two alternatives exist for extensions: central extension and local extension. Central extension uses the centralized SCOOT processing to determine the priority, while local extension grants the extension locally by the signal controller to avoid the communication delay between the SCOOT central computer and the local controller. Reported bus priority field trials using SCOOT showed to buses with no significant negative impacts to general purpose traffic. In the 10-intersection Camden SCOOT area of London, 22% average bus delay saving per intersection was measured and 70% in light volumes using both extension and recall (Bretherton, 1996). OPAC is an on-line signal timing optimization algorithm that optimizes traffic flow (as common signal control) as well as minimizes person delay at intersections by weighting different kinds of vehicles.

However, more than 90% of existing signal control systems are still fixed-timing control or closed-loop actuated with the dual-ring structure (Gettman et al. 2007). In Japan, the closed-loop actuated signal control is also named as group-based signal control. The wide-scale implementation of adaptive signal control systems may be many years away, partly due to the associated high costs for implementation and maintenance (Smith et al. 2002). Therefore, it may be more cost-effective to implement adaptive TSP on actuated control and fixed-timing control systems than replacing the existing traffic control system with another adaptive traffic control system. There is no doubt that such adaptive TSP systems would have the potential for large-scale deployment, thereby leading to fairly significant benefits.

Very limited research has been conducted in developing adaptive TSP on existing signal control systems, e.g. fixed-timing control systems or actuated control systems. Unlike adaptive traffic signal control, actuated signal control relies on actuation from detection but has no quantitative objective. Therefore, implementing adaptive TSP on an actuated system is very different from realizing adaptive TSP on an adaptive traffic control system. For example, Head et al. (2006) proposed a decision model based on the precedence graph for priority control for the ring-barrier based closed-loop signal control systems. Such model presents an analytical framework for the analysis of complex controller behavior.

In addition, current TSP strategies tend to ignore the pedestrian delays that may be imposed by reducing vehicular delays. Such an objective is reasonable for motorways and rural roads where vehicular traffic is dominant over pedestrian traffic. However, it is not the case in metropolitan cities with relatively high volume of pedestrian demands. Such ignorance can lead to unnecessary long delays for pedestrians, dangerous behavior by impatient pedestrians, and potential reductions in pedestrian traffic and transit usages.

Another important stakeholder at signalized intersections is the pedestrian. An improved public transportation system and public acceptance always leads to more pedestrian on streets. However, the existing signal control strategies including TSP strategies only focus on safety aspects for pedestrian while fail to pay enough attention on the efficiency aspect, i.e. pedestrians' delay. Actually, pedestrians' delay can also be significant when comparing with vehicular delays. It happens at intersections with consistent medium-to-high pedestrian demands where typically in large cities with good public transportation system, e.g. New York, London, Tokyo, etc. Moreover, the optimized signal timing from the perspective of minimizing vehicular delays usually is not optimal for pedestrians flow. It is because the directional demand ratios (DDRs) among vehicle flows are not likely the same as those for pedestrian flows.

Moreover, more pedestrian demand will be generated when more passengers shift the mode to take the transit service. With the purpose of promoting transit services, TSP should pay attentions on pedestrian flows and their delays.

1.7 Research Objectives

The objective of this study is to develop adaptive TSP systems specifically for the state-of-practice traffic signal control systems, i.e. fixed-time and actuated control systems. More specifically, this study is to develop methodologies for such popular traffic control systems to provide transit vehicles with signal priority meanwhile quantitatively balance the impacts to other traffic.

The overall research framework is presented in **Figure 1-4**. The research starts from TSP system design, which provides an overall picture of an adaptive TSP system. Among the many system components in an ATSP system, the research focuses on the core signal operation module in PRG. A series of models have been developed towards different objectives and system constraints. For example, the multiple objectives have been categorized based on subjects like transit vehicles, vehicular traffic and pedestrian traffic,

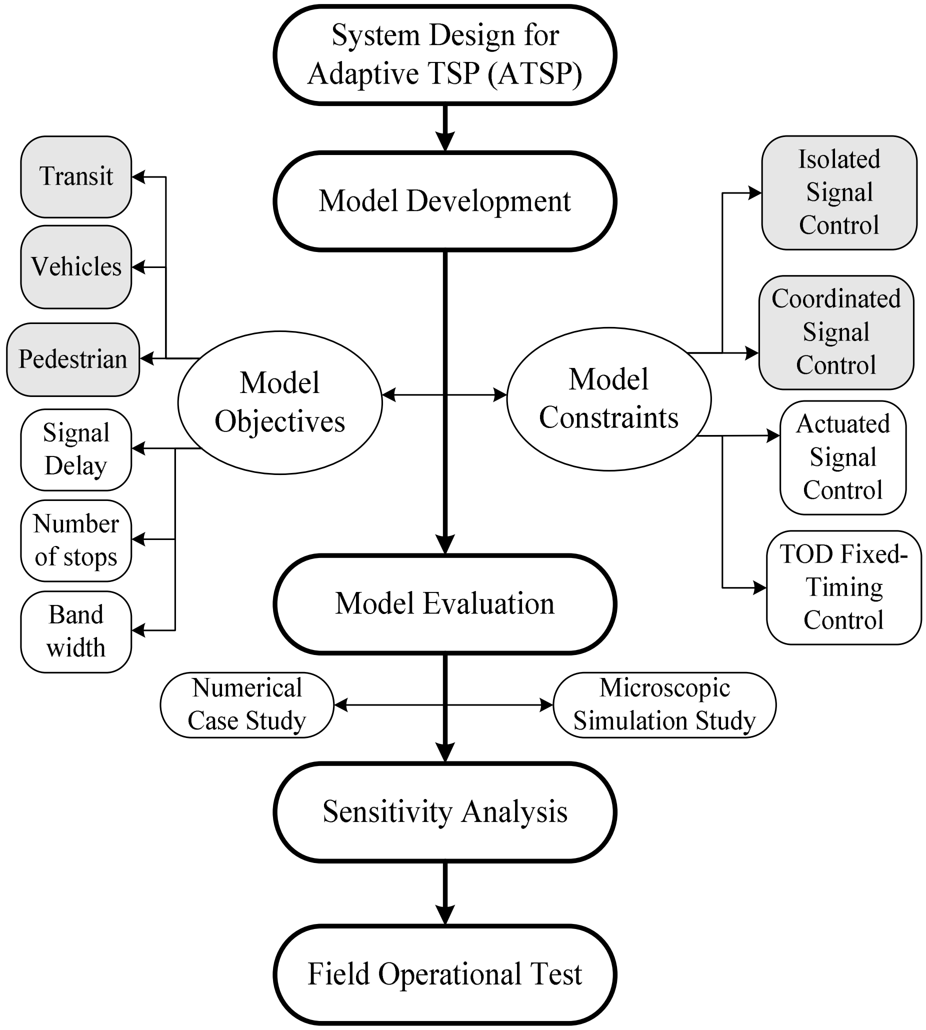


Figure 1-4 Overall research framework

and also based on measures of effectiveness like traffic signal delay, number of stops, and bandwidth. The system constraints have been designed for different signal control systems such as time-of-day (TOD) fixed-timing control and actuated signal control, and for different control scope such as discrete isolated intersection and coordinated arterial or urban networks.

After the development of the models, two evaluation methods were adopted to demonstrate the model performance and also to conduct parametric sensitivity analysis. The two methods are 1) mathematical numerical analysis using MATLAB and 2) microscopic traffic simulation using PARAMICS. With full confident of the system performance in the lab and assumed environments, a few field operational tests have been conducted to finally demonstrate the systems in the field environments.

1.8 Research Flow and Organization of the Dissertation

Figure 1-5 illustrates the organization of this dissertation. In summary, ***Chapter 2*** describes the design and system architecture of a typical ATSP system with detailed introduction on each system component. ***Chapter 3*** presents a discrete ATSP model which can be applied to signalized intersections under actuated signal control. The model considers isolated intersection and aims to minimize the weighted bus delay together with all vehicular traffic delay meanwhile considering all the real-time inputs from actuated signal control and traffic detections. ***Chapter 4*** expands the discrete ATSP model to a centralized ATSP model which considers green bandwidth along multiple intersections for transit vehicles rather than total signal delay at each intersection. The model objective is to minimize weighted bandwidth for a transit vehicle and also the total delay for other traffic. ***Chapter 5*** summarizes all findings from the proposed discrete and centralized ATSP models and develops an integrated centralized ATSP model which also considers pedestrian delays at intersections. The integrate model aims to minimize the weighted transit vehicle delay and number of stops while crossing multiple intersections plus the total vehicular traffic delay and the total pedestrian traffic delay. The numerical model application to the Key Route Bus System in Nagoya, Japan has been presented, followed by a sensitivity analysis for the modeled weighting factors. Last, ***Chapter 6*** concludes all findings from the development and applications of ATSP systems and compares the differences of TSP development in Japan and in the Untied States. The dissertation ends with the potential future directions as a continuous of this research subject.

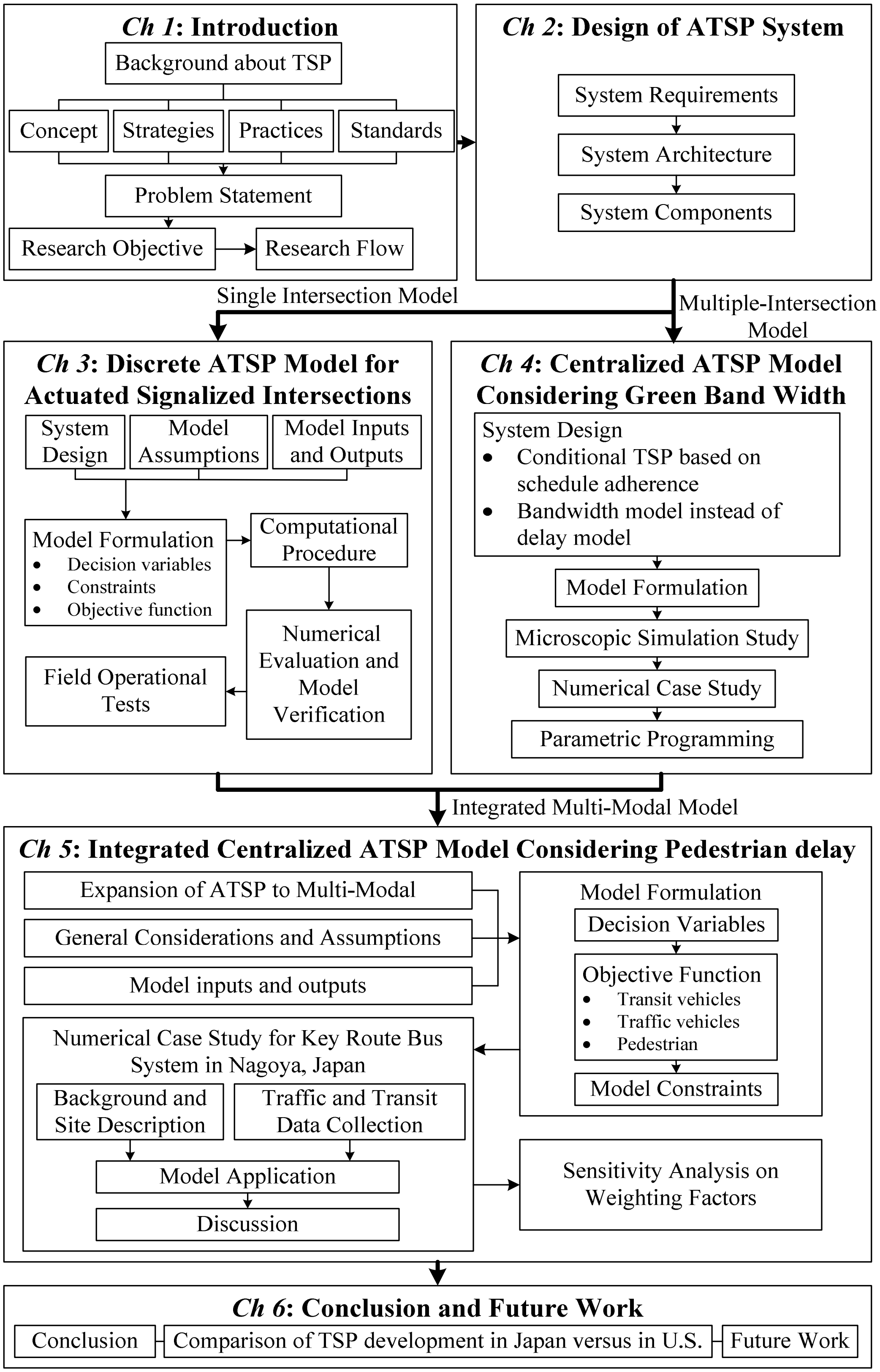


Figure 1-5 Organization of the dissertation

Chapter 2

DESIGN OF ATSP SYSTEMS

2.1 System Requirements

2.1.1 System Objectives and General Requirements

The primary objectives that the developed ATSP system attempts to achieve are to:

- Reduce transit intersection delay and thus trip time
- Improve reliability of transit trip time and schedule adherence
- Reduce transit operating cost, air pollution and noise
- Minimize negative impacts of granting priority to transit on minor-phase traffic

In addition to some general requirements for a TSP system such as easy of maintenance, there are several requirements here:

- Cost-effectiveness

The system should be cost-effective. The capital cost of a TSP system depends on the types of transit priority treatments to be used and the ways in which they will be deployed. By carefully designing the system concepts and choosing appropriate technologies, integrated deployment of a TSP system can be realized, which would reduce the associated capital costs significantly. Indeed, the TSP system architecture and the corresponding deployment strategy, and the resulting effectiveness further depends on several factors including the type and operation of the traffic control system in place, the extent to which traffic congestion interferes with transit operations and the nature of the interference, and frequency and characteristics of transit service (Skabardonis, 2000).

- Minimal operator/equipment interaction (Gifford et al. 2001)

The specifics of a TSP system will determine the extent to which transit operators need to interact with the system, that is, how much attention operators must pay to activate and/or monitor the system. With everything the transit operator currently needs to do as part of his/her job, giving the operator additional tasks related to the operation of TSP would likely be problematic leading to a preference for either no or only minimal interaction with the operator.

- Flexible and adjustable (Gifford et al. 2001)

The TSP system should be flexible enough to accommodate various preferences or trade-offs that decision-makers may have among different control criteria such as person delay, transit delay and traffic delay. The system should be easily adjusted to suit changing needs.

In this study, the ATSP systems were developed to achieve the aforementioned system objectives while trying to satisfy the system requirements stated as above.

2.1.2 TSP Guidelines

There are currently no world-wide guidelines and regulations on transit signal priorities. Many national or local transportation departments and county traffic management agencies provide guidelines to confine TSP strategies, and these guidelines are negotiable. In California, USA, the Traffic Signal Committee of Caltrans has defined the TSP operation for isolated and coordinated traffic signal controls. Basically, operational requirements for transit priority shall conform to manual on uniform traffic control devices (MUTCD) Section 4D.13 and California Vehicle Code Section 25352, but with several exceptions. When developing the ATSP systems in this study, particular attention was paid to the following requirements/exceptions:

- The shortening or omission of minimal vehicle times and clearance times shall not be permitted;
- The shortening of any pedestrian walk interval and the omission of a pedestrian walk interval and its associated change interval shall not be permitted;
- No transit vehicle priority with signals operating level of service (LOS) E or F as per highway capacity manual (HCM) definition of LOS;
- No manual operation by the transit operator;
- Transit priority is to be used only when transit is running late to enable the vehicle to make up time;
- Transit priority shall not cause coordinated signals to go into “free” operation;
- Transit priority shall apply only to express bus/transit services with few stops.

2.2 ATSP System Architecture and System Components

The physical parties directly or indirectly involved in a TSP system include transit vehicles, transit management center, signal control system, traffic management center, transit vehicle detection means and communications links among them. In terms of functionality, every implementation of a TSP system shall have two primary components: priority request generator (PRG) and priority request server (PRS). The former aims to initiate a priority request while the latter manages and prioritizes one or more priority requests and generates service requests, which are then sent to and executed by signal controllers (AASHTO/ITE/NEMA, 2008). The system topology of a TSP system is illustrated as **Figure 2-1**.

Elements of PRG and PRS can be physically located in different locations and fulfilled by different means, hereby resulting in multiple system architectures available for a TSP system. The following issues are determinant to the system architecture (functional and physical) for a specific TSP implementation:

- Type of traffic control system: distributed vs. centralized; closed-loop vs. adaptive control;
- Detection means to be used: loop detectors, optical emitters, radar detectors, video detectors, radio frequency tags and GPS/AVL systems etc;
- Locations of elements of PRG and PRS, and the corresponding realization

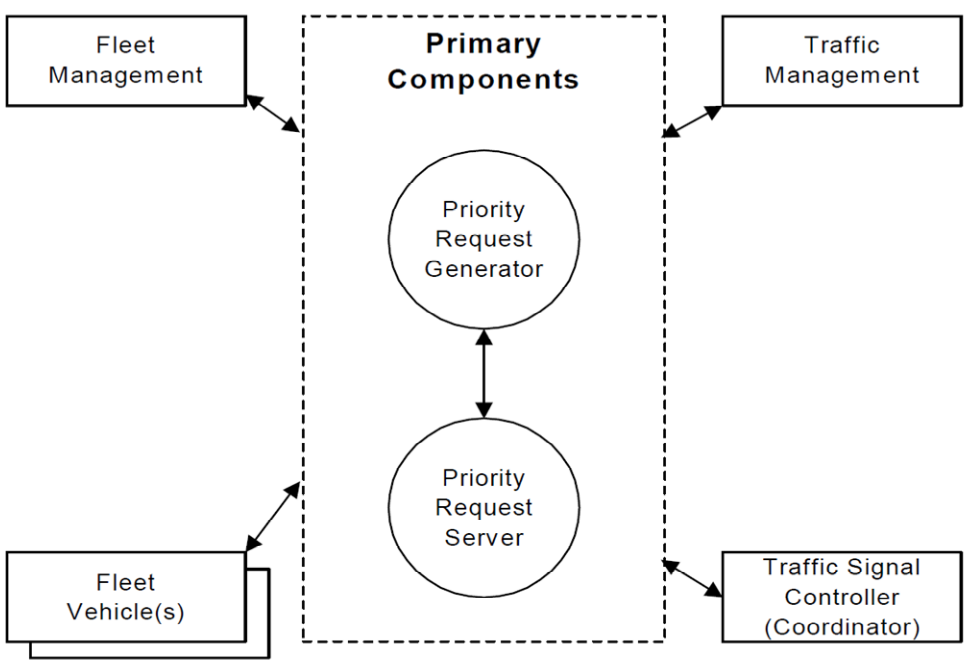


Figure 2-1 System topology of TSP system (source: NTCIP 1211 standard)

means;

- Data/information flow paths among components of the system, and the corresponding communication links and means;

The above issues can not be considered independently because they are interrelated. In order to achieve a cost-effective deployment, these issues should be determined with considering field conditions, customization requirements, budget constraints and more importantly, the infrastructure in place (and/or in planning), such as existing traffic control system, current transit management system, equipped transit ITS technologies and communication links. In order to achieve a cost-effective deployment, the architecture should be determined with considering field conditions, customization requirements, budget constraints and more importantly, the infrastructure in place (and/or in planning), such as signal control system, transit management system, equipped transit ITS technologies and communication links.

2.2.1 Physical System Architecture

The system architecture and system components for an example adaptive TSP system is illustrated by **Figure 2-2** and elaborated by the following three components. It is noted that the functional architecture and physical architecture can be different. For example, the physical architecture as shown in **Figure 2-2** is a typical centralized system because the central communication from each local signal controller to the traffic management center and data center. However, the functional architecture can still be discrete if the PRG and PRS decide the priority requests only based on the information from one isolated intersection.

2.2.2 Fleet Vehicles with Location Detections

The adaptive TSP system uses GPS instrumented on buses as detection means to continuously monitor bus locations. Bus arrival times to intersections are predicted and updated by an arrival time predictor (ATP). Many previous studies have conducted bus arrival time prediction using regression models (Tan, et al. 2008; Zhou 2004), Kalman filtering (Wall and Dailey 1999) or neural networks (Chien et al. 2002). Accurate bus arrival information is essential for TSP systems to be 'adaptive' to the bus movement. More importantly, this concept allows all buses instrumented with GPS/Automatic Vehicle Location (AVL) systems to become signal priority capable without additional equipment on buses. Many transit agencies have deployed or planned to deploy GPS/AVL system to their fleets. In 2006, 56% of fixed route buses in the U.S. are equipped with the system (USDOT, 2008). Although most existing AVL and advanced communication system

(ACS) only provide bus location data every two to five minutes, many existing systems are believed to be adequate to support adaptive TSP operations. For example, Tan et al. (2007) developed a dynamic polling model to leverage on the existing communication and contention channels.

2.2.3 Signal Control and Traffic Detection Systems in the Field

As previously mentioned, the adaptive TSP system is built upon a distributed closed-loop signal control system where controllers receive calls or actuations from inductive loop detectors, indicating that a service is demanded for a particular movement. In California, advance loops and four 6’×6’ presence loops, if any, are placed. Arrival and departure traffic counts and occupancies can be made available. In addition, high frequency (e.g. 1HZ or 0.5HZ) signal status information can be archived and retrieved for all phases. In the field, many coordinated actuated systems have frame relay communication in place. Such communication is capable of transmitting signal status data in high frequency.

2.2.4 Traffic Management Center with Priority Request System

The PRG and PRS are hosted by a TSP master computer and physically located in the traffic management center as well as the ATP and a real-time database. The TSP master computer is connected with the super master of the signal control system through a direct serial port connection, allowing traffic data and signal status to be received by the real-time database. And, bus status data are also received by the database via a wireless

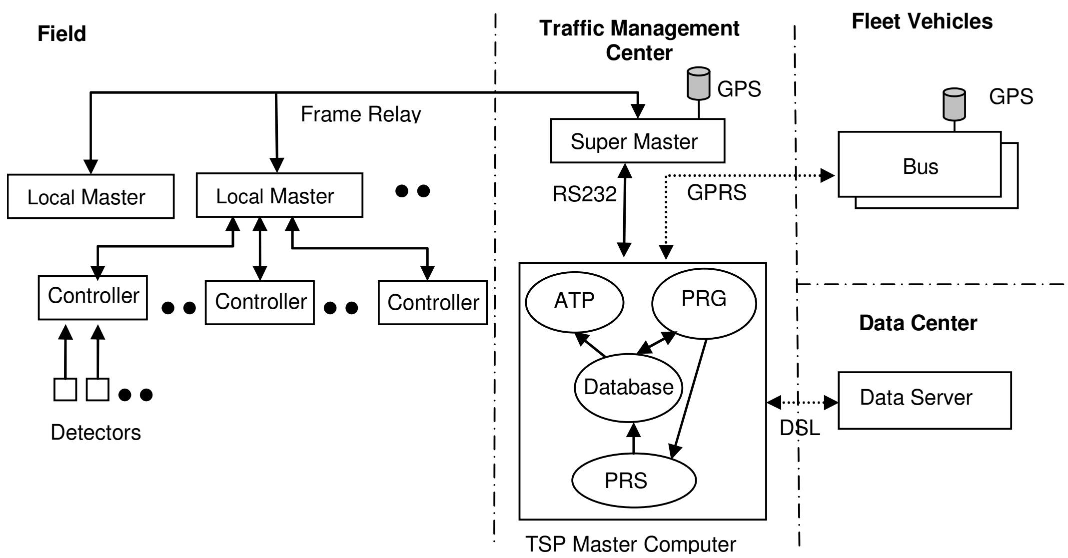


Figure 2-2 System architecture for a typical adaptive TSP system

communication. The database also logs TSP events such as priority requests, service requests and request receipt confirmations.

An adaptive TSP model, embedded in the PRG, uses information of predicted bus arrival information, estimated queue condition, signal status and pedestrian presence to optimize TSP strategies. The PRG sends a priority request message to the PRS whenever a bus needs it and a check-out request after the vehicle has passed the signalized intersection. Upon receiving priority requests from multiple buses, the PRS will prioritize all the different priority requests based on the requested priority treatments, requested phase, and desired service time, and then generate a service request and eventually send the service request to signal controllers for execution. It is noted that PRS in the proposed model follows a first-come-first-serve rule and only considers the time when the service is requested to prioritize requests. Only with additional information of schedule adherence or number of passengers on board, PRS can better prioritize requests.

Because of fluctuated traffic conditions and various driver behaviors, there are uncertainties in predictions of arrival times at downstream intersections. Thus, the closer buses getting to the intersections the higher the predictions' confidence levels will be due to fewer uncertainties. So the later the PRG generates TSP request, the better data input it is based on. However, the earlier the PRG can send the service request, the more flexibly the signal controller is able to adjust signal timings. There is no optimal location or time to generate TSP request. PRG keeps listening to the real-time inputs, e.g. bus arrival time, signal status, pedestrian button information, and traffic flows. Based on such latest information, PRG will update its request if necessary. PRS will check difference among requests and send the appropriate one to signal controllers.

The core of the adaptive TSP system is a TSP algorithm that manipulates signal controllers to grant priority to buses. The focus of this study is the signal operation model and the performance. For other developments, such as ATP, readers of interest may refer to other literatures, e.g. Zhou et al. (2004).

Chapter 3

A DISCRETE ATSP MODEL FOR ACTUATED SIGNALIZED INTERSECTIONS

3.1 System Design

In this chapter, a discrete ATSP model has been developed and evaluated. The proposed model is designed for a discrete ATSP system which generates TSP requests only for one intersection. The signalized intersections are under closed-loop actuated signal control.

3.1.1 Functional System Architecture

With real-time traffic data and signal status data, a queue prediction model was developed to predict the queue length at each intersection. An ATSP algorithm, embedded in the PRG, uses the predicted bus arrival information, traffic queuing condition, signal status and pedestrian presence information to determine the signal priority timing strategies. The PRG sends a priority request message to the PRS whenever a bus needs it and a check-out request after the vehicle passed the signalized intersection. Upon receiving priority requests from multiple buses, the PRS will prioritize all the different priority requests based on the requested priority treatments, requested phase, and desired service time, and then generate a service request that can be used by signal controllers to provide priority to buses and eventually send the service request to signal controllers for execution.

Figure 3-1 shows the functional system architecture of the proposed ATSP concept. There are four types of real-time inputs on the left side coming into the system, including bus input from GPS instrumented on buses, traffic input, pedestrian call input and signal input from signal controllers. All these inputs will be updated up to every one second. At the bottom of the figure, the ATSP system outputs the service request to signal controllers whenever a service request is generated by PRS.

3.2 General Consideration and Assumption

A timing optimization model is developed to minimize a weighted sum of traffic delay and bus delay at an isolated intersection. In order to facilitate the model formulation, the following consideration and assumptions are made about intersection geometry, traffic demand, and signal settings:

1. The model considers a single bus request for one particular intersection along a corridor that is coordinated by an actuated system. As defined by National Electrical Manufacturers Association (NEMA) on **Figure 3-2**, movements 1, 6, 2, and 5 are on the main corridor streets; movements 4, 7, 3, and 8 are on cross streets. Movement 2 or

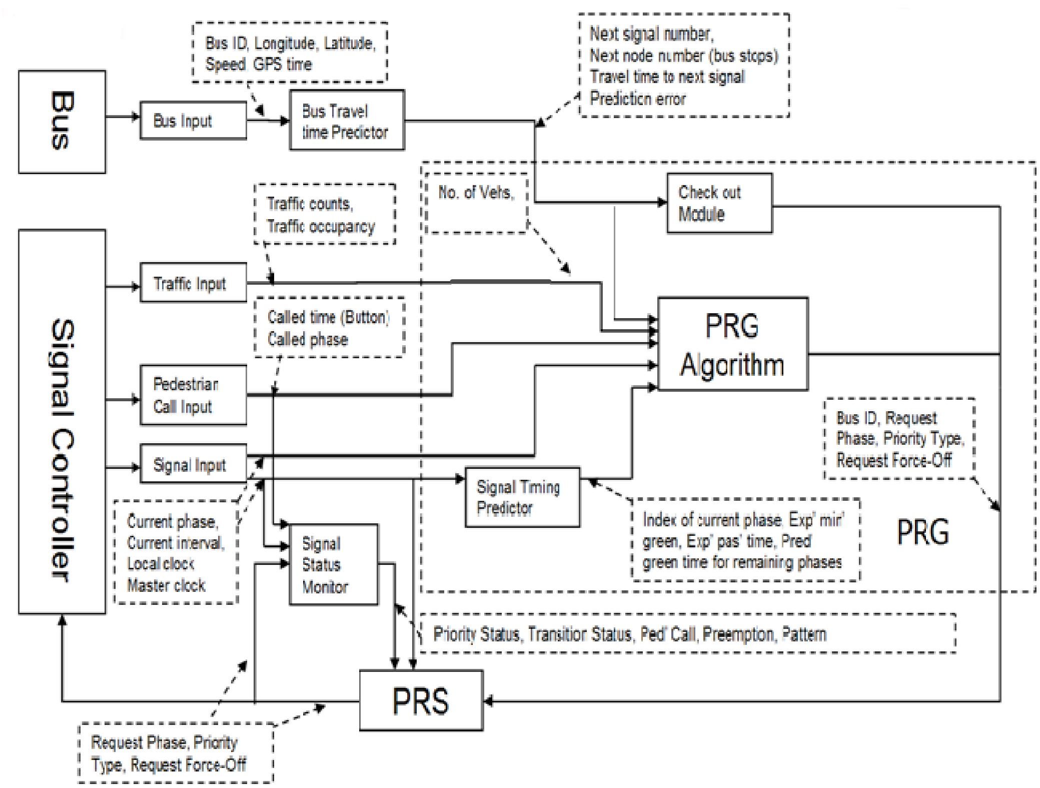


Figure 3-1 Functional system architecture for the proposed system

6 is the sync movement, which actually represents the coordination direction.

2. A new definition for signal cycle is used to facilitate the formulation. In contrast to the traditional NEMA-defined signal cycle, which references to the on/off of sync movements, we refer a cycle with respect to the onset of cross-street movements. It is noted that the new definition does not impact the model outputs as described below.
3. The adaptive TSP model attempts to change green splits for at most three consecutive cycles.
4. Traffic demand within the three control cycles is stationary.
5. TSP operations should not cause residual queues for any movement after three TSP control cycles. It is noted that the number of cycle for transitions can be readily customized in the proposed model. The intersection with high traffic demand on all approaches might need more cycles in transition than the intersection with low traffic demands. It is noticed that when existing traffic demand is over-saturated. Due to the saturation constraint, the proposed system would not generate any TSP requests to make traffic condition even worse.

3.3 Inputs and Outputs

As shown in **Figure 3-3**, the optimization model takes five real-time inputs,

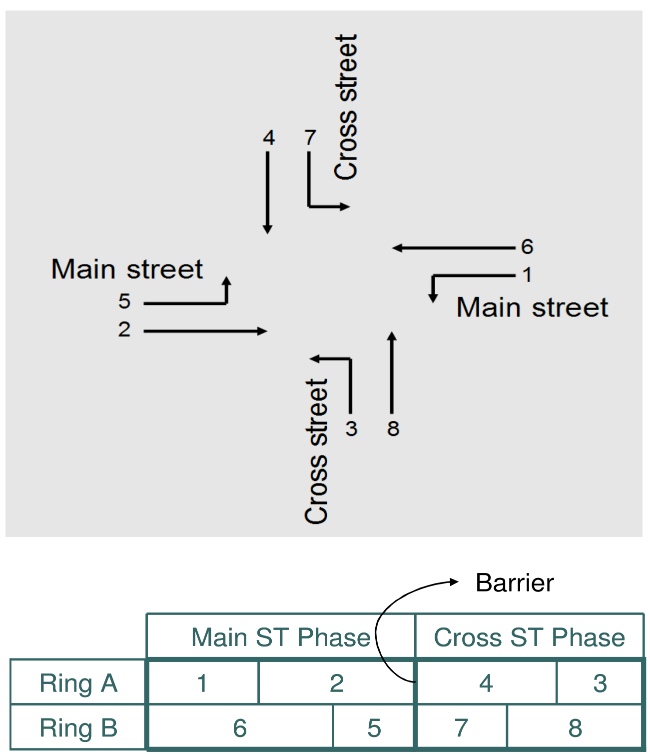


Figure 3-2 Definition of standard NEMA phases, rings and barrier

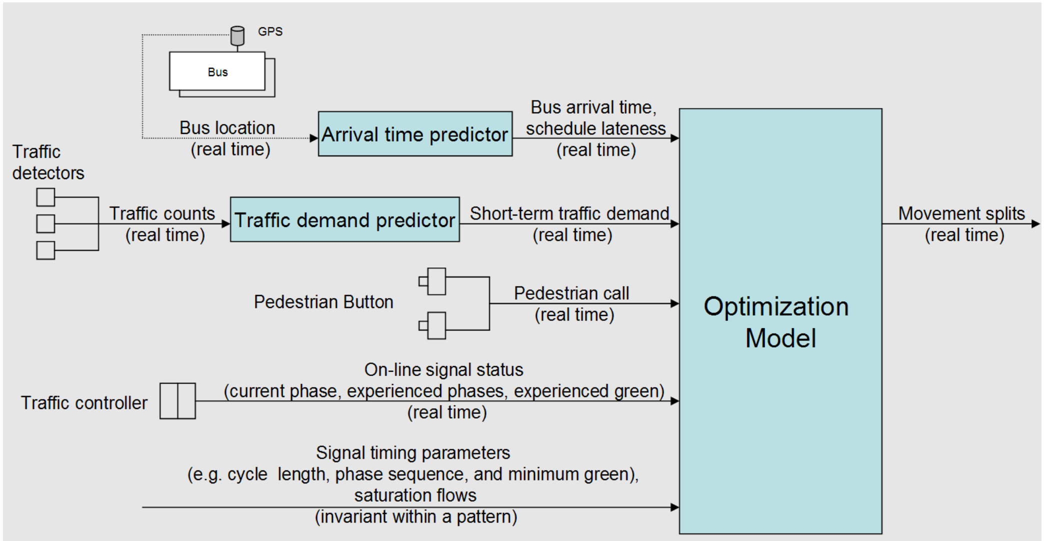


Figure 3-3 Input/output control diagram

including bus arrival time and schedule adherence (early, on time or late) generated and updated by ATP; short-term traffic demand prediction obtained by using a moving average method that analyzes the time-series traffic counts from traffic detectors; pedestrian calls and online signal status received in real time from the signal controller; and other static inputs such as signal timing parameters (e.g. cycle length and minimum green) and saturation flow rates, which are invariant within a pattern typically defined by time of day.

The model outputs are priority requests in the form of movement splits. The movement splits can be converted to any form of controllable parameter, e.g. green split, force-off point, or maximum green. Zhou et al. (2004) validated that 170E signal controller, a popular model for actuated systems primarily in California, New York as well as some other states in the United States, is capable of performing more adaptively through online updating timing parameters, such as force-off points, gaps and maximum green etc. NEMA-type controller, the other popular model of traffic signal controllers, is also capable of performing such operations. However, an actuated control system may not be able to work the same way as an adaptive system due to two constraints in their control logic: the first one is cycle length constraint, which requires the duration between the end of the sync movement and the end of the next sync movement to be a constant while the other concerns the movement sequence. No movement can be revisited before the cycle ends in many controllers (some latest version of the control firmware has been modified to allow longer cycles and phase re-service. Such features are not considered in the paper). Essentially, both constraints aim to keep all signals of the corridor in coordination and make the control logic simple and applicable to the field controllers. Because neither constraint can be overridden, the proposed model must satisfy them.

3.4 Model Formulation

As aforementioned, the optimization model manipulates movement splits in three consecutive cycles for an approaching bus. We denote the cycle that contains the predicted bus arrival time as cycle 1. Correspondingly, the previous and following cycles are labeled cycle 0 and 2, respectively. The TSP model confirms accurate prediction of bus arrival by the end of cycle 0, and provides bus priority in cycle 1, and then uses cycle 2 as a transition cycle to compensate the loss of other traffic due to the priority operation. Note that the signal cycles mentioned here and hereinafter are based on our definition in the previous section.

Phase sequence can be defined by lead-lag relationships between the four conflicting movement pairs: 1&2, 3&4, 5&6, and 7&8. Four binary variables are introduced in Equation 3-1 to uniquely represent a particular phase sequence.

$$L_i = \begin{cases} 1, & \text{if movement } i \text{ is lead} \\ 0, & \text{if movement } i \text{ is lag} \end{cases}, \forall i = 1,3,5,7 \qquad \textbf{Equation 3-1}$$

Figure 3-4 shows an example phase sequence, which is consistent with **Figure 3-2**. The corresponding binary variables are (1, 0, 0, 1). Phase 6 is the sync phase. Although the newly defined cycle starts from the beginning of phase 4 and 7 and ends after phase 2 and 5, the traditional constant cycle length C is between the end of sync phase and its next end, as shown in **Figure 3-4**.

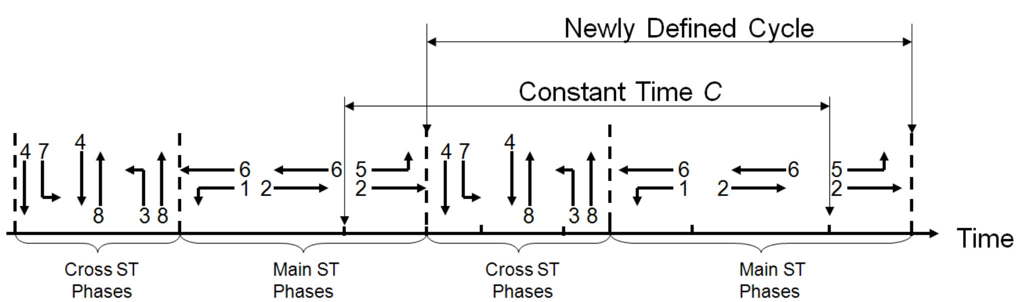


Figure 3-4 An example phase sequence

3.4.1 Decision Variables

As depicted in **Figure 3-5**, cycle 1 and cycle 2 are control cycles, during which the TSP algorithm manipulates the splits of green time for different movements. All the movement splits within the control cycles are decision variables of the optimization model. In contrast, the green splits in the background cycle are not controlled by the TSP model. The green split for movement i in cycle j is denoted as g_{ji}, while red time as r_{ji}.

3.4.2 Constraints

The optimization model may satisfy six sets of constraints: 1) minimum green; 2) cycle length; 3) barrier; 4) under-saturation; 5) red-green relationship and 6) real-time updates. All these constraints are elaborated as follows. Many binary variables are defined to represent the actuated signal control logic.

3.4.2.1 Minimum green durations

The minimum green constraint requires a minimum protected green for each movement. Pedestrian crossings are consolidated into this minimum constraint. We introduce a variable to indicate pedestrian presence as Equation 3-2. When the pedestrian button is pushed, the minimum green for the corresponding movement is elongated to the

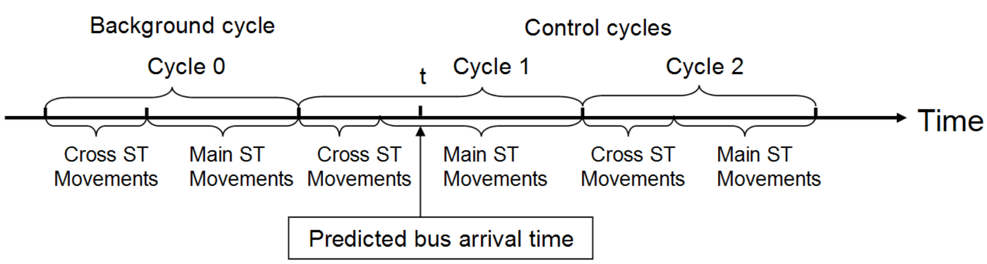


Figure 3-5 Background and control cycles

protected "walk" plus "flash don't walk" time, as described by Equation 3-3.

$$Ped_{ji} = \begin{cases} 1, & \text{if ped' button is pushed for mov' } i \text{ in cycle } j \\ 0, & \text{if ped button is not pushed for mov' } i \text{ in cycle } j' \end{cases} \quad (\forall i = 1,..,8; j = 1,2)$$ **Equation 3-2**

$$g_{ji} \geq (1 - Ped_{ji}) \cdot G_i^{min} + Ped_{ji} \cdot G_i^{Ped} \quad (\forall i = 1,..,8; j = 1,2)$$ **Equation 3-3**

where G_i^{min} is the minimum green for movement *i* and G_i^{Ped} is the protected "walk" plus "flash don't walk" time.

3.4.2.2 Fixed cycle length

The cycle length constraint is formulated as Equation 3-4. The first expression represents a lead-lead phase sequence while the second one represents the lead-lag or lag-lag sequence. Lead or lag operation suggests whether the left-turn traffic is released before or after the opposing traffic.

$$\begin{cases} L_1 \cdot L_5 \cdot \left(C - \sum_{i=1}^{4} g_{ji}\right) = L_1 \cdot L_5 \cdot \left(C - \sum_{i=5}^{8} g_{ji}\right) = 0 \\ (j = 1,2) \\ (2 - L_1 - L_5)[C - L_5(g_{j-1,1} - g_{j1}) - L_1(g_{j-1,5} - g_{j5}) \\ -(1 - L_1)(1 - L_5)(g_{j-1,i} - g_{ji}) - g_{ji} - g_{j,i+1} \\ -g_{j,i+2} - g_{j,i+3}] = 0 \\ (i = 1,5; j = 1,2) \end{cases}$$

Equation 3-4

where *C* is the signal cycle length.

3.4.2.3 Barrier and rings for actuated signal control

The barrier constraint, as shown in Equation 3-5, means that ring A and B at the same side of the barrier should have the same duration:

$$\begin{cases} g_{j1} + g_{j2} = g_{j5} + g_{j6} \\ g_{j3} + g_{j4} = g_{j7} + g_{j8} \end{cases} (j = 1,2)$$

Equation 3-5

3.4.2.4 Under-saturation for control cycles

The under-saturation constraint, in the form of Equation 3-6, is to guarantee that no residual queue will be present after the two control cycles.

$$\frac{\lambda_i \cdot \sum_{k=j}^{2}(g_{ki} + r_{ki})}{\mu_i \cdot \sum_{k=j}^{2} g_{ki}} \le 1$$
$$(\forall i = 1, .., 8; j = 1,2)$$

Equation 3-6

where λ_i is traffic arrival rate for movement *i* and μ_i is saturation flow for movement *i*.

3.4.2.5 Relationship between green and red durations

Except for the predefined all-red period, a traffic signal must show green to one movement while showing red to the conflicting movements. Such red-green relationships form another set of constraints for the optimization model, as described in Equation 3-7.

$$
r_{ji} = \begin{cases} g_{j-1,i+1} + g_{j-1,i+2} + g_{j-1,i+3} \\ -L_i\left(g_{j-1,i+2} + g_{j-1,i+3} - g_{j,i+2} - g_{j,i+3}\right) \\ (i = 1,5; j = 1,2) \\ \\ g_{j,i-1} + g_{j,i+1} + g_{j,i+2} \\ (i = 2,6; j = 1,2) \\ \\ g_{j,i-2} + g_{j-1,i-1} + g_{j,i+1} \\ +L_{i-2}\left(g_{0,i-2} - g_{1,i-2}\right) + L_i\left(g_{0,i+1} - g_{1,i+1}\right) \\ (i = 3,7; j = 1,2) \\ \\ g_{j,i-3} + g_{j-1,i-2} + g_{j,i-1} + L_{i-3}\left(g_{0,i-3} - g_{1,i-3}\right) \\ +(1 - L_{i-1})\left(g_{0,i-1} - g_{1,i-1}\right) \\ (i = 4,8; j = 1,2) \end{cases} \quad \textbf{Equation 3-7}
$$

3.4.2.6 Real-time updates

In order to achieve the "adaptive" goal, another real-time updating constraint is needed, as shown in Equation 3-8. One major advantage of the adaptive TSP system is that the central control module can update timing plans real time based on real-time information, such as bus arrival time. In addition, if the control module is aware of the execution status of a particular movement, whether skipped or ended, it will not consider the length of this movement g_{ji}^{exp} as a decision variable any more. For other statuses, either ongoing or forthcoming, g_{ji}^{exp} will be another lower bound of the decision variable g_{ji} other than that in Equation 3-3.

$$
\begin{cases} g_{ji} \geq g_{ji}^{exp} \\ M_{ji} \cdot (M_{ji} - 1) \cdot g_{ji} \leq M_{ji} \cdot (M_{ji} - 1) \cdot g_{ji}^{exp} \end{cases} \quad \textbf{Equation 3-8}
$$

where g_{ji}^{exp} is the experienced green time for movement *i* in control cycle *j* and is the execution status for movement *i* in control cycle *j*, defined as follows

$$
M_{ji} = \begin{cases} 0,\ \text{if mov' } i \text{ is not started yet} \\ 1,\ \text{if mov' } i \text{ is ongoing} \\ 2,\ \text{if mov' } i \text{ is ended or skipped} \end{cases} \quad \textbf{Equation 3-9}
$$
$$
(\forall i = 1, .., 8; j = 0,1,2)
$$

3.4.3 Objective Function

The adaptive TSP operation is to grant priority to buses while minimizing the impacts on other vehicular traffic. To make a tradeoff between these two objectives, a weighting factor on bus delay is used, which represents the preference between reducing bus delay and reducing traffic delay. Therefore, the objective function of the proposed model is to minimize a weighted sum of bus and other traffic delay. To compute traffic delay, we have two scenarios for each movement to consider:

- Scenario I: no residual queue at the end of cycle 1
- Scenario II: residual queues exist in cycle 1 but not in cycle 2.

A classic deterministic queuing model is applied to estimate delays at signalized intersections, assuming uniform traffic arrivals and vertical queues at the intersection stop lines. It is known that the model may not accurately represent the exact number of queued vehicles at a given instant. However, the model does not bias the delay estimation over an entire queue formation and dissipation process and works for both under- and over-saturated traffic conditions (Dion et al. 2004). It is noted that the focus of the model is not on delay calculation model but the optimization and balance of TSP benefits and negative impacts on other traffic. The model can actually relax the assumption of uniform arrival by two approaches. First, a scenario-based stochastic model was developed (Yin, 2008) to address the fluctuating traffic conditions. Second, the data driven model (Li et al., 2009) was proposed to utilize the existing detection system upon closed-loop actuated control system.

According to the deterministic queuing model, traffic delays in cycle 0, 1, and 2 are calculated by Equation 3-10 which can be consolidated into Equation 3-11. It is noted that the overall impact on traffic delay by the TSP system should not be limited to the one intersection. Because of the system coordination, the traffic along the coordinated directions may experience additional delay at adjacent intersections due to the timing changes at one intersection. However, this part of delay is not captured by the current model.

$$d_i \begin{cases} (\text{Scenario I}) = \frac{\mu_i}{2}\rho_i \cdot r_{0i}^2 + \frac{\mu_i}{2}\rho_i \cdot (r_{1i}^2 + r_{2i}^2) \\ (\text{Scenario II}) = \frac{\mu_i}{2}\rho_i \cdot r_{0i}^2 + \frac{\mu_i}{2}\rho_i \cdot (r_{1i} + r_{2i})^2 - r_{2i} \cdot \mu_i \cdot g_{1i} \end{cases} \qquad \textbf{Equation 3-10}$$

$$d_T = \sum_{i=1}^{8} [\frac{\mu_i}{2}\rho_i \cdot (r_{1i} + r_{2i})^2 - r_{2i}\mu_i \cdot \min\,(g_{1i}, \rho_i r_{1i}) + \frac{\mu_i}{2}\rho_i r_{1i}^2] \qquad \textbf{Equation 3-11}$$

where: $\rho_i = \frac{\lambda_i}{\mu_{i-\lambda_i}}$

Regarding the bus intersection delay, if a transit vehicle is expected to arrive before its normal green in control cycle 1, the optimization model would make the decision before control cycle 1 to reduce green times of phases prior to the bus phase. Such a strategy is called "early green". "Green extension," another popular TSP strategy, will be executed instead if the transit vehicle is expected to barely miss its original green. Because green extension may disrupt existing coordination for main street phases, traffic engineers often impose some restrictions on this strategy. For example, the extended green cannot be longer than 10% of the cycle length.

The bus that requests signal priority can arrive at any phase in the proposed model. The most complicated scenario is that the phase of bus arrival is the last phase of a cycle because the green extension strategy under this scenario would break the cycle length constraint for two consecutive cycles. Furthermore, most rapid transit services that need TSP run along major corridors. Therefore, we assume that buses are running on movements 2 and 6 in the delay calculation. The model can be readily adapted by changing the phase number in Equations (12)~(14) when a bus is actually not on movement 2 or 6. Here we introduce a binary variable as in Equation 3-12 to indicate buses' running directions:

$$B = \begin{cases} 1, & \text{if bus on mov' 2} \\ 0, & \text{if bus on mov' 6} \end{cases}$$ **Equation 3-12**

The predicted bus arrival time is referenced to the end of a sync movement or a real clock (Zhou et al., 2004). To compute bus delay, we convert t_{bus} into T_{bus}, which is referenced to the end of green of the bus phase:

$$T_{bus} = t_{bus} + B(1 - L_1)g_{01} + (1 - B)(1 - L_5)g_{05}$$ **Equation 3-13**

For early green, the model will shrink the red time for the bus phase, from R' to R, as shown in **Figure 3-6**. At T_{bus}, the bus is expected to arrive at the intersection to join a standing queue. The number of queued vehicles ahead of the bus is N_T, and the corresponding queue discharging time is bus delay d_{bus} because the bus leaves the intersection at $T_{bus} + d_{bus}$. The queue disappears at t_q, which can be computed as Equation 3-14.

$$t_q = R + B\rho_2 r_{12} + (1 - B)\rho_6 r_{16}$$ **Equation 3-14**

where R is the red time for the bus movement, $R = Br_{12} + (1 - B) \cdot r_{16}$.

From the geometry of **Figure 3-6**, the relationship of Equation 3-15 can be derived. Thus, bus delay can be obtained by Equation 3-16.

$$\frac{d_{bus}}{R} = \frac{\max(t_q - T_{bus}, 0)}{t_q}$$ **Equation 3-15**

$$d_{bus} = \frac{R}{t_q}\max(t_q - T_{bus}, 0)$$ **Equation 3-16**

Therefore, the objective function for early green strategy is:

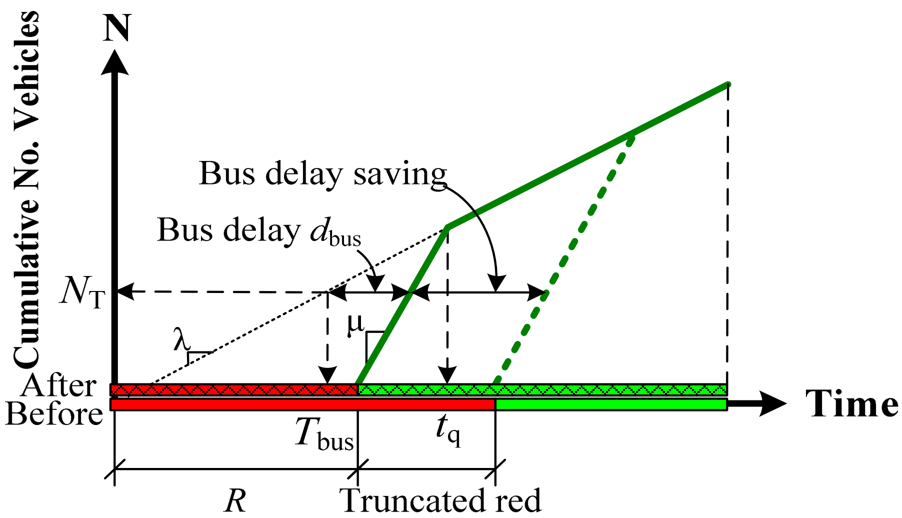


Figure 3-6 Flow-time diagram for bus movement with TSP

$$\min d = \sum_{i=1}^{8}[\frac{\mu_i}{2}\rho_i \cdot (r_{1i} + r_{2i})^2 - r_{2i}\mu_i \cdot \min(g_{1i}, \rho_i r_{1i}) + \frac{\mu_i}{2}\rho_i r_{1i}^2] + w_b \frac{R}{t_q} \max(t_q - T_{bus}, 0) \quad \textbf{Equation 3-17}$$

where w_b is the weighting factor for buses.

For green extension, the green of the bus phase in cycle 0 is extended until the approaching bus leaves the intersection. Therefore bus delay will be zero. So the objective function for green extension is simply to minimize Equation 3-11. Changes are also needed on the signal timing constraints for the green extension strategy. Because the bus arrived at the beginning of a cycle, the sync phase in the cycle before the bus arrival is extended by G_{ext}. As a result, the cycle length of the previous cycle is elongated and that of the bus arrival cycle is shrunken by as much as G_{ext}.

In summary, the TSP optimization models are to minimize Equation 3-17 or Equation 3-11. Given specific setting of the signal and real-time traffic information, all the constraints are linear. By introducing additional auxiliary variables, the objective function can be easily transformed into quadratic functions. Moreover, we treat all decision variables as continuous since signal controller works at 10 hertz and their working frequency is 10 times per second. Therefore, the formulated models are standard quadratic programming models, which can be easily solved by commercial solvers.

Table 3-1 General information and parameters for the case intersection

Movement	1	2	3	4	5	6	7	8
Minimum Green (sec)	4	6	4	6	4	6	4	6
Demand (veh/h)	200	1200	200	800	200	1200	200	800
Saturation flow (veh/h)	1200	5400	1200	3600	1200	5400	1200	3600
Green split (sec)	20	53	20	27	20	53	20	27
Delay (sec/veh)	50	23.8	50	46.7	50	23.8	50	46.7

3.5 Computation Procedure

Given a set of traffic signal information and transit movement data, an optimization solver for convex quadratic objective with linear constraints, may output two sets of phase splits for early green and green extension strategy, respectively. By comparing the values of the two objective functions, the optimal strategy is determined for the coming bus. The final priority request, which is the output to PRS, consists of the phase splits in the form of force-off or green splits together with other information in consistent with the NTCIP 1211 specification.

3.6 Numerical Case Study

We present a numerical example here to demonstrate the proposed models. We also conducted the sensitivity analysis on weighting factor in the objective. Although the selection of weighting factor can be political, policy and circumstance dependent, the results presented in the sensitivity analysis can provide some guidance to decision makers on the benefits and cost comparison resulted from different weighting factors.

In this example, the intersection has four lanes on each main street approach, one of which is the left-turn lane. On the cross streets, there are one left-turn lane and two through lanes. **Table 3-1** reports basic settings for the example under a medium-congested scenario whose saturation degree is 0.67. For a simplification of the calculation, traffic arrivals were assumed to be uniformly distributed in the numerical case study. The phase sequence is shown in **Figure 3-4** and the cycle length is 120 seconds. Suppose that a bus is coming along movement 6 and pedestrian buttons will not be pushed in the example.

Assuming that bus can arrive at any second of the local clock, we used the optimization toolbox provided in MATLAB to solve the optimization models. The constraint nonlinear programming problem is solved by computing a quasi-Newton approximation to the Hessian, the second derivatives of the Lagrangian. The interior-point algorithm is applied to the solver.

Table 3-2 presents the performance of the TSP algorithm under the medium-congested scenario. Both the average and total vehicle delays are computed by considering cycle 0, 1, and 2 and averaging across different bus arrival times. When the weighting factor is 1, the bus is treated as important as any other vehicle. Therefore, the objective of this case is to minimize total vehicle delay, including bus delay, which is essentially the adaptive signal control logic. As the weighting factor increases, the approaching bus has relatively higher priority over the other traffic. Accordingly, bus delay will be reduced at the cost of the other traffic. For active rule-based TSP systems, the priority treatment also favors the traffic moving along the bus traveling direction (Zhou, et al., 2004). However, it is not necessarily true with adaptive TSP, because the model optimally allocates the disturbance of bus priority treatment to all other traffic. The longer bus phase in cycle 1 may incur a shortened green for the same phase in cycle 2, because other movements need to be compensated in the transition cycle. Consequently, it can be seen in **Table 3-2** that average vehicle delays at the bus and other directions rise up to by 3.38% and 4.6% respectively as the weighting factor increases.

On the other hand, bus delays are more sensitive to changes in the weighting factor comparing with other traffic delays. When the weighting factor is 50, the average bus delay under different predicted arrival times is reduced by 51.34% while delays to traffic at the bus and non-bus movement only increases by 1.13% and 0.52%, respectively. When the

Table 3-2 Performance of the adaptive TSP algorithm (medium-congested scenario)

Weighting factor	Average vehicle delay (sec/veh)						Total vehicle delay	
	Bus		Traffic at bus movement		Traffic at other movements			
	(sec)	Diff'	(sec)	Diff'	(sec)	Diff'	(sec)	Diff'
1 (Ref')	10.24	0.00%	19.05	0.00%	37.46	0.00%	15782.41	0.00%
50	4.98	-51.34%	19.27	1.13%	37.65	0.52%	15877.40	0.60%
100	3.12	-69.54%	19.37	1.67%	38.02	1.50%	16018.45	1.50%
150	1.1	-89.24%	19.48	2.24%	38.68	3.25%	16263.63	3.05%
200	0.2	-98.04%	19.60	2.88%	39.07	4.29%	16416.62	4.02%
250	0.14	-98.61%	19.64	3.06%	39.09	4.35%	16428.58	4.09%
300	0.02	-99.85%	19.66	3.19%	39.18	4.60%	16464.55	4.32%
350	0.00	-100%	19.70	3.38%	39.18	4.60%	16469.16	4.35%
400	0.00	-100%	19.70	3.38%	39.18	4.60%	16469.16	4.35%

weighting factor increases to 350, buses experience no delay no matter when they arrive at the signal, while average vehicle delay for other traffic rises 0.65 sec and 1.72 sec only. We conclude that the proposed adaptive TSP model works well in the medium-congested scenario because it can significantly reduce bus intersection delay without incurring much extra delay for the other traffic.

Rakha (2004) recommends active TSP for medium- or low-congested conditions, because such systems always incur significantly delay to non-bus movements in highly congested scenarios. The proposed adaptive TSP system, however, can use the weighting factor to make an explicit tradeoff in heavily congested traffic. **Table 3-3** presents the performance of the adaptive TSP algorithm in a scenario with a saturation degree of 0.89. Similar to the results in **Table 3-2**, the average bus delay decreases dramatically as the weighting factor increases, while the average delay for other traffic shows a much slower trend of increase. However, the delays experienced by other traffic are more significant than those in medium-congested conditions, because time resource available to conflicting traffic is scarcer when it is highly congested.

Figure 3-7 and **Figure 3-8** show average bus and other traffic delays versus weighting factor and bus arrival time at the local clock for the heavily-congested scenario. If the bus arrives at the beginning of the signal cycle when the bus phase is red, the bus experiences more delay. Note that neither surface is smooth due to the fact that the optimized values are not differentiable with bus arrival time. The surfaces break when the system decides to switch its strategy from green extension to early green.

Table 3-3 Performance of the adaptive TSP algorithm (heavily-congested scenario)

Weighting factor	Average vehicle delay (sec/veh)						Total vehicle delay	
	Bus		Traffic at bus movement		Traffic at other movements			
	(sec)	Diff’	(sec)	Diff’	(sec)	Diff’	(sec)	Diff’
1 (Ref’)	25.09	0.00%	28.60	0.00%	42.44	0.00%	22475.62	0.00%
100	10.95	-56.38%	29.50	3.15%	43.80	3.20%	23190.88	3.18%
200	5.45	-78.29%	30.47	6.53%	45.22	6.55%	23932.43	6.48%
300	1.69	-93.27%	31.49	10.10%	46.98	10.71%	24834.72	10.50%
400	0.96	-96.19%	31.82	11.26%	47.50	11.92%	25102.70	11.69%
500	0.31	-98.75%	31.97	11.78%	48.19	13.55%	25421.80	13.11%
600	0.27	-98.92%	31.96	11.75%	48.24	13.68%	25444.25	13.21%

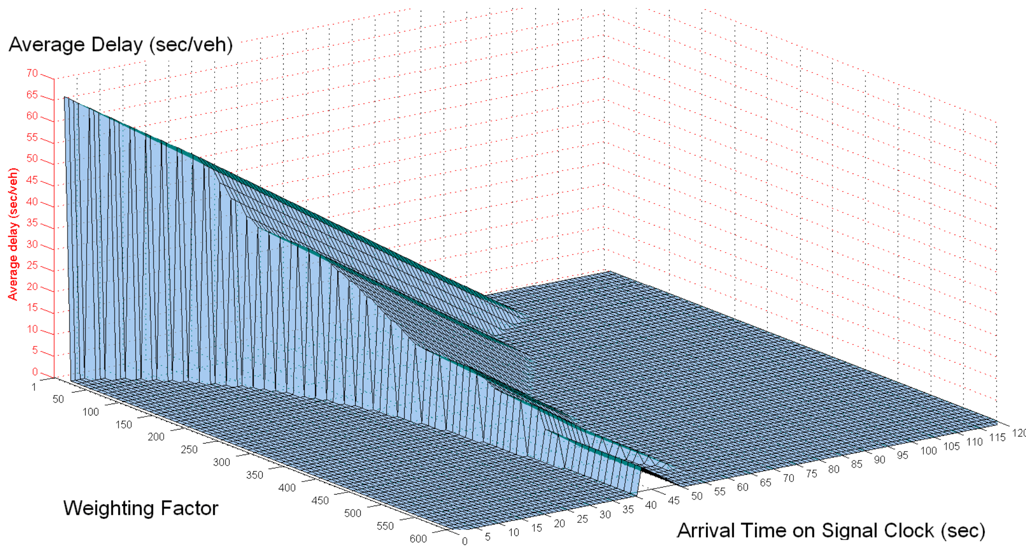


Figure 3-7 Average bus delays in the heavily-congested scenario

According to the trends of the surfaces, we can see bus delays decrease as the weighting factor grows and the arrival time increases, while other traffic delays rise as the weighting factor grows. When bus arrival time falls at either end of a cycle, the TSP algorithm can easily extend green or do nothing to manipulate TSP requests. When bus arrival time falls in the middle of a cycle, the TSP algorithm has to provide priority, which would incur greater delay for other traffic. Therefore, other traffic delays peak when arrival time is in the middle of a cycle. Moreover, the peak value increases with the increase of the

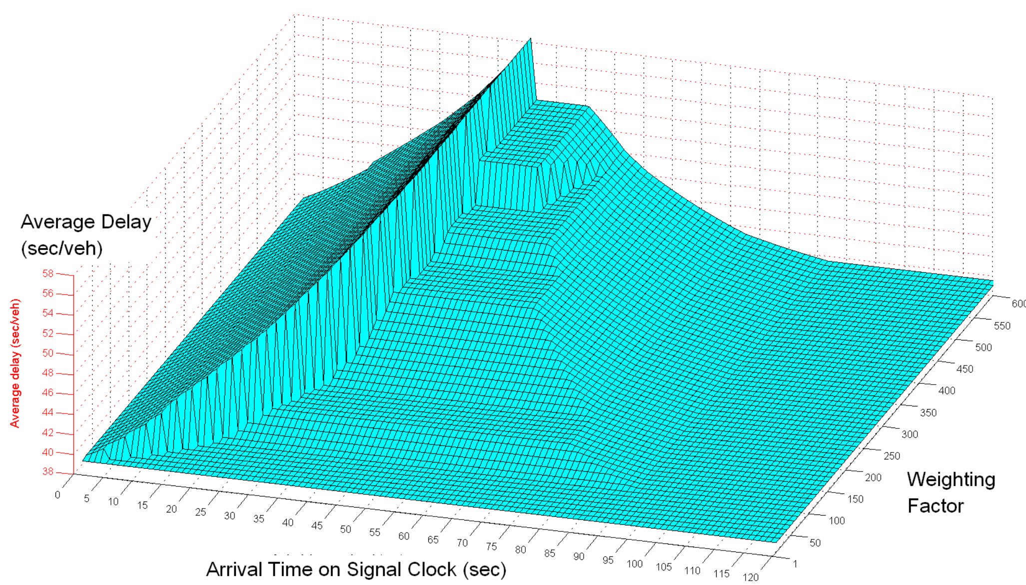


Figure 3-8 Intersection delays for other traffic in the heavily-congested scenario

weighting factor.

3.7 Field Operational Test

The developed adaptive TSP system has been tested in a field environment in 2006. The testing site is a stretch of El Camion Real corridor that is a major connector between San Francisco and Silicon Valley, CA. The testing site is two-mile-long and consists of seven signalized intersections: from 9th Ave. to 28 Ave. All the traffic signals are under coordinated semi-actuated control and are installed with 170E signal controller together with California Department of Transportation (Caltrans) C-8 firmware. A quadratic programming solver COPL_QP was selected to solve the problem with convex quadratic objective and linear constraints. The solver used an interior-point algorithm and outputted movement splits, which were then covered into force-off points. The TSP requests were sent to 170E controllers running C-8 firmware. The system operational latency, including data collection, data processing, optimization, and request transmission, was within five seconds, which is adequate for real-time operation.

A not-in-service bus from San Mateo Country Transit District (SamTrans) was equipped with the GPS and wireless communication based data acquisition system for the field test. During the two-week-long testing period, the assigned bus driver drove the testing bus back and forth along the testing site within three designed time windows: morning peak, mid-day, and afternoon peak. The bus arrival time at intersection was predicted using the recursive least-squares method based on both historical data and real-time bus movement data. The prediction error was within 5 seconds when buses were within the range of 300 meters (984 feet). A traffic flow prediction model, based on an adaptive RLS method and real-time loop detector data, has been developed to provide an estimation of traffic arrival flow for every 5 minutes.

Traffic delay was calculated based on the field data from loop detectors. As shown in **Figure 2-2**, high frequency (0.5 to 1 HZ) of traffic signal data such as running phase and local cycle timer together with traffic volume data for each loop detector was collected. For most of the coordinated actuated systems particularly in California, there is frame-relay communication in place for coordination. Meanwhile, all controllers are compliant with NTCIP standard, such as AB3418 in California. Such communication system and protocol are capable of transmitting data frequently to the field master. For actuated control system, advance loops and four 6’×6’ presence loops, if any, are placed. Arrival and departure traffic counts and occupancies can be made available. In addition, second-by-second signal status information can be archived and retrieved for all phases. The traffic delays shown below were calculated based on the signal arrival and departure curves given the historical right-turn turning ratio. When the presence loops were not placed, a uniform departure curve was built once the signal phase changed its color. For the oversaturation case when the advanced loop is always occupied by the waiting queue, a uniform arrival

Table 3-4 Adaptive TSP impacts on intersection delays

	Delay (sec/veh or sec/pax)		Derived "before" scenario				"after" scenario			
			Bus	Major	Minor	Pax*	Bus	Major	Minor	Pax*
9th Ave	Mean		41.58	14.16	14.42	15.57	1.98	2.70	15.35	6.98
	Standard deviation		19.15	8.50	6.36	5.36	6.86	1.36	4.83	1.88
	Chg*	sec/veh	N/A	N/A	N/A	N/A	-39.60	-11.46	0.93	-8.59
		%	N/A	N/A	N/A	N/A	-95%	-81%	6%	-55%
		t-test*	N/A	N/A	N/A	N/A	sig't*	sig't*	insig't*	sig't*
17th Ave	Mean		61.38	33.20	9.61	25.93	28.56	28.48	11.11	22.19
	Standard deviation		19.49	10.71	3.09	7.34	29.64	12.29	3.33	7.60
	Chg*	sec/veh	N/A	N/A	N/A	N/A	-32.82	-4.72	1.49	-3.74
		%	N/A	N/A	N/A	N/A	-53%	-14%	16%	-14%
		t-test*	N/A	N/A	N/A	N/A	sig't*	insig't*	sig't*	sig't*
25th Ave	Mean		51.30	36.67	13.72	27.42	29.09	30.88	15.11	24.19
	Standard deviation		27.65	10.39	2.76	6.54	28.34	8.07	2.37	5.40
	Chg*	sec/veh	N/A	N/A	N/A	N/A	-22.21	-5.79	1.39	-3.23
		%	N/A	N/A	N/A	N/A	-43%	-16%	10%	-12%
		t-test*	N/A	N/A	N/A	N/A	sig't*	sig't*	sig't*	sig't*
27th Ave	Mean		45.35	18.26	16.94	19.13	17.93	11.63	17.15	12.36
	Standard deviation		17.49	8.58	7.00	7.52	21.74	5.29	3.31	4.30
	Chg*	sec/veh	N/A	N/A	N/A	N/A	-27.42	-6.62	0.21	-6.76
		%	N/A	N/A	N/A	N/A	-60%	-36%	1%	-35%
		t-test*	N/A	N/A	N/A	N/A	sig't*	sig't*	insig't*	sig't*
28th Ave	Mean		45.58	18.83	13.24	18.76	14.07	4.95	16.77	7.20
	Standard deviation		15.06	5.94	2.50	4.40	18.81	2.54	4.23	2.73
	Chg*	sec/veh	N/A	N/A	N/A	N/A	-31.50	-13.89	3.53	-11.56
		%	N/A	N/A	N/A	N/A	-69%	-74%	27%	-62%
		t-test*	N/A	N/A	N/A	N/A	sig't*	sig't*	insig't*	sig't*

Note:
chg*: change; Pax*: passengers; sig't*: statistically significant;
insig't*: statistically insignificant.

curve was built for the delay calculation.

Table 3-4 compares intersection delays for the "before" and "after" scenarios. It is noted that the "before" scenario here is not real "before" scenario due to the limit samples for each time of day period. Instead, an emulation program was developed to mimic the original semi-actuated signal control logic under Caltrans C-8 control firmware. The emulation program generated green splits based on the loop detector data and pedestrian button information we collected from the field and created the "before" case without the TSP request for each of the "after" sample case. Such a derived "before" scenario is more comparable with the "after" scenario with TSP.

With those derived "before" scenarios, it is shown in **Table 3-4** that traffic delays for both of major phases and minor phases were slightly increased after executing TSP. When calculating the average passenger delay at intersections, the average number of passengers on regular vehicles is assumed to be 1.2 persons. For SamTrans buses, the average number of passengers onboard is assumed to be 15 persons per bus.

For example, at 9th Avenue, TSP reduced the average bus delay significantly by 95% to 1.98 seconds per bus; the average major-phase traffic delay was reduced by 81% to 2.70 seconds per vehicle; the minor-phase delay increased by 6% to 15.35 seconds per vehicle. The statistic t-test results show that the delay reductions for buses and major-phase traffic are significant, while the incurred-delay for minor-phase traffic is negligible. Overall, the average passenger delay for all approaches including buses was reduced by 55%, which is also statistically significant.

Two busiest intersections along the testing corridor are 17th and 25th Avenue. In the field test, a constant weighting factor was applied for all seven intersections. Because the weighting factor is the key to balance the level of priority and incurred additional delay to other phases, at those busy intersections the TSP optimization models may reduce the level of priority given to buses. At 17th Avenue, average bus and major-phase delay was reduced by 53% and 14% respectively. Meanwhile, TSP caused additional minor-phase traffic delay of 1.49 seconds per vehicle. The average passenger delay at 17th Avenue was reduced by 14%, which is statistically significant. Similarly, at 25th Avenue, TSP saved 43% of bus delay and 16% of major-phase traffic delay with costing extra 1.39 seconds per vehicle for minor-phase traffic. The average passenger delay saving is 12%, which is also statistically significant.

Table 3-5 Sensitivity analysis of passenger intersection delay (sec/pax)

Scenario	Number of pax	9^{th} Ave	12^{th} Ave	Barneson	17^{th} Ave	25^{th} Ave	27^{th} Ave	28^{th} Ave
Before	1	14.35	6.49	16.40	24.37	26.78	18.20	17.94
	5	14.71	6.72	16.62	24.83	26.96	18.47	18.18
	10	15.14	7.00	16.89	25.39	27.19	18.80	18.47
	15	15.57	7.27	17.15	25.93	27.42	19.13	18.76
	20	15.98	7.52	17.41	26.46	27.64	19.44	19.04
After	1	7.21	5.44	16.86	21.99	24.06	12.17	6.99
	5	7.14	5.35	16.70	21.99	24.10	12.22	7.05
	10	7.06	5.25	16.51	22.09	24.14	12.29	7.12
	15	6.98	5.15	16.32	22.19	24.19	12.36	7.20
	20	6.90	5.05	16.14	22.29	24.24	12.43	7.27
Change	-49.69%	-16.18%	2.80%	-9.77%	-10.16%	-33.19%	-61.04%	-49.69%
	-51.39%	-20.39%	0.48%	-11.44%	-10.65%	-33.84%	-61.22%	-51.39%
	-53.43%	-25.00%	-2.25%	-13.00%	-11.22%	-34.63%	-61.45%	-53.43%
	-55.17%	-29.16%	-4.84%	-14.42%	-11.78%	-35.34%	-61.62%	-55.17%
	-56.82%	-32.85%	-7.29%	-15.76%	-12.34%	-36.06%	-61.82%	-56.82%

One of primary incentives for TSP is that transit vehicles carry more passengers than other vehicles, so that giving priority to transit vehicles may reduce overall passenger delay. **Table 3-5** presents results of a sensitivity analysis to see how the number of passengers on buses affects overall passenger delay at intersections. Intuitively, more passengers on buses will lead to more significant reduction of overall passenger intersection delay. According to **Table 3-5**, Barneson Avenue has higher sensitivity than other intersections due to its relatively smaller traffic volumes. TSP would reduce the average passenger intersection delay if there are more than six passengers onboard. For the other six intersections, TSP operations would always reduce average passenger delay, largely due to the fact that existing semi-actuated signal control is less optimal and adaptive optimization of signal timing is always beneficial.

Chapter 4

A CENTRALIZED ATSP MODEL CONSIDERING GREEN BANDWIDTH

4.1 Expansion of ATSP to Consider Multiple Intersections

A TSP algorithm typically calculates what type and how much priority to provide for an approaching bus at an intersection. Observations from analyzing the TSP testing data that uses such an algorithm (a single intersection ATSP algorithm as described in Chapter 3) shows that sometimes, benefit from receiving priority treatment at an upstream intersection could be compromised if the bus has to stop at a downstream intersection. Thus, a multiple intersection algorithm is proposed for a stretch of intersections (defined as a number of continuous signalized intersections that are located along the same roadway and that are not interrupted by bus stops). The proposed algorithm determines the appropriate amount of priority for a bus at a stretch of intersections and it could be beneficial both for the bus and for traffic, because (1) for the bus, the priority could be given so that the bus could travel through the stretch of intersections smoothly without additional stops; and (2) for the traffic, it saves the unnecessary amount of priority for the bus, thus reduce the impact on traffic.

As illustrated in **Figure 4-1**, the TSP strategy which focuses on single intersection would provide the maximum priority at both of the two intersections and create the most negative impacts on other traffic. As a result, the bus still need to make two stops at both of the two intersections. In contrast for the same case, the TSP strategy which considers bus trajectory crossing multiple intersections might only provide the maximum priority at intersection #2, as illustrated in **Figure 4-2**, because anyway the bus cannot depart intersection #2 earlier than with the maximum priority. As a result, the bus experiences the

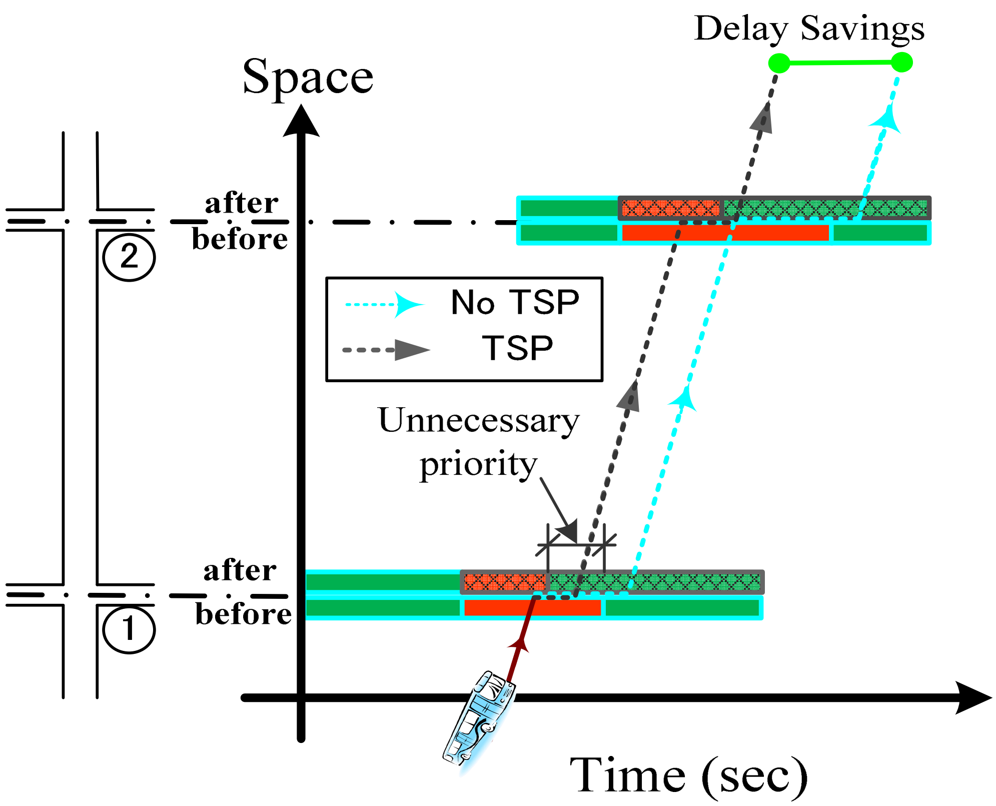


Figure 4-1 Unnecessary priority under single intersection algorithm

same amount of delay but reduces one stop at intersection #2. Meanwhile, there would be fewer impacts on other traffic because no priority was requested at intersection #1. Overall, it is a better result with less impact. Certainly, the difference between TSP for isolated intersections and for multiple intersections would not be the same when the bus arrives at different time. However, the TSP considering multiple intersections should at least perform no worse than the TSP for isolated intersections.

In this chapter, the development of an adaptive TSP strategy considering bus movement along multiple intersections is presented and discussed.

4.2 System Design

The proposed ATSP system consists of four major components: transit vehicle detectors, transit vehicle travel and dwelling time predictors, the priority request generator (PRG), and traffic signal controllers.

The transit vehicle detectors could be either the selective vehicle detectors (SVD) embedded at predetermined locations or the automatic vehicle location (AVL) system

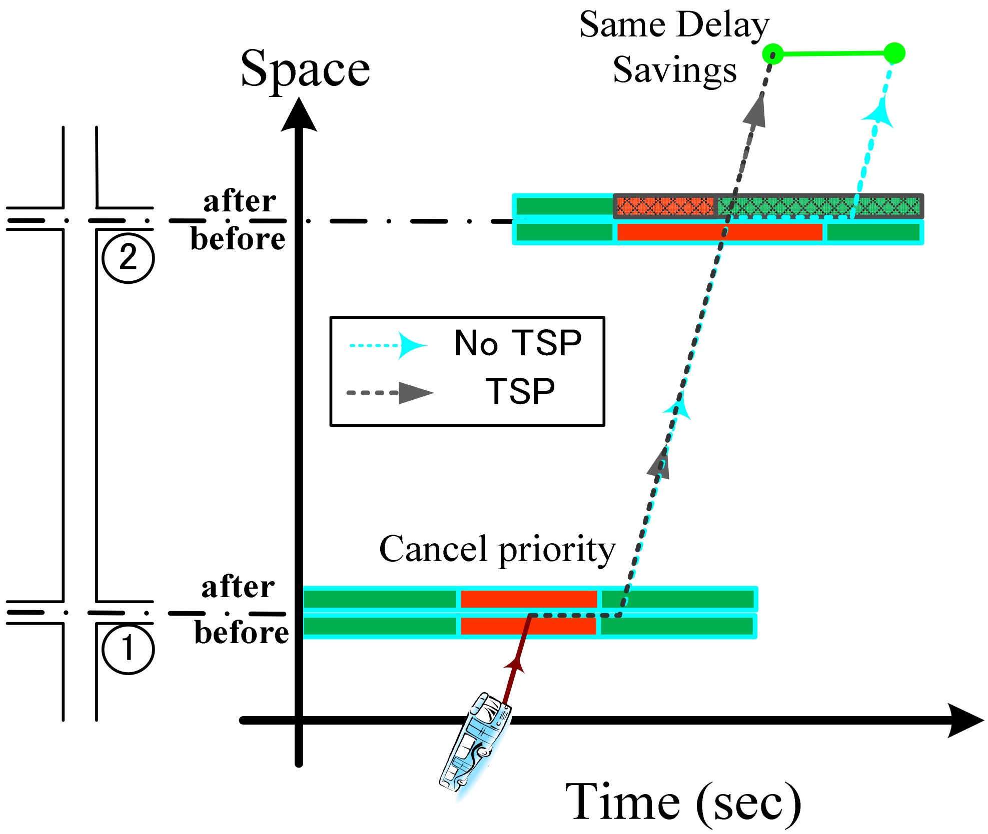


Figure 4-2 TSP considering bus trajectory crossing multiple intersections

installed on each transit vehicle. The distance or time to arrival at an intersection for priority triggering will depends on the nature of the signal control system. For example, the SDT system in downtown San Diego runs fixed-time control. All signal controllers are the 170 type using BITrans 223 control program. Such a system needs at most one cycle, which is 70 seconds, priori to transit vehicles' arrivals at an intersection in order to timely implement the TSP request.

In the PRG, the transit vehicles' route is divided into several independent sections, each of which starts from a station and ends at the downstream station. The intersections between two adjacent stations belong to one section. Within each section, three priority schemes are designed based on transit vehicles' schedule adherence:

- Scheme I: When a transit vehicle is running late, a timing optimization model and a time-to-arrival (TTA) predictor will be applied.
- Scheme II: When a transit vehicle is running early or on-time, a simple logic creates a narrow band for the transit vehicle's TTA.

- Scheme III: When no transit vehicle is going to approach in the next cycle, only the minimum green for pedestrians is provided along the trolley direction.

As shown in the system flow chart **Figure 4-3**, when no transit vehicle is to approach in the next cycle, scheme III with a set of fixed signal timings is applied. If a transit vehicle is detected, the PRG predicts the TTA at the downstream section through a travel time predictor and a dwelling time predictor. (The two predictors are developed separately under the SDT project). The PRG compares the transit vehicle's current location and time with its target schedule. If the transit vehicle is running early or on-time, scheme II with a simple logic creates a narrow band for the transit vehicle's TTA. For this scheme, PRG intends to minimize the traffic delay meanwhile guaranteeing a band that is wide enough to cover the transit vehicle's TTA. For a 68% chance of coverage, the bandwidth

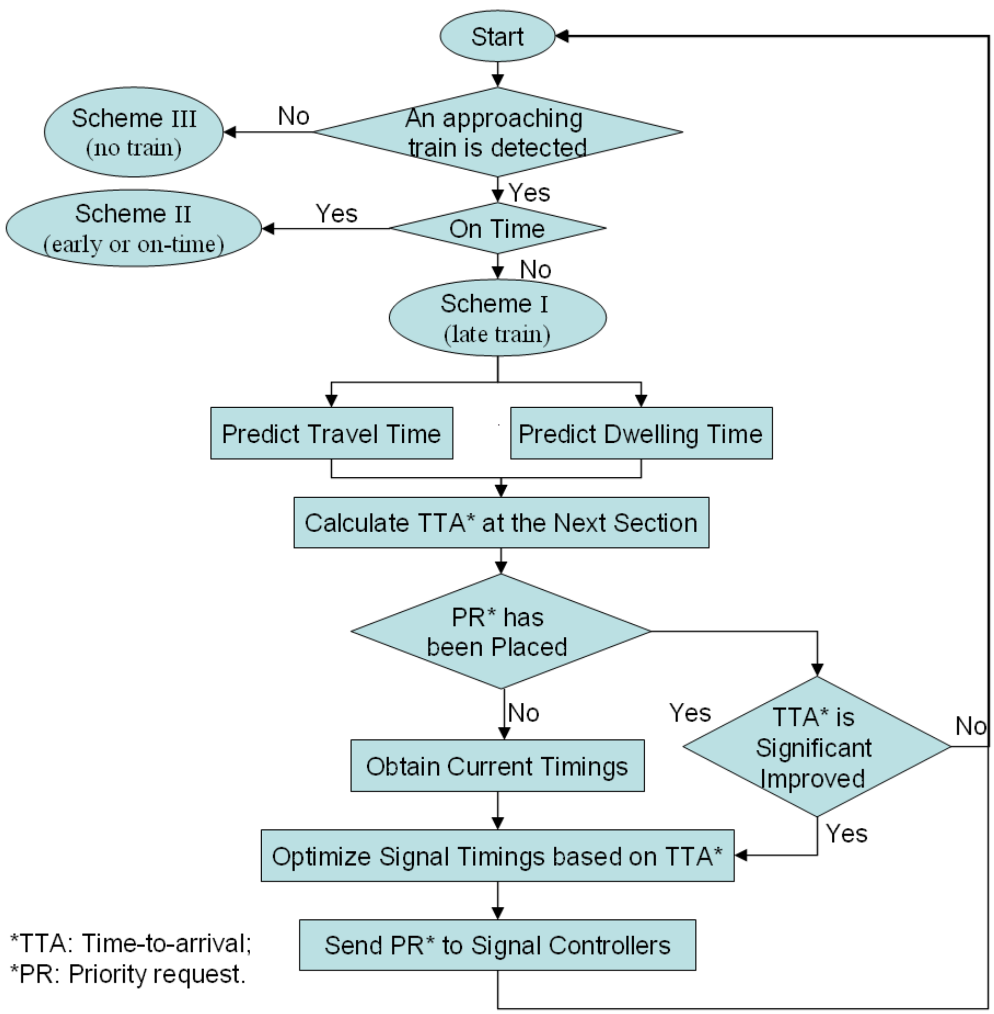


Figure 4-3 Flow chart for the ATSP model in PRG

would be double the length of the standard deviation of transit vehicles' historical travel time. When for a late transit vehicle is detected, scheme I with a signal timing optimization model, which will be particularly described in the following sections, will obtain current signal timings for intersections in the next section and optimize the timing plans based on the predicted TTA. Then the PRG will send optimized signal timings to the downstream signal controllers.

4.3 TSP Optimization Model

The objectives of this optimization model are two-fold: 1) to minimize intersection delays for trolleys by providing signal priority; and 2) to minimize impacts on other traffic. Unlike existing signal priority studies which typically focus on isolated intersections, the proposed model deals with multiple intersections signal timing plans to provide an optimized green band for an incoming transit vehicle. The optimized green band would start at the right time to cover the predicted transit vehicle TTA and should be wide enough to accommodate prediction errors. The proposed model adjusts green bands by changing signal offsets and green lengths.

Figure 4-4 illustrates the principle of the proposed model. Because of driver behaviors and other environmental factors, the transit vehicle's TTA at the first intersection of a section is a random variable. In the existing scenario, the mean of TTA falls into the red phase, and accordingly, the area of "transit vehicle delay free zone", which represents the probability that TTA falls within the green band, is relatively small. The optimized scenario presents the situation with the optimized green band. The start of green is moved backward by Δ^{offset} so that the new green band starting from B_{start}^{after} and ending at B_{end}^{after} covers a much wider "transit vehicle delay free zone" than that in the existing scenario. As a result, the expected transit vehicle delay is much smaller. Furthermore, G^{after} , the duration of the new green phase for the transit vehicle movement need not be as long as G^{before} . Thus, with a fixed cycle length, the duration of the green phase for cross traffic could be potentially increased. Using different weights on transit vehicle delays against traffic delays, the model can limit the incurred traffic delays.

Equations 4-1 to 4-15 present a mixed integer quadratic programming (MIQP) model. In the objective function, the first term is the total traffic delay. Traffic arrivals are assumed to be uniform. Following the aforementioned two-fold objectives, the second term should be the expected transit vehicle delay. However, the mathematical programming problem will be extremely hard to solve if a statistical function is built into the objective function. Therefore, the buffer width within the green band that accommodates TTA prediction error, $\gamma = 2\times\min(\mu^{TTA} - x_0, y_0 - \mu^{TTA})$, is used to represent the expected transit vehicle delay in the objective function, where x_0 and y_0 are the beginning and end of the band at the first intersection, respectively. Also, note that γ is a linear term which is inversely correlated to the expected transit vehicle delay. ω is the weighting factor which quantitatively represents the preference to transit over other traffic.

To minimize:

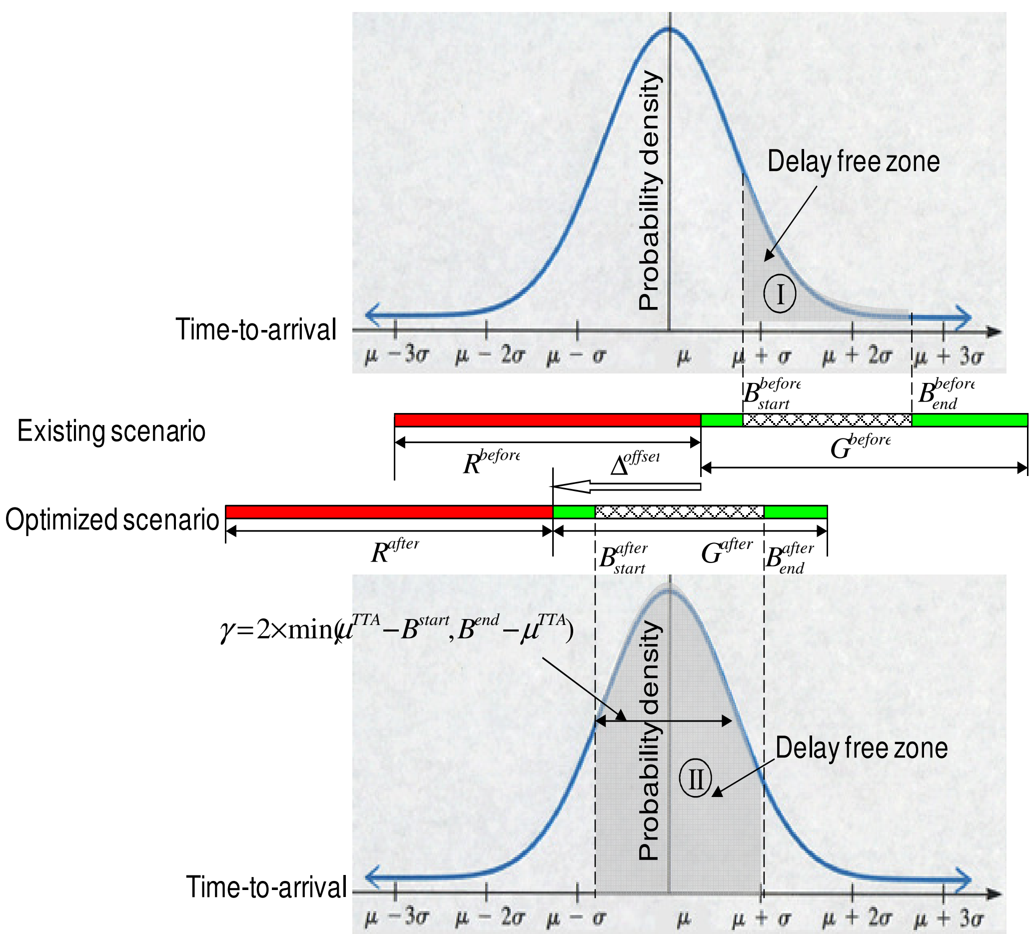


Figure 4-4 Principle of the proposed signal priority model

$$N_C \sum_{i=0}^{N} \sum_{j=1}^{M_i} \frac{\mu_{ij}\lambda_{ij}}{\mu_{ij}-\lambda_{ij}} \left(\frac{R_{ij}^2}{2}\right) - \omega(2 \times \min(\mu^{TTA} - x_0, y_0 - \mu^{TTA})) \qquad \textbf{Equation 4-1}$$

Subject to:

$$x_i = \frac{1}{S_0}(L_i - L_0) + x_0 \quad \forall i = 1, \dots, N \qquad \textbf{Equation 4-2}$$

$$y_i = \frac{1}{S_0}(L_i - L_0) + y_0 \quad \forall i = 1, \dots, N \qquad \textbf{Equation 4-3}$$

$$w_i = \frac{1}{S_1}(L_i - L_0) + w_0 \quad \forall i = 1, \dots, N \qquad \textbf{Equation 4-4}$$

$$z_i = \frac{1}{S_1}(L_i - L_0) + z_0 \quad \forall i = 1, \dots, N \qquad \textbf{Equation 4-5}$$

$$FDW_i + o_i - g_i + C \cdot n_{0i} \le x_i, y_i \le FDW_i + o_i + C \cdot n_{0i} \quad \forall i = 0, \dots, N \qquad \textbf{Equation 4-6}$$

$$FDW_i + o_i - g_i + C \cdot n_{1i} \le w_i \le FDW_i + o_i + C \cdot n_{1i} \quad \forall i = 0, \dots, N-1 \qquad \textbf{Equation 4-7}$$

$$FDW_i + o_i - g_i + C \cdot n_{1i} \le z_i \le FDW_i + o_i + C \cdot n_{1i} \quad \forall i = 0, \dots, N \qquad \textbf{Equation 4-8}$$

$$w_n = FDW_n + o_n - g_n + C \cdot n_{1n} \qquad \textbf{Equation 4-9}$$

$$O_i - \Delta^{\max} + C \cdot n_{2i} \le o_i \le O_i + \Delta^{\max} + C \cdot n_{2i} \quad \forall i = 0, \dots, N \qquad \textbf{Equation 4-10}$$

$$y_0 - x_0 \ge B_0^{\min} \qquad \textbf{Equation 4-11}$$

$$z_0 - w_0 \ge B_1^{\min} \qquad \textbf{Equation 4-12}$$

$$0 \le o_i \le C - 1 \quad \forall i = 0, \dots, N \qquad \textbf{Equation 4-13}$$

$$G_i^{\min} \le g_i \le G_i^{\max} \quad \forall i = 0, \dots, N \qquad \textbf{Equation 4-14}$$

n_{ji}, o_i, and g_i are all integers. $\forall i = 0, \dots, N$, and $\forall j = 0,1,2,3$ **Equation 4-15**

where, *C*: the cycle length;

ω: the weighting factor in the objective function;

N_C : the number of signal cycles impacted by the requested signal priority;

$N+1$: the total number of intersections within the section;

M_i: the total number of traffic movements at intersection *i*;

μ_{ij}: the cross street lane capacity at intersection *i* in the *j*-th movement;

λ_{ij}: the cross street traffic demand at intersection *i* in the movement *j*;

R_{ij}: the red clearance time at the *i*-th intersection for the *j*-th movement;

μ^{TTA}: the mean of TTA;

x_i: the beginning of the band for the transit vehicle of interest at intersection *i*;

y_i: the end of the band for the transit vehicle concerned at the *i*-th intersection;

w_i: the beginning of the band for the other bound at intersection *i*;

z_i: the end of the band for the other bound at the *i*-th intersection;

L_i: the relative distance of intersection *i* w.r.t. a reference point;

S_0: the speed of the transit vehicle of interest, $S_0 > 0$;

S_1: the speed of the transit vehicle of the other bound, $S_1 < 0$;

o_i: the offset of intersection *i* w.r.t. the Master Clock after performance;

O_i: the offset of intersection *i* w.r.t. the Master Clock before performance;

FDW_i: the flash-don't-walk time at the *i*-th intersection;

n_{ji}: the dummy integer variable which balances the gaps of signal offsets;

g_i: the green length of intersection *i* along the transit vehicle's direction;

$\Delta^{\max}$: the maximum offset change within a signal cycle;

$G_i^{\min}$: the minimum green length for g_i, i.e. the pedestrian walking time including the Flash Don't Walk time;

$G_i^{\max}$: the maximum green length for g_i;

$B_0^{\min}$, $B_1^{\min}$: the minimum bandwidths for the prioritized bound and the opposite bound.

Equation 4-2 to Equation 4-5 represent the relationship between sides of the green bands with transit vehicle floating speed and intersection distances; Equation 4-6 to Equation 4-9 mean that the band should lie within the green phase, and particularly, Equation 4-9 is a specific constraint for our application case for San Diego trolley system. It is noted that a general model does not have to have this constraint. It provides the opposite transit vehicle with a green band starting from the onset of green at the first intersection of the same section. Thus by following the current rule, the opposite transit vehicle can receive green lights at all of the downstream signals till it reaches the next station. Equation 4-10 guarantees the generated timing plans' applicability on existing signal control hardware. In this study for 170 signal controllers, the constraint guarantees that the signal transition can be completed within a signal cycle. As a result, it restricts the maximum offset change. Equation 4-11 to Equation 4-12 are the requirements for the minimum bandwidth for each direction. The wider bands provide higher tolerances for TTA variations. Equation 4-13 to Equation 4-14 are bounds for decision variables o_i's and g_i's, respectively.

The above model, which is labeled as the scenario I model deals with the cases when the green band can be moved to cover μ^{TTA}. However, the green band cannot always cover μ^{TTA} because of constraint Equation 4-10. For such cases, a scenario II model, with two minor changes from the Scenario I model, is defined. The first change, as shown in Equation 4-16, is in the second term of the objective function. In scenario II, the second term is the transit vehicle waiting time at the first intersection of the section if the transit vehicle arrives at μ^{TTA}. Moreover, for scenario II, the transit vehicle has a good chance to wait for the start of green. Then to avoid a second stop in the section, the start of green band for the transit vehicle's movement direction is moved to the onset of green at the first intersection, as shown in constraint Equation 4-17.

$$\begin{cases} \text{scenario I}: -\omega\left(2\times\min(\mu^{TTA}-x_0, y_0-\mu^{TTA})\right) & \text{if } x_0 \le \mu^{TTA} \le y_0 \\ \text{scenario II}: \begin{cases} \omega(x_0-\mu^{TTA}) & \text{if } \mu^{TTA} \le x_0 \\ \omega(C-\mu^{TTA}+x_0) & \text{if } y_0 \le \mu^{TTA} \end{cases} \end{cases}$$ **Equation 4-16**

$$x_0 = FDW_0 + o_0 - g_0 + C\cdot n_{00}$$ **Equation 4-17**

4.4 Case Study and Parametric Programming

4.4.1 Case Background

The San Diego Trolley (SDT) system has implemented passive priority in its downtown area for 15 years. The system works as follows:

- The trolley dwells in the station till the beginning of the next green light at the first downstream signal;
- The trolley departs within 5 second after the beginning of the green light;
- If the departure window is missed, the trolley must wait till the beginning of the next green light;
- As long as the trolley leaves the station during the departure window, it will receive green lights at all of the downstream signals till it reaches the next station;
- The two-phase, fixed-time signal timing favorable to the trolley is always in place (no matter the trolley is present or not) and is fitted into a larger network of signals.

The trolley priority system was proven to be successful in increasing the efficiency of trolley operations through downtown San Diego. Also, the system is a simple and easily implemented solution to the complex problem of accommodating motor vehicles, pedestrians and trolleys. However, some concerns regarding the system remain. First, significant transit vehicle delay is experienced if the transit vehicle's operator is not ready to depart the station during the initial green light. Second, there is no clear indication for the departure window and the trolley operator has to guess in borderline situations, thus sometimes misses the window and hit a red light before reaching the next station. Third, a transit vehicle waiting for the green light might block the following transit vehicle from entering the station platform. In even worse situations, the two transit vehicles could block one or more intersections and thus mess up the entire traffic flow. Finally, the passive priority strategy typically makes the overall intersection operation less efficient, in particular when traffic demand is high, because the signal setting still favors trolleys even if transit vehicles are not present. Therefore, an active priority system is indispensable to improve the efficiency of the whole system, including both trolleys and motor vehicles.

4.4.2 Model Application

The timing optimization model described in the previous section can be applied for TSP purpose to most signalized LRT or other transit crossings where transit has the exclusive or semi-exclusive right of way. For a better understanding and validation, the proposed priority system is applied to a particular case.

As shown **Figure 4-5**, a three-intersection-corridor between two San Diego trolley stations in downtown area is selected as the study case. For the southbound Blue Line trip, a train departs from the upstream Civic Center station, crosses 3rd Avenue, 4th Avenue, and 5th Avenue, and arrives at 5th Avenue station. The three intersections are controlled by

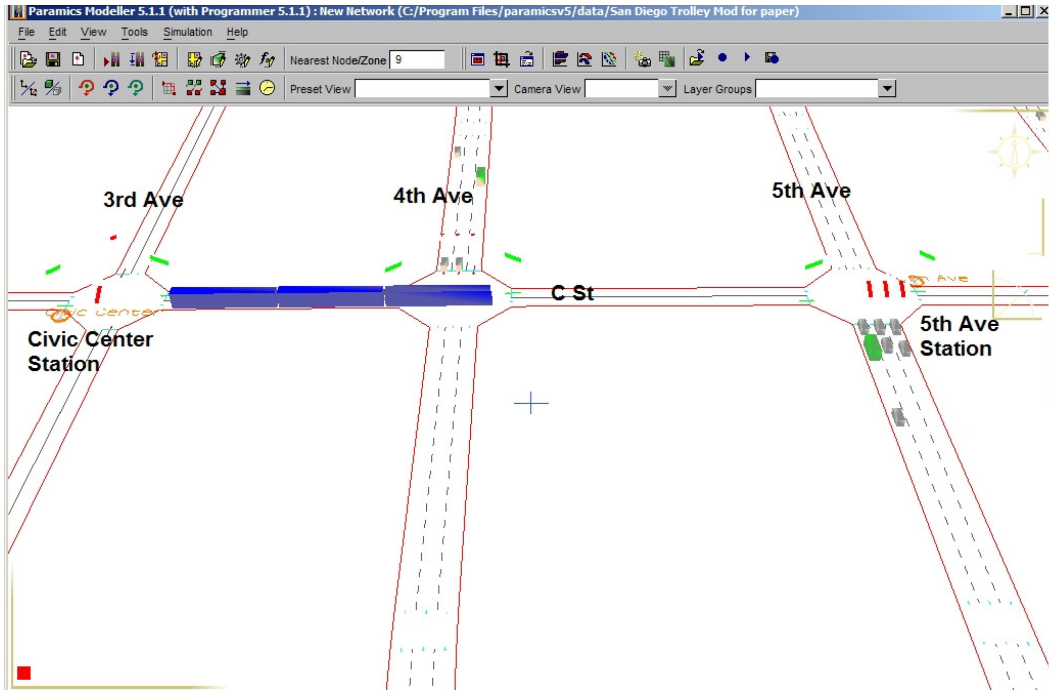


Figure 4-5 Case network at San Diego downtown area

BITrans 170 controllers in a coordinated fixed-time mode. The maximum offset change Δ^{max} for such 170 controllers is 20% of its signal cycle. From 5A.M. to 3P.M., the three signals run time-of-day plan #2 with the cycle length 70 seconds and two phases for trolleys and traffic respectively. The traffic along train tracks is ignored in delay calculation in this case because through traffic on those directions is prohibited.

As described in the previous section, bandwidths for transit approaches, instead of transit delays, are included in the objective function for the simplicity of the model and the ease of calculation. However, it is not appropriate to combine the bandwidth together with the traffic delay to measure the effectiveness of a signal priority model. Moreover, a major reason for transit vehicles priority is that transit vehicles typically have much higher occupancies, thus TSP has the potential to reduce the overall delays at intersections on a per person basis. Accordingly, the performance index (PI), which will be used to measure the model performance, is defined as the total intersection passenger delay. The passengers here refer to not only those on TSP favored transit vehicles but also those on other vehicles which are impacted by the priority.

To reflect the statistical property of train TTA, as illustrated **Figure 4-4**, the transit part of PI is the expected trolley passengers' intersection delay. The predicted TTA consists of two components: the trolley movement part and the station dwelling part. Based on the analysis of a great amount of trolley movement data, it is observed that, without the disturbances of traffic signals and train stations, train travel time between stations is a random variable with normal distribution. According to the collected train movement data at the example site, μ and σ for the dwelling time at 3rd Avenue station are 15.6 seconds and 5.53 seconds, respectively. Given that the longest transition period is one signal cycle, the trains need to be detected or the train travel time predictors need to be activated about 40 seconds or 318 meters away from 3rd Avenue station. Assuming the trains' dwelling time and travel time follow independent normal distributions, we calculate that μ^{TTA} and σ^{TTA} are 56.2 seconds and 7.78 seconds, respectively. According to **Figure 4-3**, the PRG is triggered when a late train is 318 meters upstream of 3rd Avenue station. The TTA gives long lead time and accurate prediction for the optimization model. Then model generates a set of optimized signal timings. Finally, the expected trolley passengers' intersection delay can be readily obtained by multiplying the expected train delay by the average number of on-board passengers, which is 84, according to the SDT system-wide annual survey for the past five years.

For the part of PI that represents the impact on traffic, the first term of Equation 4-1 depicts the total traffic delays within the impacted cycle. Under the assumption that the average occupancy per vehicle is 1.2 passengers, the traffic passengers' intersection delay can be readily obtained.

In the proposed optimization model, some parameters, such as ω, C, and $B_0^{\min}$, and $B_1^{\min}$, are arbitrary constants. The performance of the model is also subject to the choices of such parameters. Thus the parametric programming is needed to further optimize the model objective over the arbitrary parameter space.

For the SDT case, the cycle length C is 70 seconds. For the incoming southbound train, $B_1^{\min}$ is 7 seconds, which is a double of the standard deviation of northbound trains' historical travel time. Thus the arbitrary parameter space only has two variable dimensions, which are ω and $B_0^{\min}$. Given a combination of ω and $B_0^{\min}$, a set of optimal signal timings could be calculated based on a predicted TTA and the current signal timings. Assuming μ^{TTA} follows a uniform distribution, the average PI for each parameter pair $(\omega, B_0^{\min})$ can be calculated over $TTA \in [0, Cycle)$. As illustrated by **Table 4-1**, the PIs along each of the two dimensions have an obvious optimum point. Thus the classic local search method can be applied to search for the best parameter combination.

Table 4-1 Sensitivity analysis of passenger intersection delay (sec/pax)

$B_0^{min}=5$	ω		5	10	15	**20**	25	30	35	40	45	50
	PI*	Mean	2033.3	1598.5	1350.4	**1193.3**	1228.5	1217.0	1219.7	1219.6	1218.2	1219.9
		Std*	357.2	677.0	667.8	**570.7**	555.6	538.9	539.3	539.0	539.3	539.8
$\omega=20$	B^{min}		3	5	7	9	10	15	20	**25**	27	30
	PI*	Mean	1197.1	1192.9	1180.7	1157.8	1149.7	1077.7	1020.4	**973.9**	1001.3	1010.0
		Std*	587.9	570.2	667.8	495.7	479.7	386.4	332.4	**312.1**	353.0	351.4

Note:
PI*: performance index;
Std*: standard deviation.

As shown in **Table 4-1** and **Figure 4-6**, for the particular three-intersection case, the minimum average PI, when applying the existing cycle length 70 seconds, the existing offsets, and $B_0^{min}=5$, is 1193.3 seconds. The best ω when $B_0^{min}=5$ is 20. Then moving along the dimension of B^{min} at $\omega=20$, the minimum PI 973.9 is found when B_0^{min} is 25 seconds, as shown in **Table 4-1** and **Figure 4-7.** Therefore, based on the current signal

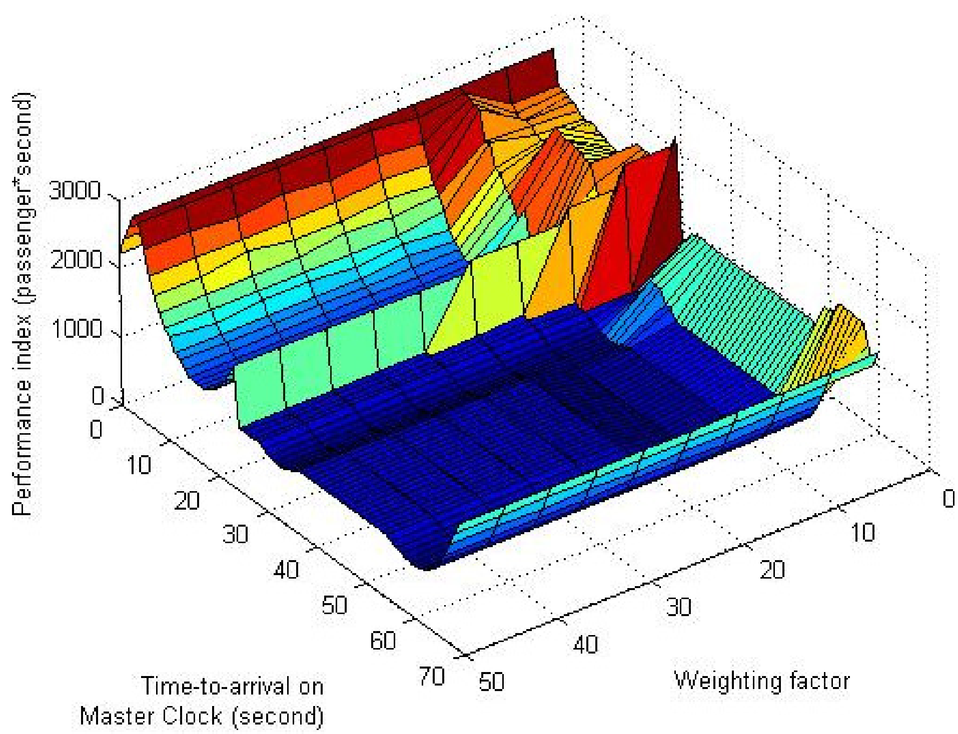


Figure 4-6 Model performance for ω from 5 to 50 and $B_0^{min}=5$

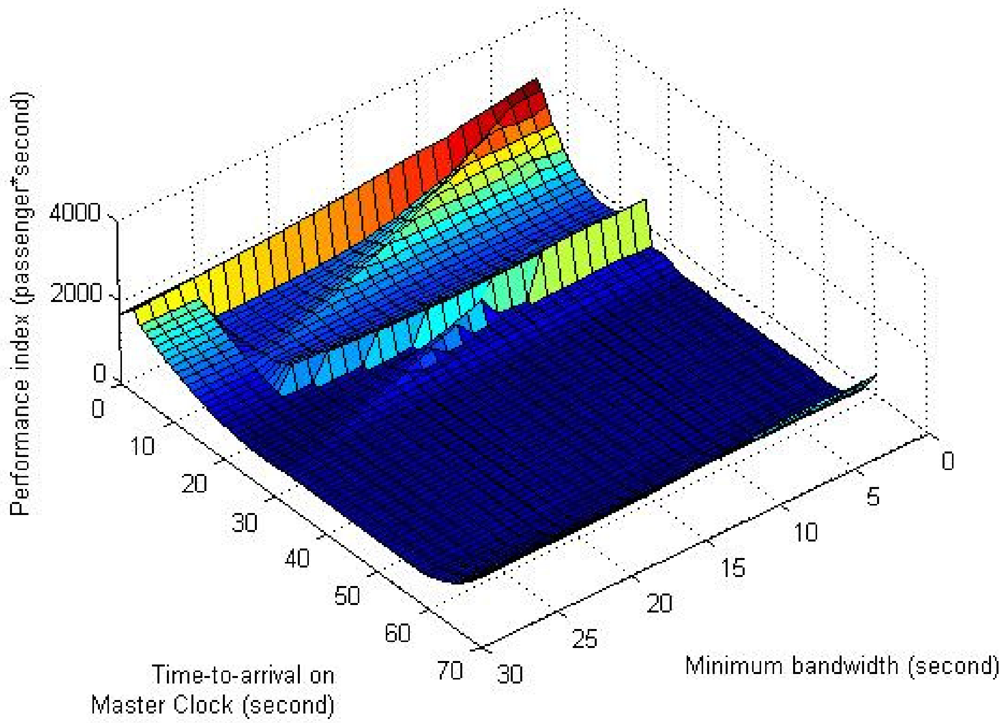


Figure 4-7 Model performance for B_0^{min} from 3 to 30 and $\omega = 20$

timings, the optimal arbitrary parameters are space $\omega = 20$ and $B_0^{\min} = 25$.

Figure 4-8 compares the total PI, which consists of the transit delay and the traffic delay, for the optimized scenario and the existing scenario. In the existing scenario, the traffic delay is constant because of the unchanged red time for traffic at these three intersections. The trolley delay in the total PI is the expected delay with respect to $\mu^{TTA}, \sigma^{TTA}, B_{start}^{before}, B_{end}^{before}$, as shown in **Figure 4-4**. Obviously, the farther μ^{TTA} is from the band, the higher expected trolley delay will be. Nevertheless, the expected values are not symmetric to the center of the band because a trolley will wait for a longer time when it just missed the band than when it arrived right before the band start. As shown in **Figure 4-8**, the solid curve reaches its nadir at 44 while the band is from 49 to 56. Furthermore, the dotted curve is below the solid curve no matter where the TTA is on the master clock. It means the proposed optimization model performs stably better than the existing scenario whenever trains arrive.

Table 4-2 compares the performance of the three proposed signal priority schemes with the existing scenario. Scheme I is applied when a late train is approaching. In this case,

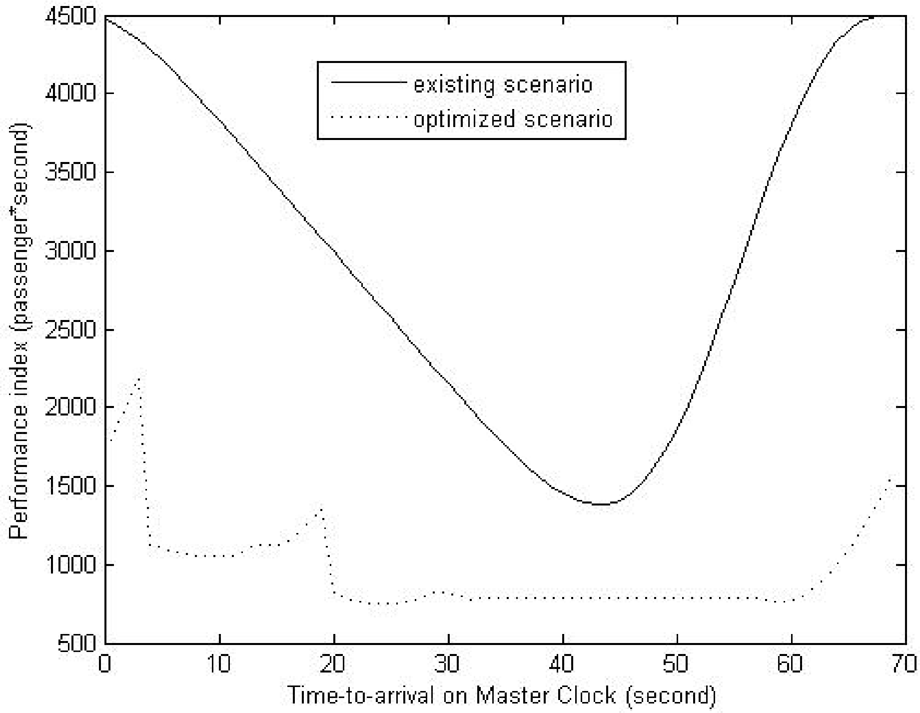


Figure 4-8 Comparison of PI for existing optimized scenario

signal priority is desired by the incoming train. By applying the proposed optimization model, the average trolley PI, which is the expected trolley passenger delay, is reduced enormously by 89.5%. Moreover, the standard deviation of trolley PI is reduced significantly by 68.6%, which means trolleys' travel time is more stable with the signal priority. Within the priority impacted cycles, the traffic delay is increased by 30.4%. So each traffic vehicle that arrives in the priority cycle will wait for 4.1 more seconds in exchange with 25.3 seconds delay savings for the trolley. The total intersection passenger delay is reduced by 66.8%. And its standard deviation is reduced by 70.8%. Scheme II is applied when an early or on-time train is approaching. For this scheme, the southbound and northbound bands are predetermined as 8 seconds and 7 seconds based on the trains' historical travel time. Similarly as scheme I, trains will receive green lights at all of the downstream signals till they reach the next station. The tighter but special designed band can save 32.5% of traffic delay for cross traffic, which is 4.4 sec/veh. Meanwhile, the average trolley delay is reduced by 67.5%, which is 19.1 sec/veh. Scheme III is applied when no train is approaching the section. In this case, only $G_i^{\min}$ for pedestrian is provided for the direction of train movement, so the traffic delay is minimized. The results show a 52.0% delay reduction from the existing scenario, which is 7.0 sec/veh. Based on the report from San Diego Trolley Inc. (SDTI), their on-time performance is higher than 90% in FY-

Table 4-2 Sensitivity analysis of passenger intersection delay (sec/pax)

				Trolley PI* ($pax \cdot$sec)		Traffic PI* ($pax \cdot$sec)	Total PI* ($pax \cdot$sec)		Vehicle Delay ($veh \cdot$sec)	
				Mean	Std*	Mean	Mean	Std*	Trolley	Traffic
Existing Scenario		Measures		2381.4	1068.0	555.7	2937.1	1068.0	28.3	13.5
Optimized	Scheme I	Measures		249.1	335.7	724.8	973.9	312.1	3.0	17.6
		Change	(sec)	**-2132.3**	**-732.3**	169.1	**-1963.2**	**-755.9**	**-25.3**	**4.1**
			(%)	**-89.5%**	**-68.6%**	30.4%	**-66.8%**	**-70.8%**	**-89.5%**	**30.4%**
	Scheme II	Measures		776.9	526.8	375.2	1152.1	526.8	9.2	9.1
		Change	(sec)	**-1604.5**	**-541.2**	**-180.5**	**-1785**	**-541.2**	**-19.1**	**-4.4**
			(%)	**-67.5%**	**-50.7%**	**-32.5%**	**-60.8%**	**-50.7%**	**-67.5%**	**-32.5%**
	Scheme III	Measures		0	0	266.6	266.6	N/A	0	6.5
		Change	(sec)	N/A	N/A	**-289.1**	N/A	N/A	N/A	**-7.0**
			(%)	N/A	N/A	**-52.0%**	N/A	N/A	N/A	**-52.0%**

Note:
PI*: performance index;
Std*: standard deviation.

2002, which means that a minority of trolley runs would require signal priorities. In such sense, scheme I can keep most trains running on-time, and then scheme II and scheme III, which are applied more frequently than scheme I, can provide lots of benefits to other traffic.

4.4.3 Simulation Tests

The simulation model, which was set up in PARAMICS, has been calibrated using field data. The proposed signal control algorithm is then implemented at three intersections, 3rd Ave through 5th Ave in San Diego downtown area. To illustrate the improvement obtained by applying our system, the existing trolley operation is reproduced in simulation. In the existing case, the green band starts at 49 sec and ends at 56 sec on the Master clock. Of the total 87 southbound trips during the period of 5:00 a.m. through 3:00 p.m. on a typical weekday, there are only six trips that travel through these three intersections without any stop. In the optimized scenario, as soon as the trolley leaves America Plaza station, the arrival time for this trolley at 3rd Ave is predicted. Meanwhile, the signal timings at 3rd Ave through 5th Ave are adjusted according to our control algorithm. In the optimized scenario, there are 74 out of 87 trips without any stops at these intersections. The errors in the prediction of arrival time, which is composed of the travel time and the dwelling time, account for the rest 13 trips. In addition, the predicted speed of the trolley is responsible for the simulation results. Obviously, the simulation results after optimization largely depend on the precision of the prediction. If the actual arrival time deviates too much from the predicted value or the aforementioned buffer width γ is too small, the trolley will miss the green band and wait until the signal light turns green.

Table 4-3 Simulation study results for existing and optimized scenarios

			Trolley PI* ($pax \cdot sec$)		Traffic PI* ($pax \cdot sec$)		Total PI* ($pax \cdot sec$)		Vehicle Delay ($veh \cdot sec$)	
			Mean	Std*	Mean	Std*	Mean	Std*	Trolley	Traffic
Existing	Measures		2339.4	1631.6	555.7	N/A	2895.2	1631.6	27.9	16.2
Optimized	Measures		546.1	1172.4	708.7	123.2	1254.8	1152.3	6.5	20.7
	Change	(sec)	-1793.3	-459.2	153	N/A	-1640.4	-479.3	-21.4	4.5
		(%)	**-76.7%**	**-28.1%**	27.5%	N/A	**-56.7%**	**-29.4%**	**-76.7%**	**27.5%**

Note:

PI*: performance index;

Std*: standard deviation.

Table 4-3 shows the comparison of simulation results between the existing scenario and the optimized scenario. The trolley PI decreases by as much as 76.7% if the proposed system is applied, although the traffic PI street traffic increases by 27.5%. By adjusting the weighting factor in our MIQP model, the cross street traffic delay can be limited. However, the time saved for trolleys will not be so noticeable.

Chapter 5

AN INTEGRATED CENTRALIZED ATSP MODEL CONSIDERING PEDESTRIAN DELAY

5.1 Multi-modal ATSP Systems

As described in Chapter 1, current traffic control strategies including TSP strategies tend to ignore the pedestrian delays that may be imposed by reducing vehicle delays. Such ignorance can lead to unnecessary long delays for pedestrians, dangerous behavior by impatient pedestrians, and potential reductions in pedestrian traffic and transit usages.

Li, M. et al. (2009) developed a traffic signal optimization strategy that considers both vehicular and pedestrian flows. The objective of the model is to minimize the weighted vehicular and pedestrian delays. The deterministic queuing model is used to calculate vehicular traffic delay and pedestrian delay on sidewalk. Pedestrian delay on crosswalk is calculated based on an empirical pedestrian speed model, which considers interactions of pedestrian platoons and their impacts on average walking speed.

The model was applied to a typical Japanese intersection as a case study. It is found that the proposed model can significant reduce pedestrian delay particularly when the phase for major vehicular flow conflicts with the phase for major pedestrian flow. The directional demand ratio (DDR) is defined as the ratio of either pedestrian demand or vehicular demand on the major vehicular approach over the pedestrian demand or vehicular demand on the minor vehicular approach. As shown in **Table 5-1**, the proposed model considering pedestrian traffic in the signal control can reduce average pedestrian delay (APD) by 4.1% when the pedestrian and vehicular traffic are both directional balanced. The average person delay (APRD) is calculated with 1.2 passengers per vehicle.

When the DDR for vehicles is 1.4, while DDR for pedestrian is 0.8, the longer phase serving major vehicular phase would cause major pedestrian traffic to be delayed. For this case, APD can be reduced by 29% by the proposed model.

Moreover, more pedestrian demand will be generated when more passengers shift the mode to take the transit service. With the purpose of promoting transit services, TSP should pay attentions on pedestrian flows and their delays.

5.2 Delay Model for Multiple-Intersection Algorithm

Chapter 4 describes a centralized ATSP model considering both green bandwidth for transit vehicles and the total vehicular delays. Because the units of green bandwidth and traffic delay are different. It creates significant difficulties in choosing the weighting factor in the overall objective function. Moreover, the design of the centralized model in Chapter 4 is appropriate for dedicated bus lane but might not fit for mixed-traffic situations. It is because the design of the dedicated green band for transit vehicles could greatly disrupt traffic flows.

Table 5-1 Signal Control with and without Considering Pedestrian Traffic

DDR*	MOEs	Existing Model	Proposed Model	Difference
Vehicles (1.0) Pedestrian (1.0)	APRD*	38.2	37.9	-0.3 (-1%)
	APD*	42.3	38.2	**-4.1 (-8%)**
	AVD*	35.4	35.8	+0.4 (+1%)
Vehicles (1.4) Pedestrian (0.8)	APRD*	43.6	37.3	-6.3 (-14%)
	APD*	59.1	42	**-17.1 (-29%)**
	AVD*	29.9	33.1	+3.2 (+11%)

Note:
DDR: directional demand ratio; APRD: average person delay; APD: average pedestrian delay; AVD: average vehicular delay.

In this chapter, the adaptive TSP strategy considers total weighted delay along multiple intersections and for all the subjects of transit vehicles, vehicular traffic and pedestrian traffic.

5.3 General Considerations and Assumptions

In order to facilitate the model formulation, the following consideration and assumptions are made about intersection geometry, traffic demands, and signal settings:

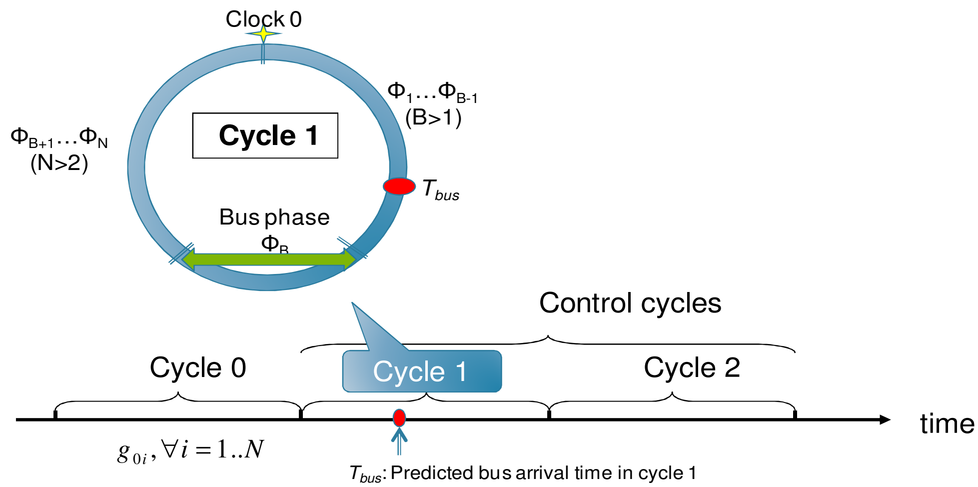


Figure 5-1 Control time horizon

- The model considers one single request at a time for a stretch of a few intersections between two adjacent bus stops;
- Traffic signals are coordinated, under fixed-timing control and under a fixed phase sequence;
- No phase can be skipped or shorter than its predefined minimum green;
- Pedestrian phase cannot be skipped because no pedestrian button or detections are in place;
- Buses start to generate TSP requests after getting off from a bus stop;
- Bus stops are far-side stops so there is enough lead-time for the first intersections to respond to the request;
- The model optimizes green splits for two cycles: the cycle with the bus arrival and the immediate following cycle, as shown in **Figure 5-1**;
- Green splits can be updated before the start of a cycle;
- If TSP request is generated, no residual queue would exist at the end of the second green since the bus arrival. It is noted that the number of cycle for transitions can be readily customized in the proposed model. However, the less number of cycles as control cycles the faster the system can get back from transition to be ready to serve the next request.

5.4 Model Inputs and Outputs

The input output diagram for the proposed system is shown in **Figure 5-2**. The inputs of the optimization model are predicted bus arrival time generated by an arrival time predictor (ATP), predicted short-term traffic demand if real-time traffic detection

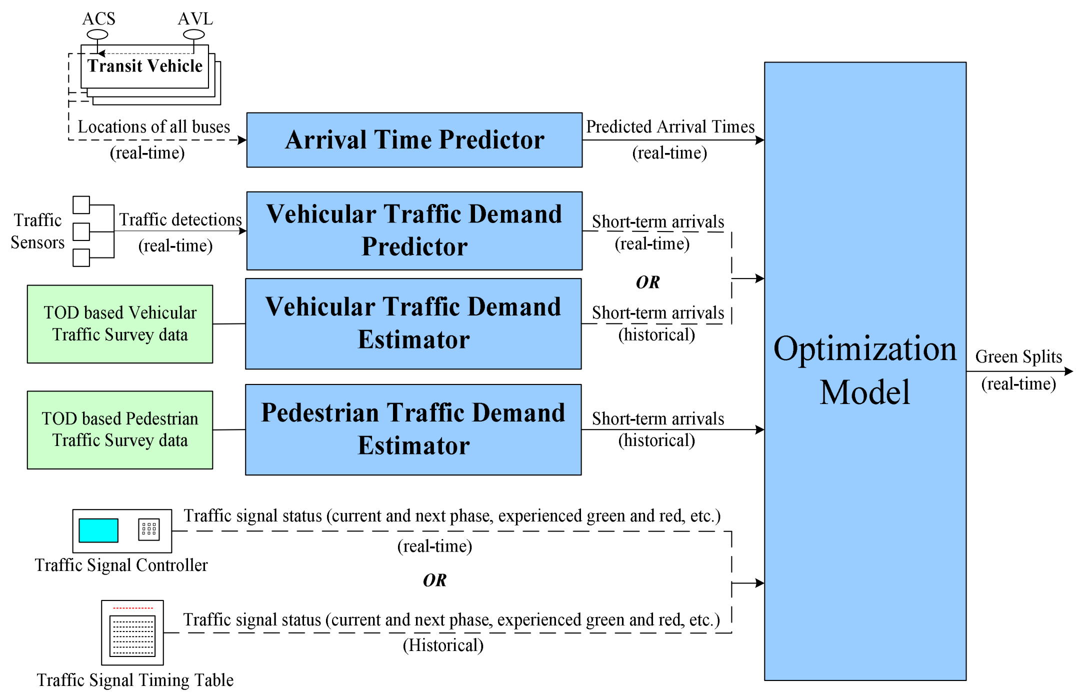


Figure 5-2 System input and output diagram

information is available, predicted short-term pedestrian demand if historical pedestrian demand information is available, static signal timing parameter (e.g. cycle length, minimum green, pedestrian green, and pedestrian flashing time), saturation flow rates which are invariant within a pattern typically defined by time of day.

The short-term traffic demand predictor is developed based on a simple moving-average algorithm. Given the real-time traffic detection information, cycle based traffic volumes are calculated for each approach. Four cycles are defined as a group. For each approach, the current traffic arrival rate is defined by the average of the arrival volumes in four most recent cycles. It is noted that the estimation interval can be shorter or longer than one cycle. When the estimation interval is one cycle, it implies that the traffic arrival within each cycle is uniformly distributed. Such assumption is not very accurate when considering the network effect. However in this study, we simplify the delay calculation by assuming uniform traffic arrival within each cycle.

The system outputs are simply the green splits for all existing phases. It is noted the model can also be applied to actuated control systems with the model outputs in the form of force-off points.

5.5 Model Formulation

The proposed optimization model consists of multiple objectives and a set of linear constraints as described below.

5.5.1 Decision Variables

Given the fixed phase sequence, each cycle has the same number of vehicular phases and pedestrian phases. The decision variables of the optimization model are $g_i^j, \forall i = 1,..,N_t; \forall j = 1,2$ and $g_i^{Ped,j}, \forall i = 1,..,N_{Ped}; \forall j = 1,2$, the vehicular and pedestrian green durations (splits) of all phase and for cycle j of the two consecutive control cycles, as shown in **Figure 5-1.** N_t and N_{ped} are number of traffic phases and pedestrian phases, respectively.

5.5.2 Objective Function

The propose adaptive TSP model has four objectives: bus delay, number of times bus stopped due to traffic signals, traffic delay, and pedestrian delay. For the multi-objective problem, there is no optimal approach to balance them all because the balance can be very political, policy and circumstance dependent. We take an approach to assign a weighting factor for each of the objective. The weighting factor is a relative number among various objectives, which also represents designers' relative preference on each objective. The integrated objective function for N_{signal} consecutive intersections is illustrated in Equation 5-1. It is noted that the relative weighting factor on bus delay over vehicular delay and pedestrian delay might also mean the policy priority or preference to shift more passengers from private vehicles to public transportation.

$$f_{objective} = \sum_{i=1}^{N_{signal}} (w_{bus} \cdot delay_i^{bus} + w_{stop} \cdot stop_i^{bus} + w_{traffic} \cdot delay_i^{traffic} + w_{ped} \cdot delay_i^{ped}) \qquad \textbf{Equation 5-1}$$

5.5.2.1 Bus Delay

The first objective is bus delay. It is similar with the bus delay model proposed in Chapter 4. The bus delay consists of signal waiting delay and queuing delay if there is any. As shown in **Figure 5-3,** a bus arrives at the signal at T_{bus} which reference to the beginning of the red duration for the bus phase. The queue clearance time is t_q, which is also reference to the beginning of the red phase.. Given the arrival flow rate λ_B and the saturation flow rate μ_B for bus phase, the queue clearance time can be calculated by Equation 5-2.

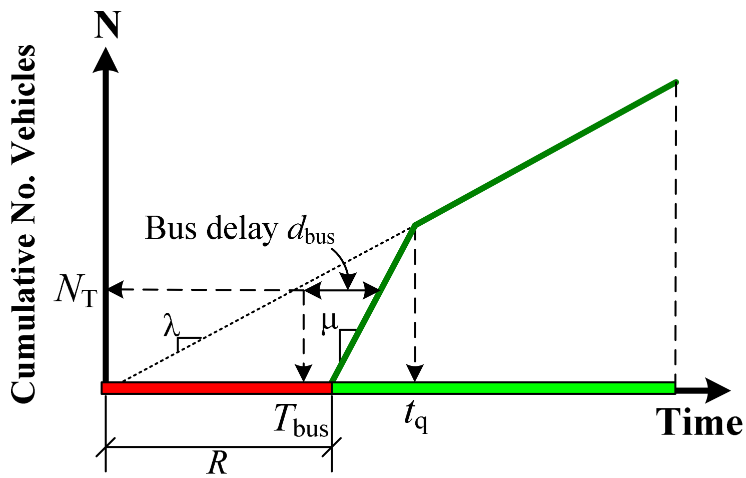


Figure 5-3 Idealized departure and arrival curves for the bus phase

$$t_q = \frac{\mu_B}{\mu_B - \lambda_B} \cdot R$$ **Equation 5-2**

From the triangle geometry of **Figure 5-3**, the relationship between total bus delay d_{bus} and the non-negative bus queuing delay $\max(t_q - T_{bus}, 0)$ can be expressed by Equation 5-3. Then, the bus delay can be calculated by using Equation 5-4, given the predicted arrival time T_{bus} from ATP.

$$\frac{d_{bus}}{R} = \frac{\max(t_q - T_{bus}, 0)}{t_q}$$ **Equation 5-3**

$$d_{bus}(T_{bus}) = \frac{R}{t_q} \max(t_q - T_{bus}, 0)$$ **Equation 5-4**

Equation (5-3) illustrates the bus delay when the bus is in mixed traffic scenario. However, some of the bus rapid transit (BRT) service also has the dedicated bus lane. It means buses are not impacted by the traffic queues. Thus bus delay is only the signal waiting delay, which can be calculated by Equation 5-5.

$$d_{bus}(T_{bus}) = \max(R - T_{bus}, 0)$$ **Equation 5-5**

When considering bus delay crossing multiple intersections, the model requires knowing the predicted bus arrival time when the bus is actually a few intersections away from the current intersection. The prediction with long lead time typically has large prediction error or flatter shape of probability density function. On the other hand, the function of bus signal delay given a bus arrival time is not continuous. At the point of bus phase turns red, there can be a huge difference for the bus signal delay around the point. Given a case when the expected bus arrival time is at the turning point, there is 50% of chance the bus would experience no delay but the half of chance the bus would experience significant long delay. The expected delay is still high combining the whole distribution. Because of the large deviation in the predicted bus arrival time, the reasonable method is to minimize the expected bus signal delay rather than the delay based only the expected bus arrival time.

Without loss of generality, it is assumed the bus travel time to the next signalized intersection follows a normal distribution $N(\mu, \sigma^2)$ as shown in **Figure 5-4**. In this case, the mean arrival time is projected in the red phase. In other words, the bus is most likely going to arrive in the red phase. It is impractical to directly incorporate probability density function (PDF), as shown in Equation 5-6,into the objective function because that would make the optimization model too hard to be solved. Some simplifications are needed to facilitate the calculations.

$$E(delay^{bus}) = \int_{-\infty}^{+\infty} \varphi_{\mu,\sigma^2}(u) \cdot d_{bus}(u)du = \int_{-\infty}^{+\infty} \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}} \cdot d_{bus}(u)du \qquad \textbf{Equation 5-6}$$

First, we discrete the continuous PDF function into K groups as shown in **Figure 5-5.** Each group has the same cumulative probability or the same area in the PDF plot. If we have five sub-groups, i.e. K=5, each group has the same cumulative probability, which is 0.2. The calculation of probability for group 2 (W_2) is shown in Equation 5-7. For each of the sub-group, we select a representative point $\mu - \beta_2\sigma$. The representative point divides the sub-group into two equal size areas, as illustrated by Equation 5-8. For group i,

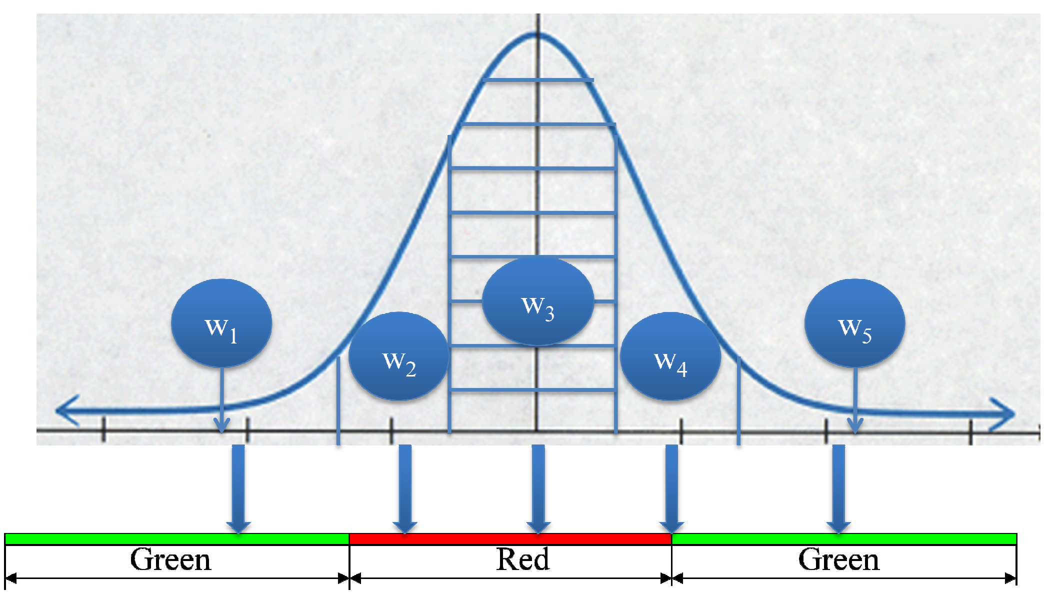


Figure 5-4 N-T diagram for bus phase

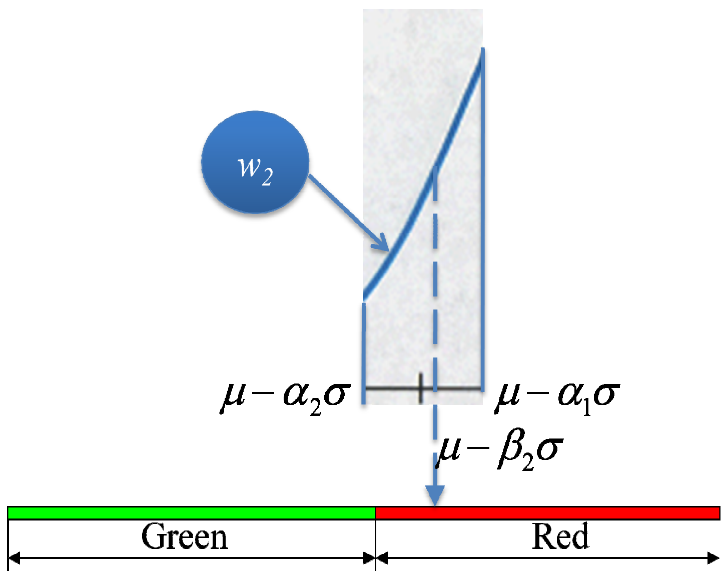


Figure 5-5 Discrete approximation of PDF

the cumulative probability from $-\infty$ to the representative point can be calculated by Equation 5-9. The inverse of error function can assist in calculating the parameter β_i, as illustrated by Equation 5-10 and Equation 5-11.

$$W_2 = \int_{\mu-\alpha_2\sigma}^{\mu-\alpha_1\sigma} \varphi_{\mu,\sigma^2}(u)du = 0.2 = \frac{1}{K} \quad \textbf{Equation 5-7}$$

$$\frac{W_2}{2} = \int_{\mu-\alpha_2\sigma}^{\mu-\beta_2\sigma} \varphi_{\mu,\sigma^2}(u)du = \int_{\mu-\beta_2\sigma}^{\mu-\alpha_1\sigma} \varphi_{\mu,\sigma^2}(u)du = \frac{1}{2K} \quad \textbf{Equation 5-8}$$

$$W_1 + \frac{W_2}{2} = \int_{-\infty}^{\mu-\beta_2\sigma} \varphi_{\mu,\sigma^2}(u)du = \frac{2}{K} - \frac{1}{2K} \quad \textbf{Equation 5-9}$$

$$\beta = probit(P) = \sqrt{2}\,\mathrm{erf}^{-1}(2P-1) \quad \textbf{Equation 5-10}$$

$$\beta_i = probit\left(\frac{i}{k} - \frac{1}{2K}\right) = \sqrt{2}\,\mathrm{erf}^{-1}\left(\frac{2i-1}{K} - 1\right) \quad \textbf{Equation 5-11}$$

If we continue with the discrete groups of arrival times, we would have an estimated delay $\hat{d}_{bus,i}^{j}$ and an estimated departure time at signal *j* for group *i*, as illustrated by Equation 5-12 and Equation 5-13, respectively. When considering the bus crossing *N* signalized intersections, the number of possible trajectories grows exponentially to K^N. It would create a significant burden on the optimization calculation and make the real-time operation impossible. Therefore, we need to further simplify the discrete approximation.

$$\hat{d}_{bus,i}^{j} = d_{bus}^{j}(\mu_j + \beta_i^j \sigma_j) \quad \textbf{Equation 5-12}$$

$$\widehat{dept}_{bus,i}^{j} = \mu_j + \beta_i^j \sigma_j + d_{bus}^{j}(\mu_j + \beta_i^j \sigma_j) \quad \textbf{Equation 5-13}$$

As shown in Chapter 2, the adaptive TSP relies on real-time location information from transit vehicles and real-time traffic information from traffic signal controllers. The optimization model as the core of PRG is able to correct its request based on the real time information until the beginning of the control cycle. At the beginning of the control cycle for signal *j*, the bus should not be very far from signal *j*. Therefore, we assume that the uncertainties in the travel time to signal *j*, when the bus needs to finalize the request, are mainly contributed by the variations of travel time from signal *j*-1 to *j*. In other words, we assume σ_j, the uncertainties of the arrival time to signal *j*, only depend on $\left(\sigma_j^{TT}\right)^2$, the variations of travel time between the upstream signal *j-1* to signal *j*, as shown in **Figure 5-6**.

The estimated bus trajectory crossing multiple intersections can be calculated by using $\hat{E}\left(delay_j^{bus}\right)$, the estimated expected delay as calculated by Equation 5-14, and μ_j,

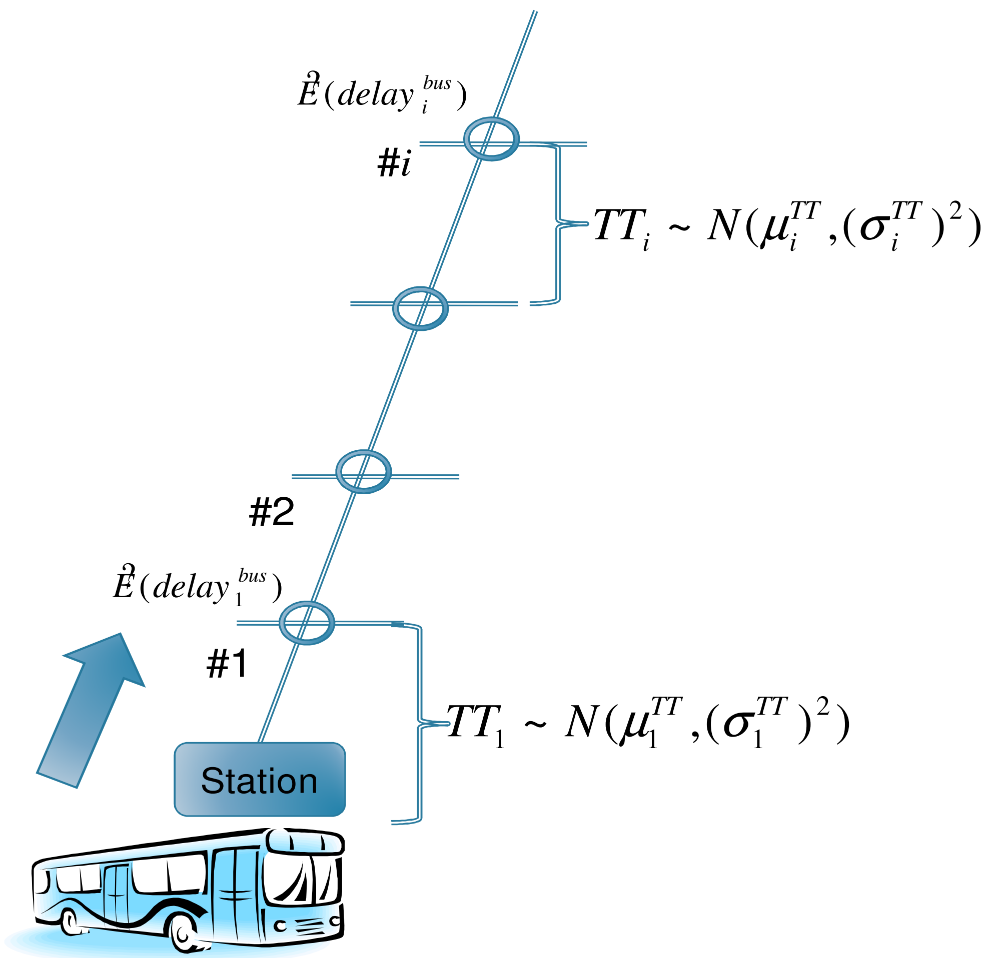


Figure 5-6 Uncertainties of bus travel time crossing multiple intersections

the expected departure time at signal *i*, as shown in Equation 5-15. For every stop, there is a constant time T^{stop} for buses to consider drivers' response time and acceleration time. $stop_j^{bus}$ is a binary variable to represent whether the bus is stopped at signal *j*.

$$\hat{E}\left(delay_j^{bus}\right) = \frac{1}{K}\sum_{i=1}^{K} d_{bus}(\mu_j + \beta_i^j \sigma) \qquad \textbf{Equation 5-14}$$

$$\hat{E}\left(departure_i^{bus}\right) = \mu_j + \hat{E}(delay^{bus}) + T^{stop} \cdot stop_j^{bus} \qquad \textbf{Equation 5-15}$$

5.5.2.2 Number of Stops for Bus Trips

When considering bus crossing multiple intersections, another important measure of effectiveness for the TSP system is the number of stops due to traffic signals. According to passenger surveys conducted in the United States, passengers actually prefer a continuous running trip rather than a high speed trip with many interruptions by traffic signal lights. In other words, the number of stops at traffic signals is actually more important than the average cruising speed to passengers' conformableness. Therefore, we also incorporate the number of stops for the bus trip into the objective function. We define the number of stops as the bus has more than 50% of chance to make a stop, i.e. experience positive delay, as shown in Equation 5-16.

$$\hat{E}\left(stop_j^{bus}\right) = \begin{cases} 1, & \frac{1}{K}\sum_{i=1}^{K} if(d_{bus}\left(\mu_j + \beta_i^j \sigma\right) > 0) > 0.5 \\ 0, & otherwise \end{cases} \qquad \textbf{Equation 5-16}$$

5.5.2.3 Vehicular Traffic Delay

Other than the benefits of TSP on the bus movements at traffic signals, we certainly need to balance the potential negative impacts on other vehicular traffic. We select vehicular traffic signal delay as the measure of effectiveness to examine the impacts on other vehicular traffic.

A classic deterministic queuing model is applied to predict delay at signalized intersection, as shown in **Figure 5-7**. For such model, it is assumed uniform traffic arrivals and vertical queues at the intersection stop line. It is known that the model may not accurately represent the exact number of queued vehicles at a given instant. However, the model does not bias the delay estimation process over an entire queue formation and dissipation process and works for both under- and over-saturated traffic conditions (Dion et al. 2004).

It is noted that the focus of the model is not on delay calculation model but the concept of quantitatively balancing TSP benefits and negative impacts on other traffic. The

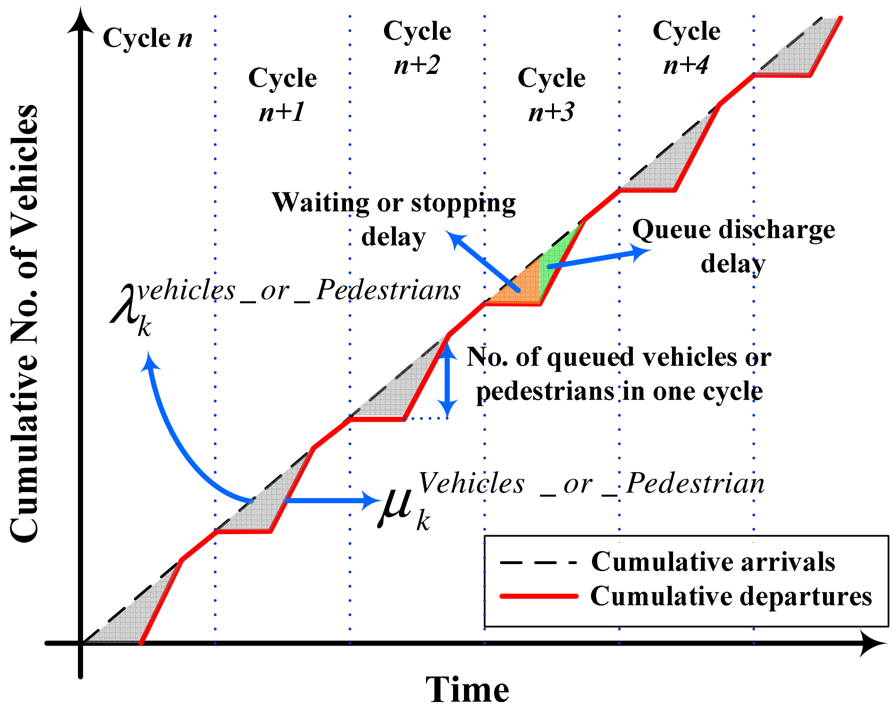


Figure 5-7 Idealized departure and arrival curves at a signalized intersection

model can actually relax the assumption of uniform arrival by either a scenario-based stochastic model (Yin 2008) to address the fluctuating traffic conditions or the data driven model (Li et al. 2009) to utilize the existing detection system upon closed-loop actuated control system.

In order to provide priority to transit vehicles, there have to be some negative impacts on other vehicular traffic. But how much the "price" should be paid for the TSP. In this model, we allow the approaches who suffer from TSP to be over-saturated for up to one cycle. In other words, the phases in the bus arrival cycle may have residual queue for one cycle. But the queues need to be cleared at the end of the following cycle, as shown in **Figure 5-8**. To compute traffic delay, we have two scenarios for each vehicular movement:

- Scenario I: no residual queue at the end of cycle 1
- Scenario II: residual queues exist in cycle 1 but not after cycle 2 (**Figure 5-8**).

According to the deterministic queuing model, traffic delays in cycle 0, 1, and 2 are calculated by Equation 5-17, which can be consolidated into Equation 5-18. It is noted that the overall impact on traffic delay by the TSP system should not be limited to the one

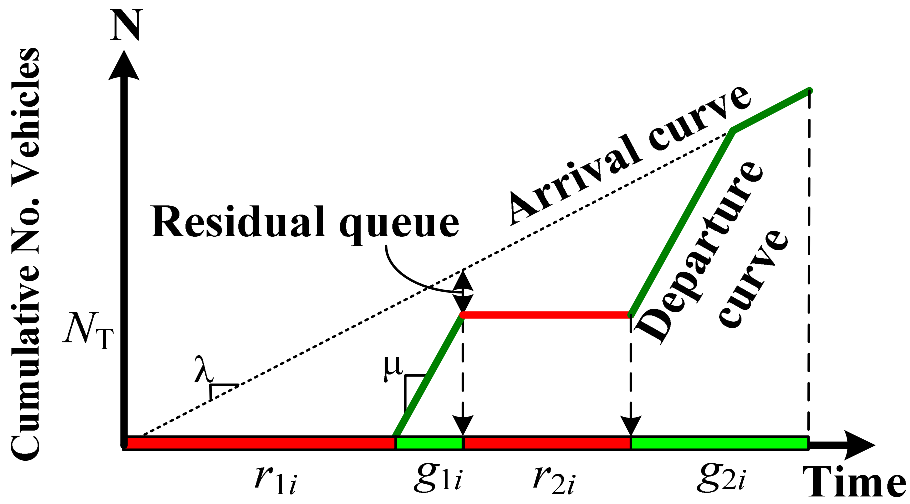


Figure 5-8 Scenario with over-saturation in control cycle 1

intersection. Because of the system coordination, the traffic along the coordinated directions might experience additional delay at adjacent intersections due to the timing changes at one intersection. This part of delay can be considered by using the aforementioned two approaches (Yin 2008; Li et al. 2009) and more information from traffic detections either in real-time or from history.

$$\begin{cases} \text{Scenario I}: d_i = \frac{\mu_i}{2}\rho_i r_{0i}^2 + \frac{\mu_i}{2}\rho_i ({r_{1i}}^2 + {r_{2i}}^2) \\ \text{Scenario II}: d_i = \frac{\mu_i}{2}\rho_i r_{0i}^2 + \frac{\mu_i}{2}\rho_i (r_{1i} + r_{2i})^2 - r_{2i}\mu_i g_{1i} \end{cases}$$ **Equation 5-17**

$$d_T = \sum_{i=1}^{8}[\frac{\mu_i}{2}\rho_i (r_{1i} + r_{2i})^2 - r_{2i}\mu_i \min(g_{1i}, \rho_i r_{1i}) + \frac{\mu_i}{2}\rho_i r_{0i}^2]$$ **Equation 5-18**

$$\text{Where: } \rho_i = \frac{\lambda_i}{\mu_i - \lambda_i}$$

5.5.2.4 Pedestrian Delay

Pedestrian delay is more complicated to compute than vehicular traffic delay because pedestrians are more active and do not form a well-organized queue as vehicular traffic does in their lane. The experienced delay by pedestrians can be divided into two parts. The first part is the experienced delay before stepping down from the sidewalk. It consists of waiting delay for green signal and discharging delay for standing pedestrian queue on sidewalk. The other part is the experienced delay while crossing the crosswalk. This delay results from the interaction between opposing pedestrian flows on the crosswalk and it is significant when pedestrian demand is high.

The waiting and discharging processes by pedestrians on sidewalk are similar with what happens to vehicular traffic before discharging from the intersection stop-line, as shown in **Figure 5-7** Therefore, the pedestrian delay on sidewalk can be calculated by using Equation 5-19. It is noted that the effective green for pedestrian phase does not include the pedestrian flash warning time because it is assumed that all pedestrians would stop stepping down from the sidewalk when the warning sign starts to flash.

$$delay_i^{PedSW} = \sum_{i=1}^{8}[\frac{\mu_i^P}{2}\rho_i^P(r_{1i}^P + r_{2i}^P)^2 - r_{2i}^P\mu_i^P \min(g_{1i}^P, \rho_i^P r_{1i}^P) + \frac{\mu_i^P}{2}\rho_i^P(r_{0i}^P)^2]$$

Equation 5-19

where: $delay_i^{PedSW}$ is the total pedestrian delay on sidewalk for pedestrian phase i; μ_k^P, λ_k^P and ρ_k^P are saturation flow rate, arrival flow rate and flow ratio for pedestrian movement k, g_{ji}^{Ped} and r_{ji}^{Ped} are effective green and red for pedestrian phase i and cycle j.

The pedestrian delay on crosswalk is due to the interaction of pedestrian platoon with the opposing pedestrian platoon. According to Alhajyaseen, et al. (2009), the pedestrian walking speed can be significantly dropped due to the size of the opposite platoon, crosswalk width and some other factors. In order to simplify our model without losing much of the accuracy, we assumed that all pedestrians on the same movement walk with an average speed $\bar{v}_k^{Ped}$ for the whole crosswalk. Thus, the pedestrian delay on crosswalk can be calculated by using Equation 5-20. The model developed by Alhajyaseen, et al. (2009) is utilized to estimate $\bar{v}_k^{Ped}$, the average speed of the subject pedestrian flow, as shown in Equation 5-21. It shows that the crossing speed of subject pedestrian platoon is function of crosswalk geometry, pedestrian demand at each side of the crosswalk and free-flow speed.

$$delay_i^{PedCW} = \sum_{k=1}^{N_i^{Ped}} \lambda_k^{Ped} \cdot \left(C - g_i^{Ped} + t_k^q\right) \cdot L_i \cdot \left(\frac{1}{\bar{v}_k^{Ped}} - \frac{1}{V_{FF}^{Ped}}\right)$$

Equation 5-20

Where: $t_k^q = \frac{\lambda_k^{Ped}}{\mu_k^{Ped} - \lambda_k^{Ped}}(C - g_i^{Ped})$

$$\bar{v}_k^{Ped} = \sqrt{\left(V_{FF}^{Ped}\right)^2 - \frac{0.02P_j \cdot \left(\frac{P_k}{P_k + P_j}\right)^{0.791} \cdot \left(V_{FF}^{Ped}\right)^2 \cdot L_i}{W_k^{CW}}}$$

Equation 5-21

Where: $P_k = \lambda_k^{Ped} \cdot (C - g_i^{Ped} + t_k^q)$

and $P_j = \lambda_j^{Ped} \cdot (C - g_i^{Ped} + t_j^q)$

where: $delay_i^{PedCW}$ is the total pedestrian delay on crosswalk for pedestrian in phase i; t_k^q is the queue discharging time for pedestrian in phase i and it is estimated according to Equation 5-20; L_i is the length of crosswalk for pedestrian phase i; $\bar{v}_k^{Ped}$ is the average walking speed for pedestrian movement k; V_{FF}^{Ped} is the free flow walking speed and is assumed as 1.45*m/s* in this study. W_k^{CW} is crosswalk width for pedestrian movement k; P_k and P_j are the subject and opposite pedestrian demands on the same crosswalk in phase i.

5.5.3 Model Constraints

In order to generate reasonable signal timings, our model has to satisfy some constraints. There are four sets of constraints: 1) minimum and maximum green splits for vehicular phases and pedestrian phases, 2) the relationship between vehicular green and pedestrian green, 3) fixed cycle length constraint, and 4) under-saturation constraint at the end of control cycles.

5.5.3.1 Minimum and Maximum Green Durations

Generally speaking, traffic signal timings have the constraints on minimum green and maximum saturation degrees. We applied the same constraints on pedestrian green. According to Manual of Traffic Signal Control-JMTSC (Japan Society of Traffic Engineers 2006) and Japanese practices, the minimum pedestrian time T_i^{PedMin} is defined as the sum of pedestrian green g_i^{Ped} and flash warning time FW_i^{Ped}, as shown by Equation 5-22. T_i^{PedMin} is a function of pedestrian free flow walking time, pedestrian demand P_k, saturation flow μ_k^{Ped} and crosswalk width W_k^{CW} for movement k. JMTSC defines FW_i^{Ped} as the walking time for half of a crosswalk. It is because pedestrians who fail to pass the mid-point of crosswalk when warning starts to flash suppose to come back although very few people actually follow this rule. Given Equation 5-20~ Equation 5-23, the minimum pedestrian green can be obtained by Equation 5-24 with the flow parameter ρ_k^{Ped} defined by Equation 5-25.

$$g_i^{Ped} + FW_i^{Ped} \geq T_i^{PedMin} = \frac{L_k}{V_{FF}^{Ped}} + \frac{P_k}{\mu_k^{Ped} \times W_k^{CW}} \quad \textbf{Equation 5-22}$$

$$FW_i^{Ped} = \frac{L_k}{2V_{PW}} \quad \textbf{Equation 5-23}$$

$$g_i^{Ped} \geq \frac{1}{W_k^{CW} + \rho_k^{Ped}} \left(\frac{W_k^{CW} \cdot L_k}{2V_{FF}^{Ped}} - \rho_k^{Ped} \cdot C\right) \quad \textbf{Equation 5-24}$$

$$\rho_k^{Ped} = \frac{\lambda_k^{Ped}}{\mu_k^{Ped} + \lambda_k^{Ped}} \quad \textbf{Equation 5-25}$$

It is noted that the minimum pedestrian green can be different for different countries under their own manuals of traffic signal control. For example in the United States, the manual on uniform traffic control devices (MUTCD) and highway capacity manual (HCM) defines a four to seven seconds interval for pedestrian green which depends on pedestrian demand. There is no quantitative method to calculate such green duration for pedestrians in US.

5.5.3.2 Relationship between Vehicular Green and Pedestrian Green

Another constraint of the model is the relationship between vehicular traffic green and pedestrian green. As shown by Equation 5-26, the green plus flashing warning time for pedestrian phase i should not longer than the duration of the corresponding vehicular traffic through phase i.

$$g_i \geq g_i^{Ped} + FW_i^{Ped}$$ **Equation 5-26**

5.5.3.3 Fixed Cycle Length

Regarding to the fixed cycle length, the sum of all vehicular traffic greens together with the yellows and all-reds is the cycle length C, as illustrated in Equation 5-27.

$$\sum_{i=1}^{N}(g_i + Y_i + AR_i) = C$$ **Equation 5-27**

5.5.3.4 Under-saturation for Vehicular Traffic and Pedestrian Traffic

If the TSP request is generated, no residual queues would be left over after the end of control cycle 2. Equation 5-28 and Equation 5-29 illustrate the two constraints from vehicular traffic movement and pedestrian traffic movement, respectively. Moreover, control cycle needs to be under-saturated, as illustrated by Equation 5-30 and Equation 5-31; otherwise longer green might be assigned to the first cycle to left residual queue at the end of control cycle 2.

$$\frac{2\lambda_i \cdot C}{\mu_i \cdot \left(g_j^1 + g_j^2\right)} \leq 1$$ **Equation 5-28**

$$\frac{2\lambda_i^{Ped} \cdot C}{\mu_{i^{Ped}} \cdot \left(g_j^{Ped,1} + g_j^{Ped,2}\right)} \leq 1$$ **Equation 5-29**

$$\frac{\lambda_i \cdot C}{\mu_i \cdot g_j^2} \leq 1$$ **Equation 5-30**

$$\frac{\lambda_i^{Ped} \cdot C}{\mu_{i^{Ped}} \cdot g_j^{Ped,2}} \leq 1$$ **Equation 5-31**

Under this constraint, the TSP system would not able to find any feasible solution when traffic condition is consistently over-saturated. As a result, the adaptive TSP system would not generate TSP request to make traffic condition even worse.

5.6 Measures of Effectiveness (MOEs)

The definition of measures of effectiveness (MOEs) is essential when evaluating the system performance. It can also represent the preference for designers, planners, engineers and managers. In this study, eight major MOEs are defined: bus trip time, BTT (*sec*), total bus delay BSD (*sec*), total number of stops that the bus made due to signals BNS, average vehicular delay AVD (*sec/veh*) and AVD on bus phase and non-bus phase as AVD(B) (*sec/veh*) and AVD(NB) (*sec/veh*), respectively, average pedestrian delay APD (*sec/ped*), and average person delay APRD (*sec/per*).

Although the decision variables for the optimization model are green durations for two control cycles, the red durations have actually been changed for three consecutive cycles since the beginning of control cycle 1. Because the average traffic delay depends on the length of red duration, the defined delay MOEs, i.e. AVD, APD and APRD, are calculated over the period of three cycles.

5.7 Numerical Model Application

In order to demonstrate and evaluated the system performance, the proposed model was firstly applied to the Key Route Bus System (KRBS) in Nagoya, Japan.

5.7.1 Site Description

Nagoya metropolitan region is the third largest populated urban region in Japan. The total population of the city in 2006 was 2.22 million in an area of 326 km^2. The total road surface in the city center is approximately 40% of the total central area, making Nagoya the "the city of wide roads" in Japan. The public transport service in the city is provided by suburban railways, subways and busses (including BRT systems). The total length of subway is 89.1 km and buses are operating on a network with approximately 700 km in length.

KRBS was first proposed as a bus rapid transit (BRT) system in 1979 by a planning committee established by many experts and researchers as a very important policy for the improvement of transportation system in the city. The speed and the punctuality of bus systems got significantly worsen in the late 1970s due to rapid motorizations. Therefore separate bus lanes were designed to provide effective solution to the increase of level of services of the bus systems

In 1982, the first section of the KRBS No. 1 named as "Toko Line" was opened. Totally 15 bus stops were selected from existing 24 stops for Toko Line. Because the central part of this street had already been occupied by pillars of the elevated expressway, the curbside bus lane was implemented as illustrated in **Figure 5-9**. Some of the characteristics of KRBS were specified as: 1) Exclusive bus lanes on the curbside; 2)

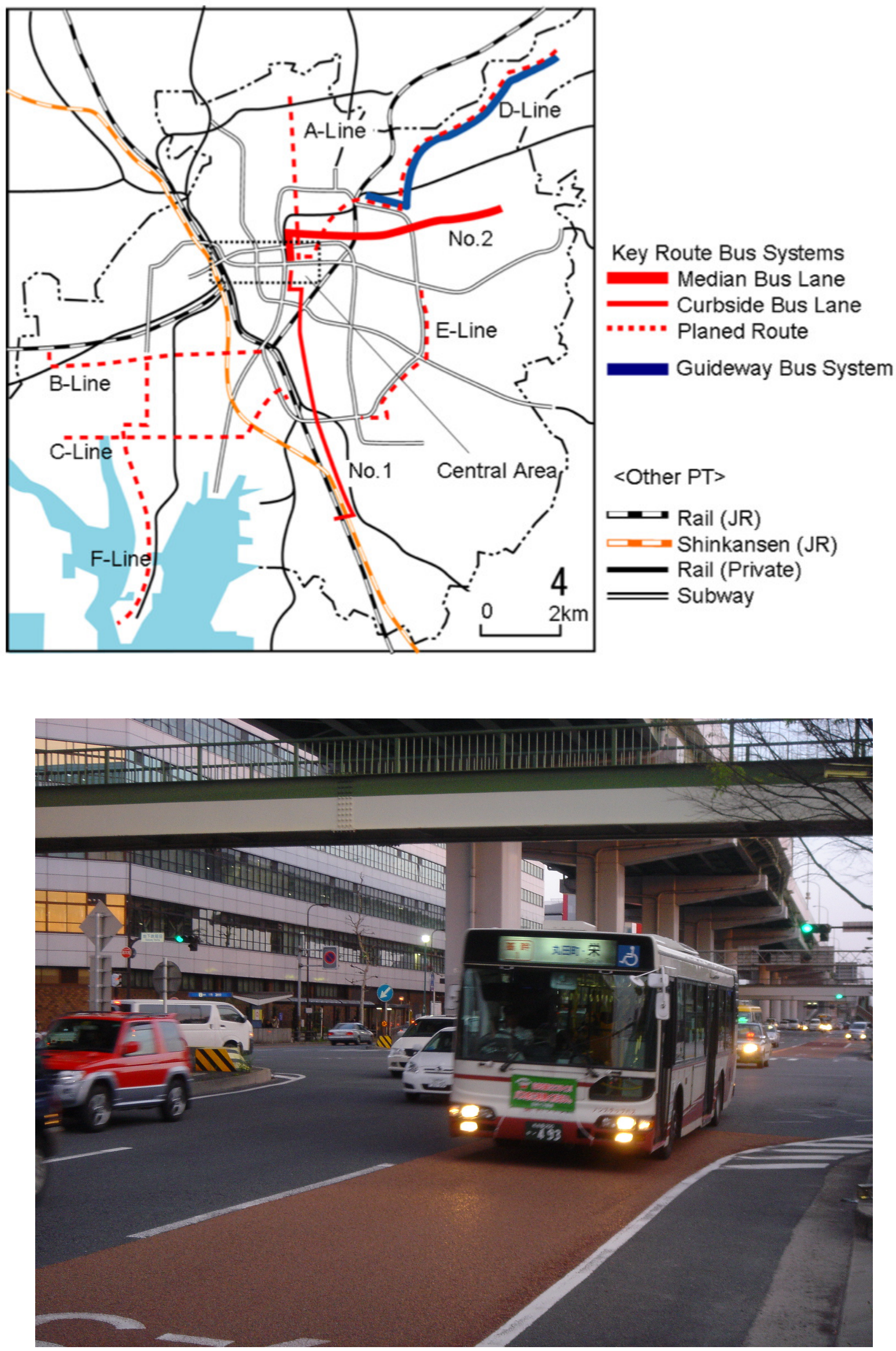


Figure 5-9 Key Route Bus System with curbside dedicated bus lane

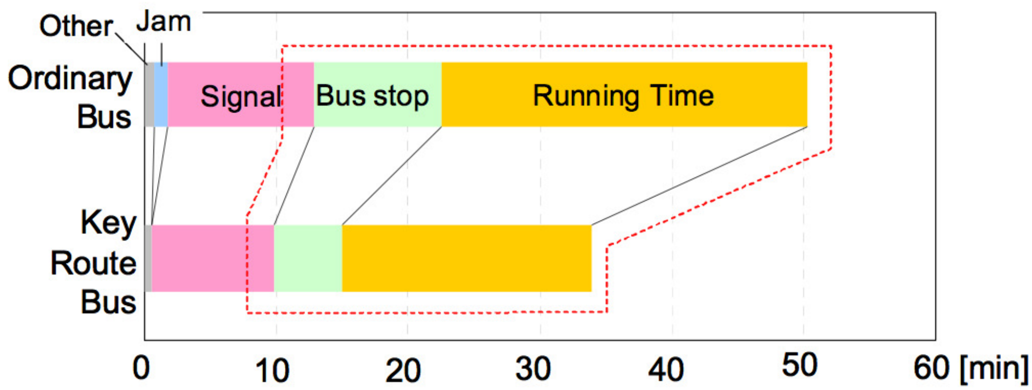


Figure 5-10 Allocations of improvements on KRBS's trip travel time

(Source: Nagoya City Office 1986)

Longer space distance between bus stops; and 3) Expedience fare collection system.

With all the improvement, the BRT system was able to increase the operational speed from 13.0 km/hr to 17.0 km/hr by over 30% (Takeshita et al. 2009). **Figure 5-10** shows the source of the improvement on the operational speed. According to the speed survey conducted by the Nagoya City Office (1986), the average running time was reduced by about 30% due to the dedicated bus lane; while the average stopping time were well shortened by more than 40% through decreasing the number of bus stops and expanding stop spatial intervals. However, the average delays at signalized intersections were barely improved.

The reduction on bus delay at signalized intersections has great potential to further improve the operational speed for KRBS. According to **Figure 5-10**, the signal delay is actually more than 27% in the total trip time. With reasonable improvement by transit signal priority, the total trip travel time for KBRS can potentially has a significant improvement. Among the reasons that a TSP system has not been implemented yet, the negative impact on other traffic is the most concerned. It is exactly what an adaptive TSP system can possibly provide.

5.7.2 Field Data Collection

For the demonstration of the system performance, we selected one of the busiest stretches of the route as the testbed, which is between two adjacent bus stops: Meitetsu Horita station and Chikatetsu Horita station, as shown in **Figure 5-11**.

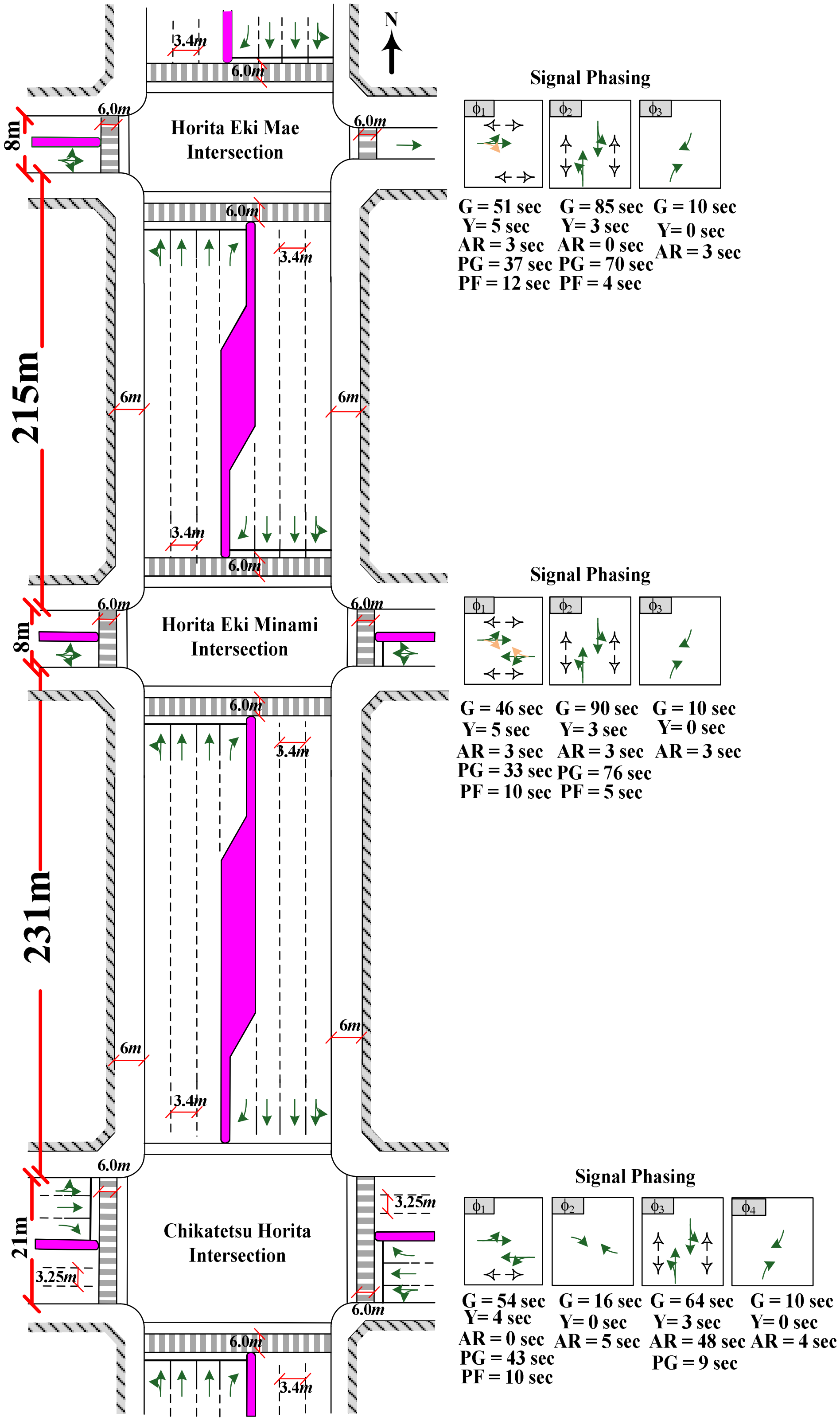


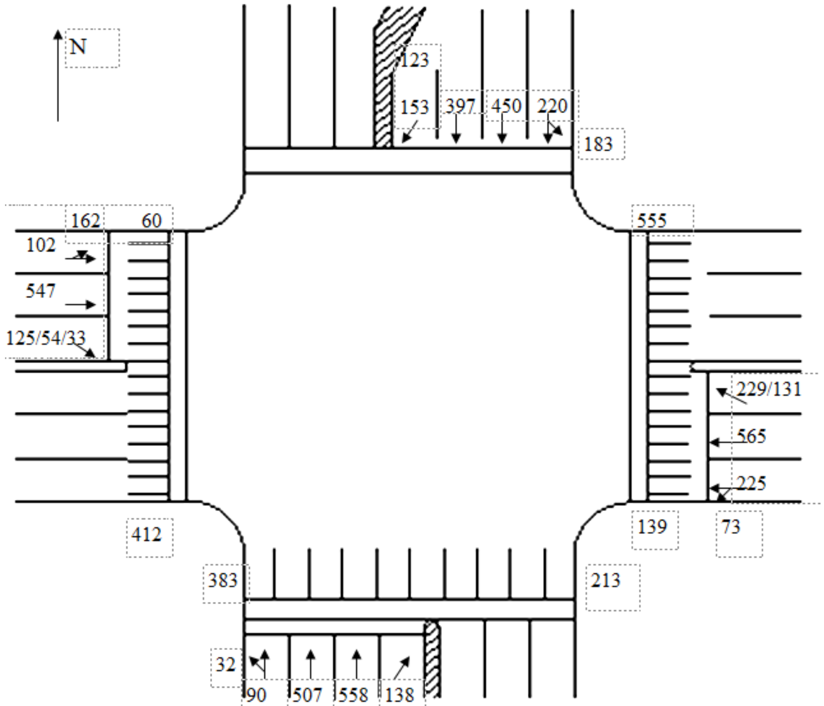
Figure 5-11 Site description for the testbed

There are totally three coordinated signalized intersections in the site. They are Horita Eki Mae, Horita Eki Minami, and Chikatetsu Horita. Under the great efforts by the members from *Interchange* Nakamura Laboratory, we were able to collect video data for vehicular flows and pedestrian flows on all approaches and all directional movements during the morning peak 7AM to 9AM on a typical weekday. As shown in **Figure 5-12**,

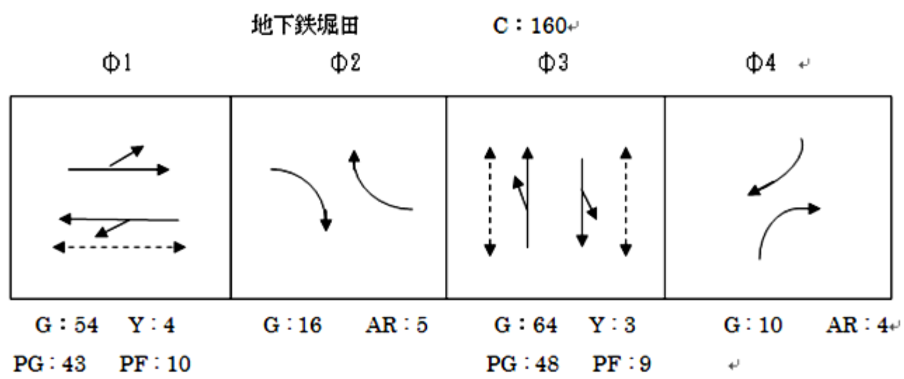
(a) Satellite view

(b) Installation locations of video cameras

Figure 5-12 Video data collection at Chikatetsu Horita intersection



(a) Vehicular and pedestrian demands (per *hour*)



(b) Signal timing information

Figure 5-13 Demand and signal timing information for Chikatetsu Horita intersection

the video cameras were installed at the intersection of Chikatetsu Horita.

We also conducted manual survey for traffic signal timing data and coordination timing data along both directions during a week-day peak-hour. The traffic demand and traffic signal timing information at Chikatetsu Horita is shown in **Figure 5-13**.

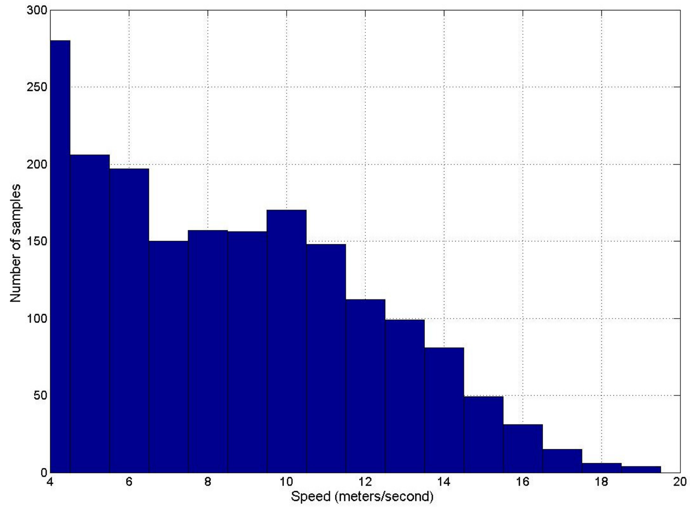


Figure 5-14 Histogram of bus cruising speed

In order to achieve bus operational data, we also collected data using GPS devices. During the same time slot in the morning peak, we carried the portable GPS receivers onto the KRBS buses running back and forth within the test site. Second by second GPS information were archived on the portable GPS receivers.

We were able to utilize the data to analyze bus operational data, e.g. average cruising speed, acceleration and deceleration. **Figure 5-14** presents the histogram of the bus cruising speed. In the calculation of the average cruising speed, those speed samples under 4 meters/second were not considered because those low speeds were under the impact of traffic conditions, e.g. queues or illegal roadside parking. The estimated average cruising speed from the samples is about 9 meters/second while the standard deviation of the cruising speed is 3.5 meters/second.

We also analyzed the collected detailed GPS trajectories to understand the existing operational condition. It is found that there are mainly two categories of trajectories in the all five southbound trips along the testbed. Those under the first group typically stopped at the first intersection (Horita Eki Mae) briefly and at the third intersection (Chikatetsu Horita) for very long time but passed through the second intersection (Horita Eki Minami) without delays, as shown in **Figure 5-15** as trip 1. For the trips under the second group, they were able to pass through Horita Eki Mae and Chikatetsu Horita without any delay but stopped at the second intersection (Horita Eki Minami), as shown in **Figure 5-15** as trip 2. The clear separation of the two groups is mainly due to the signal coordination along this direction and the different cruising characteristics between traffic and buses.

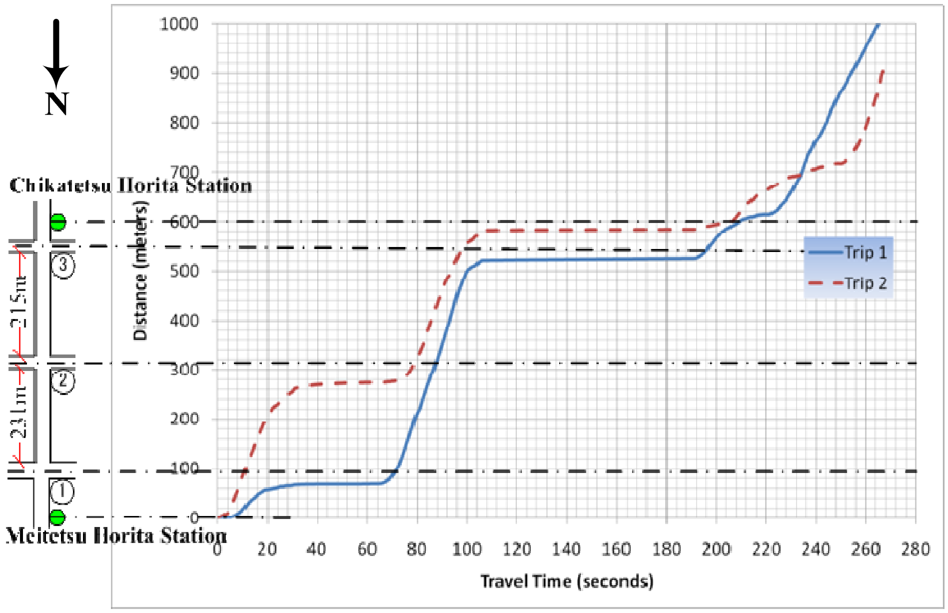


Figure 5-15 Two typical bus GPS trajectories

5.7.3 Model Application

In the numerical case study, we picked two cases to represent the two aforementioned trip groups, as illustrated in **Figure 5-15**. For the demonstration purpose, we chose the objective to minimize total person delay at the signalized intersections. According to the survey data, the average number of passengers on KRBS buses is about 20 during the peak hour and within the testbed. Thus, we applied 20 as the weighting factor for bus signal delay. Because the number of stops for the bus trip significantly impacts on passengers' comfortableness for their transit experience, we artificially assumed the weighting factor for number of stops as ten times of the weighting factor for the bus delay. The weighting on vehicular traffic delay was selected as 1.2, which is a rough estimation of average number of person on passenger cars. At last, the weighting factor for pedestrian delay is 1 because it represents the delay for one person. Finally, the multi-objective with weighting turns out to be a total person delay plus the number of stops for bus passengers at all the three intersections within three cycles.

Figure 5-16 demonstrates the performance of the proposed TSP system for the sample trip 1 from **Figure 5-15**. For the "before" scenario without TSP system, the bus departed from bus stop Meitetsu Horita at 9:01:41 AM and arrived at Horita Eki Mae at 9:02:05 AM in the middle of red. After being delayed for 43 seconds plus a 2-second response time, the bus arrived at Horita Eki Minami in green. Without any delay at the second intersection, the bus reached Chikatetsu Horita at 9:03:42 AM in red. The bus

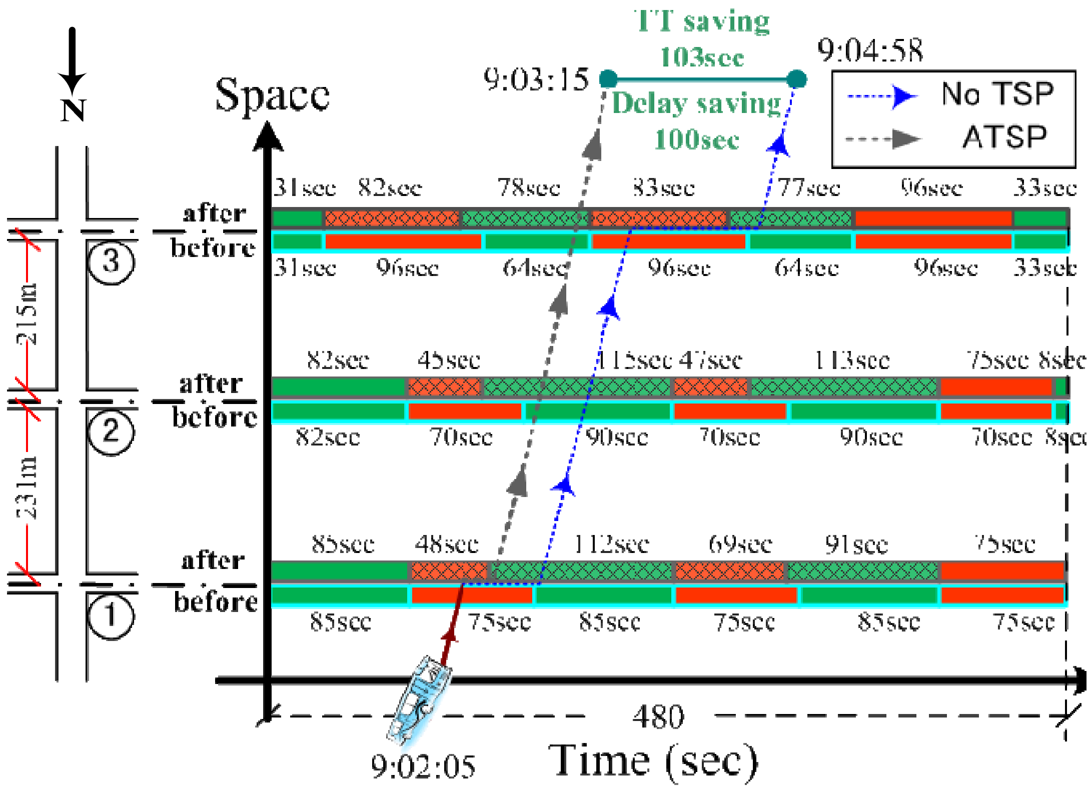


Figure 5-16 Demonstration of adaptive TSP for bus trip 1

waited 73 seconds for the onset of green. Finally, the bus departed from the third intersection at 9:04:58 AM. The total travel time for this trip is 173 seconds.

With the implementation of the proposed TSP system, the bus was able to leave Horita Eki Mae at 9:02:23 AM with 16 seconds delay plus 2 seconds as the response time. Then the bus would be able to go through the next two intersections without any delay. The total trip time could be reduced by 103 seconds and 60% to only 70 seconds. The total intersection delay would be reduced from 116 seconds to only 16 seconds with 86% reduction. The number of stops for the bus trip would also be cut 50% from 2 to 1.

For the comparison purpose, we also applied a typical active TSP model for the cases. For the typical active TSP system such as public transportation priority system (PTPS) in Japan, the bus detector is an infrared beacon which locates about 150 meters upstream of intersections (Weerasooriya, G.N. et al. 2008; Tanaka, R. et al.). Once the bus is detected, bus arrival time at the intersection is predicted based on a site-calibrated constant travel time. Priority strategies are determined based on the signal status at the predicted arrival time. If the signal is under red, the rest of green time for other phases before bus phase would be shortened, e.g. by 20%. Otherwise, the green for bus phase would be extended up to a limit, e.g. 10 seconds, until the bus checks out from the intersection (if check-out detector is installed).

Figure 5-17 illustrated the performance of the typical active TSP for the sample trip 1. At the 22nd second red, the bus triggered the infrared beacon at 150 meters upstream of Horita Eki Mae. Thus the "early green" strategy was designed for this trip. The red for bus phase was shortened by 8 seconds. The bus was able to go through Horita Eki Minami and triggered the infrared beacon at Chikatetsu Horita at 2nd second of red. With long red time, the active TSP system was able to shorten the signal delay by 16 seconds, which turns out to be the total signal delay saving for the bus trip 1.

For the second trip as shown in **Figure 5-18**, the bus arrived at Horita Eki Mae at 7:46:40 AM in the middle of green. The bus went through the first signal and arrived at Horita Eki Minami at 7:47:08 AM when at the 18th seconds in red. The bus was delayed for 52 seconds plus a 3-second response time and then reached Chikatetsu Horita at 7:48:27 AM in green. Therefore, the total trip time for this run was 107 seconds with signal delay 52 seconds.

For the "after" scenario with adaptive TSP, the signal delay at Horita Eki Minami

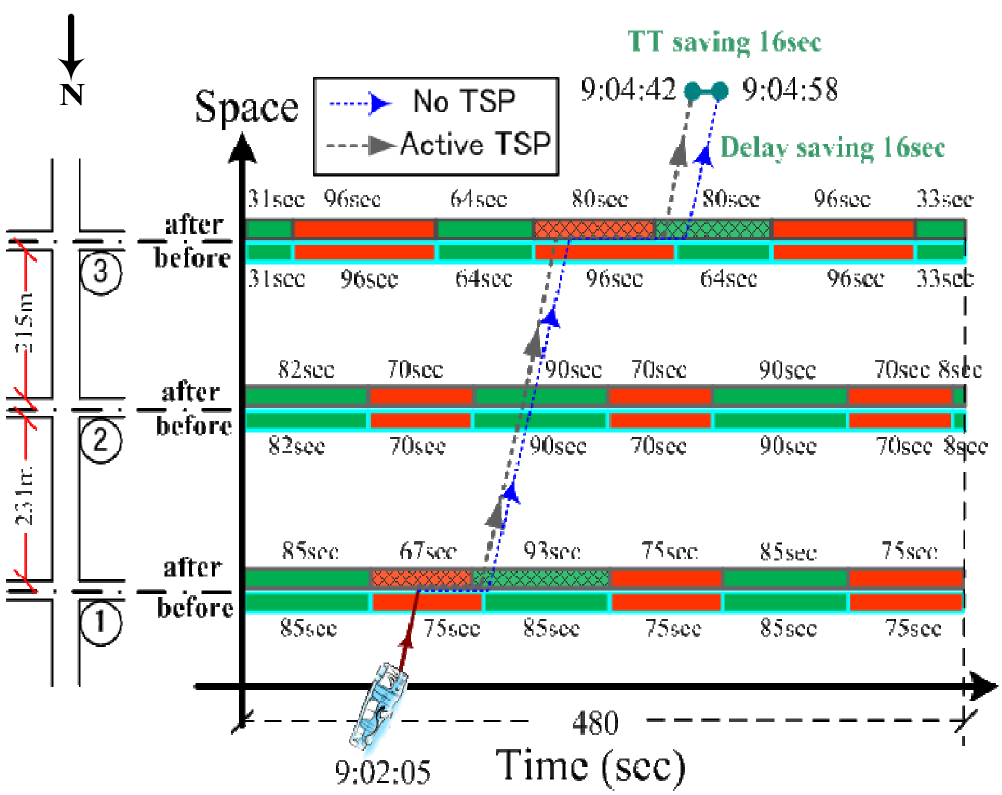


Figure 5-17 Demonstration of Active TSP for bus trip 1

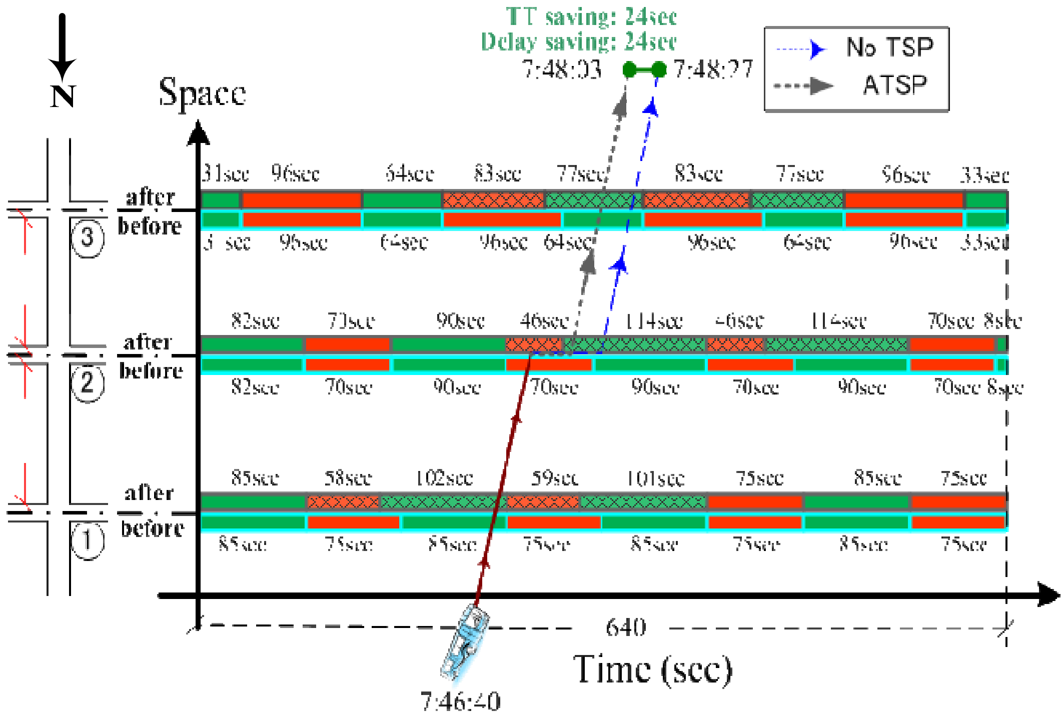


Figure 5-18 Demonstration of adaptive TSP for bus trip 2

was reduced to 28 seconds while the bus could still go through Horita Eki Mae and Chikatetsu Horita without any delay. As a result, the total bus trip time could be reduced by 22% and 24 seconds. The total bus signal delay would be reduced by 46% and 24 seconds. There is no change on number of stops for the bus trip.

Figure 5-19 demonstrated the performance of the typical active TSP for bus trip 2. The bus triggered infrared beacon at 150 meters upstream of Horita Eki Minami at 8^{th} second of red, a 10-second signal delay saving was achieved by the active TSP system.

Comparing with the typical active TSP, the significant larger bus delay savings by the adaptive TSP did not come with significant negative impacts on other vehicular traffic and pedestrian traffic. There are two major reasons. The first reason is that the quantitative model for adaptive TSP explicitly balances the TSP benefits and the impacts. Second, the transition cycle(s) after the priority cycle acts as a buffer to pay back the "price" of the priority. In other words, the "borrowed" green from minor phases will be returned in the following transition cycles. Even better, the adaptive TSP can significantly reduce average person delay.

As illustrated in **Table 5-2** for trip #1, the active TSP decreased AVD on bus phase by 5.9% with increment on AVD on non-bus phase by 4%. The adaptive TSP system was

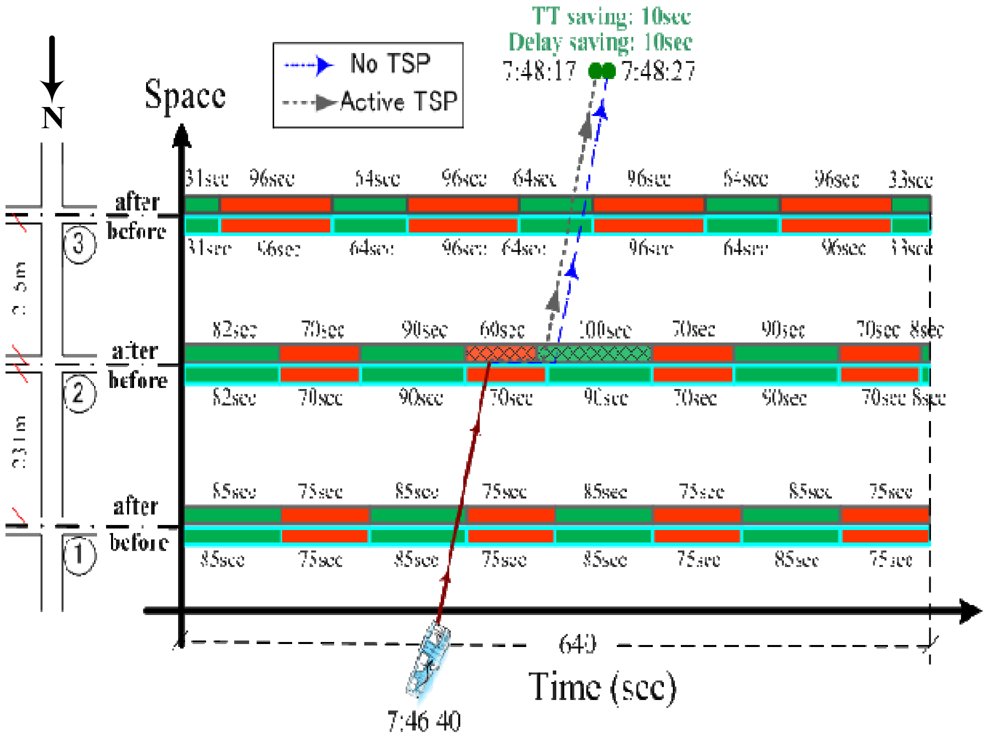


Figure 5-19 Demonstration of Active TSP for bus trip 2

able to decrease AVD on bus phase by 6.9 seconds per vehicle and 25.5% with the increment on AVD on non-bus phase by 7.5 seconds per vehicle and 14.2%. For APD, the active TSP increased the impacts on pedestrian delay by 3.5% while the adaptive TSP reduced the impacts by 2.7%. Overall, the active TSP only reduced APRD by 0.6% while the adaptive TSP saved APRD by 3.4 second per person and 9.6%. Similarly for trip #2, the active TSP reduced AVD(B) by 2.2% with increment on AVD(NB) by 0.6% and on APD by 5.2%. In contrast, the adaptive TSP reduced AVD(B) by 25.8% with increment on AVD(NB) by 11.7%. The active TSP also reduced APD by 3% and overall APRD by 9.5 and 3.3 seconds per person.

Another advantage of the adaptive TSP system over the active TSP system is that ATSP consider the queuing delay for bus movement. In most active TSP system, there is no consideration of queuing delay for bus. For example, the "green extension" strategy is normally field calibrated as a fixed duration, e.g. 10 seconds. Because it does not consider the real-time traffic situation, the bus might miss the end of the extended green due to the queuing delay. This would significant increase the bus delay. And all the impacts by "green extension" strategy would be wasted. The consideration of queuing delay would guarantee the bus to pass by the intersection if an ATSP request was generated.

Table 5-2 Model performance for two sample trips

Trip	*Scenario*	*BTT (sec)*	*BSD (sec)*	*BNS*	*AVD(B) (sec/veh)*	*AVD(NB) (sec/veh)*	*APD (sec/ped)*	*APRD (sec/per)*
1	Before	173	116	2	27.1	53.0	36.7	35.4
	Active TSP	159	102	2	25.5	55.1	38.0	35.2
	Change	-16	-16	0	-1.6	2.1	1.3	-0.2
	%	**-9.2%**	**-13.8%**	**0%**	**-5.9%**	**4.0%**	**3.5%**	**-0.6%**
	Adaptive TSP	70	16	1	20.2	60.5	35.7	32.0
	Change	-103	-100	-1	-6.9	7.5	-1.0	-3.4
	%	**-59.5%**	**-86.2%**	**-50%**	**-25.5%**	**14.2%**	**-2.7%**	**-9.6%**
2	Before	107	52	1	27.1	53.0	36.7	34.9
	Active TSP	97	42	1	26.5	53.3	38.6	34.9
	Change	-10	-10	0	-0.6	0.3	1.9	0.0
	%	**-9.3%**	**-19.2%**	**0%**	**-2.2%**	**0.6%**	**5.2%**	**0.0%**
	Adaptive TSP	83	28	1	20.1	59.2	35.6	31.6
	Change	-24	-24	0	-7.0	6.2	-1.1	-3.3
	%	**-22.4%**	**-46.2%**	**0%**	**-25.8%**	**11.7%**	**-3.0%**	**-9.5%**

5.7.4 Discussion

The proposed adaptive TSP system demonstrated very successful performances for both of the two sample trips. Comparing with the significant delay saving, the impacts on other vehicular and pedestrian traffic are almost negligent. There are two major reasons for the success.

First, the system balances the system benefits and costs through a quantitative multi-objective model. For example, trip #2 received TSP and reduced its signal delay from 52 seconds to 28 seconds. According to the model constraints, the system could have called higher priority to save more delays at Horita Eki Minami. However, it was computed that one second more delay saving on bus intersection delay would create about 27.8 person*seconds delay for total vehicular and pedestrian flows, as shown in **Figure 5-20**. Given the weighting factor on bus is 20, such reduction on bus delay was not worthwhile. If the weighting factor is higher than 27.8, the system would consider higher priority for the bus.

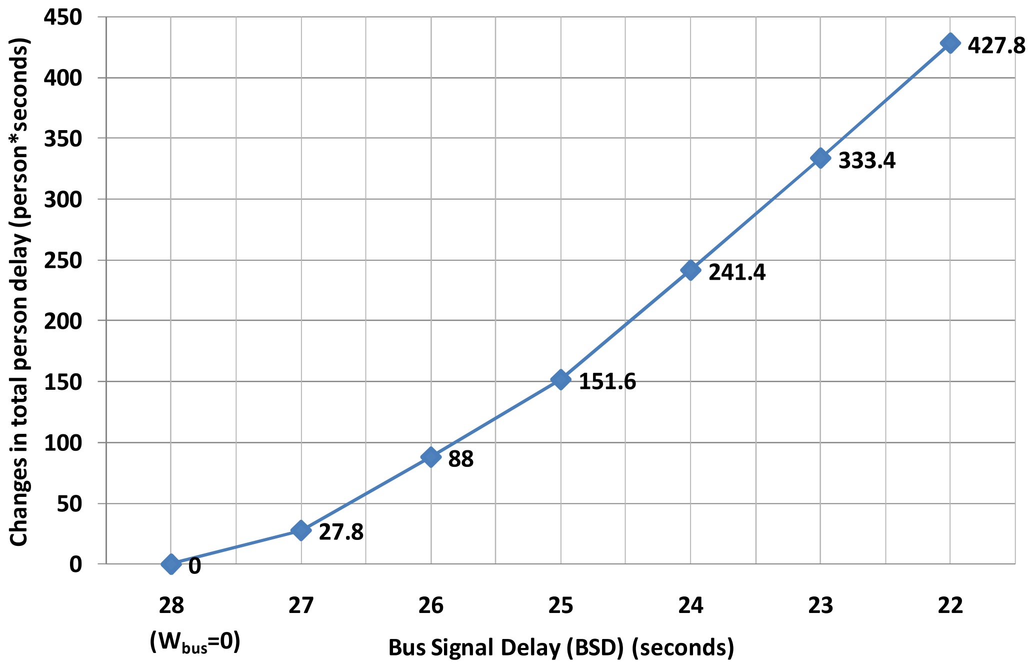


Figure 5-20 Changes in BSD versus changes in person delay (Trip#2)

For example, the bus delay would be reduced to 27 seconds when the weighting factor on BSD is between 27.8 and 88. When the weighting factor is higher than 88 and lower than 151.6, the bus delay could be reduced to 26 seconds. There is an extreme delay saving for this case because the minimum green for pedestrian for phase 1 at Horita Eki Minami is 6 seconds. The lowest bus signal delay is 22 seconds when the weighting factor is higher than 427.8.

The other reason for the negligent system impacts on other traffic is that the system considers TSP at the arterial level. For example in trip #1, the bus suffered from the difference of the cruising speed between bus and other traffic. Thus the bus just missed the green window at Chikatetsu Horita even it departs from the beginning of green at Horita Eki Mae and without traffic queues. The minor priority at Horita Eki Mae can actually save the long delay and a stop at the downstream intersection. Moreover, the downstream intersection actually doesn't need any priority and therefore have none negative impacts.

It is noted that the simple rule-based active TSP cannot achieve a similar results as demonstrated by the adaptive TSP. It is because the rule-based TSP always under- or over-prioritizes transit vehicles as shown in **Figure 5-17** and **Figure 5-19**. Moreover, the active TSP doesn't have the transition cycle as the buffer to quantitatively balance the impacts and benefits of TSP. Thus, the active TSP is unable to reduce average person delay even with priority on transit vehicles. Finally, many active TSP, such as public transportation priority system (PTPS) in Japan, doesn't have the check-out detector at the exit of intersection. Thus a constant extended green might create longer delay for a bus if it just misses the end of extended green due to the traffic queuing delay.

5.8 Sensitivity Analysis

Weighting factors, particularly on the bus delay, are the key parameters in the proposed model. The weighting factor on bus delay represents the relative preference of reducing bus delay/stop over impacts on other traffic delay. The higher relative preference on saving bus delay the larger weighting factor should be selected. As discussed in the previous section for trip #2, the weighting factor finally determined the balance between bus priority and the incurred costs on other traffic, i.e. vehicular traffic and pedestrian traffic.

In this study, we conducted a sensitivity analysis on weighting factors. For the geometry and demand information, we still utilize the same three-intersection testbed (Horita Eki Mae, Horita Eki Minami, and Chikatetsu Horita), which we chose for the numerical case study. Five weighting factors from 20 to 100 for bus delay were selected for the sensitivity analysis. The weighting factor for number of stops in the bus trip is still ten times of the weighting factor for bus delay. The weighting factor for vehicular traffic delay and pedestrian traffic delay are 1.2 and 1.0, respectively.

Eight MOEs, i.e. BTT, BSD, BNS, AVD(B), AVD(NB), AVD, APD, and APRD, were chosen for the comparison of the system benefits and costs. As demonstrated in the numerical case study, the proposed TSP system performs differently when the bus reached the first intersection at different time on the local signal clock. Therefore, we ran the model for all the possible arrival times from the beginning till the end of the cycle at Horita Eki Mae. All The results are shown in **Figure 5-21** to **Figure 5-26** and **Table 5-3**.

When a bus arrives at different time, the system performances have different sensitivities on the selection of weighting factors. As shown in **Figure 5-21**, the differences of bus delays for weighting factors between 20 and 100 are insignificant. The largest difference of bus delay is about 20 seconds when the bus arrives at signal #1 (Horita Eki Mae) between local clock 0 and 25 and between 155 and 160. Because the local clock at Horita Eki Mae circulates with 160 seconds. Thus the two intervals can be combined into one interval from -5 seconds to 25 seconds.

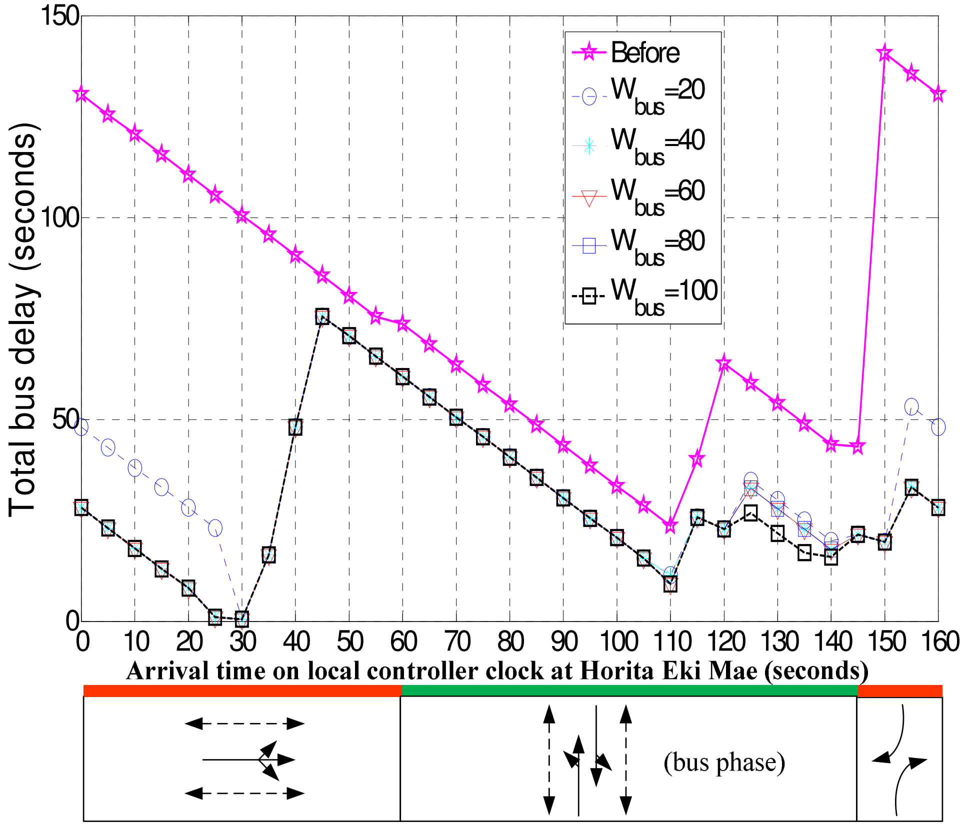


Figure 5-21 Total bus intersection delay versus weighting factors on BSD

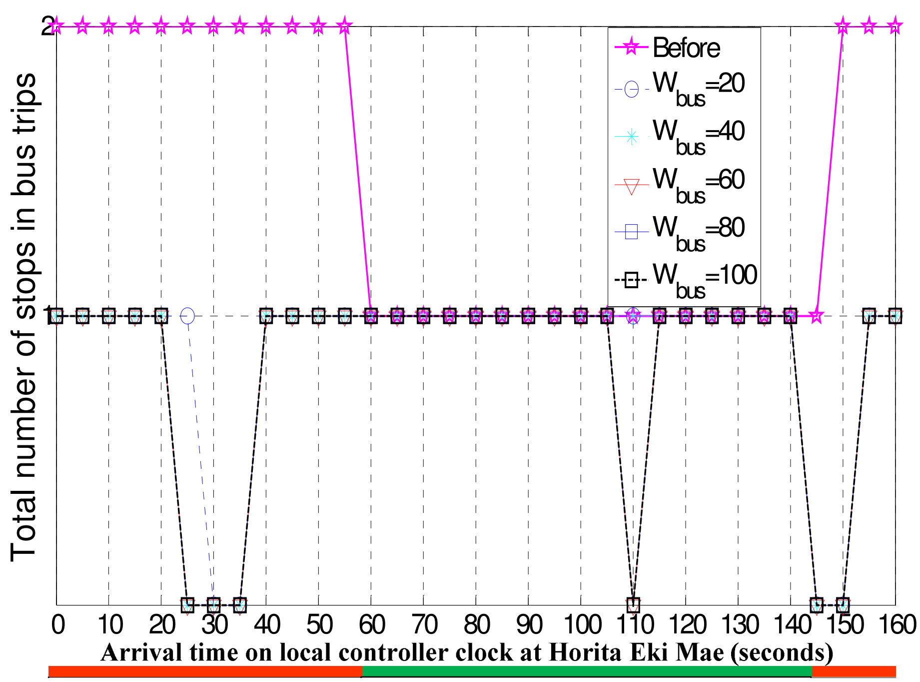


Figure 5-22 Number of bus stops for bus trips versus weighting factors on BSD

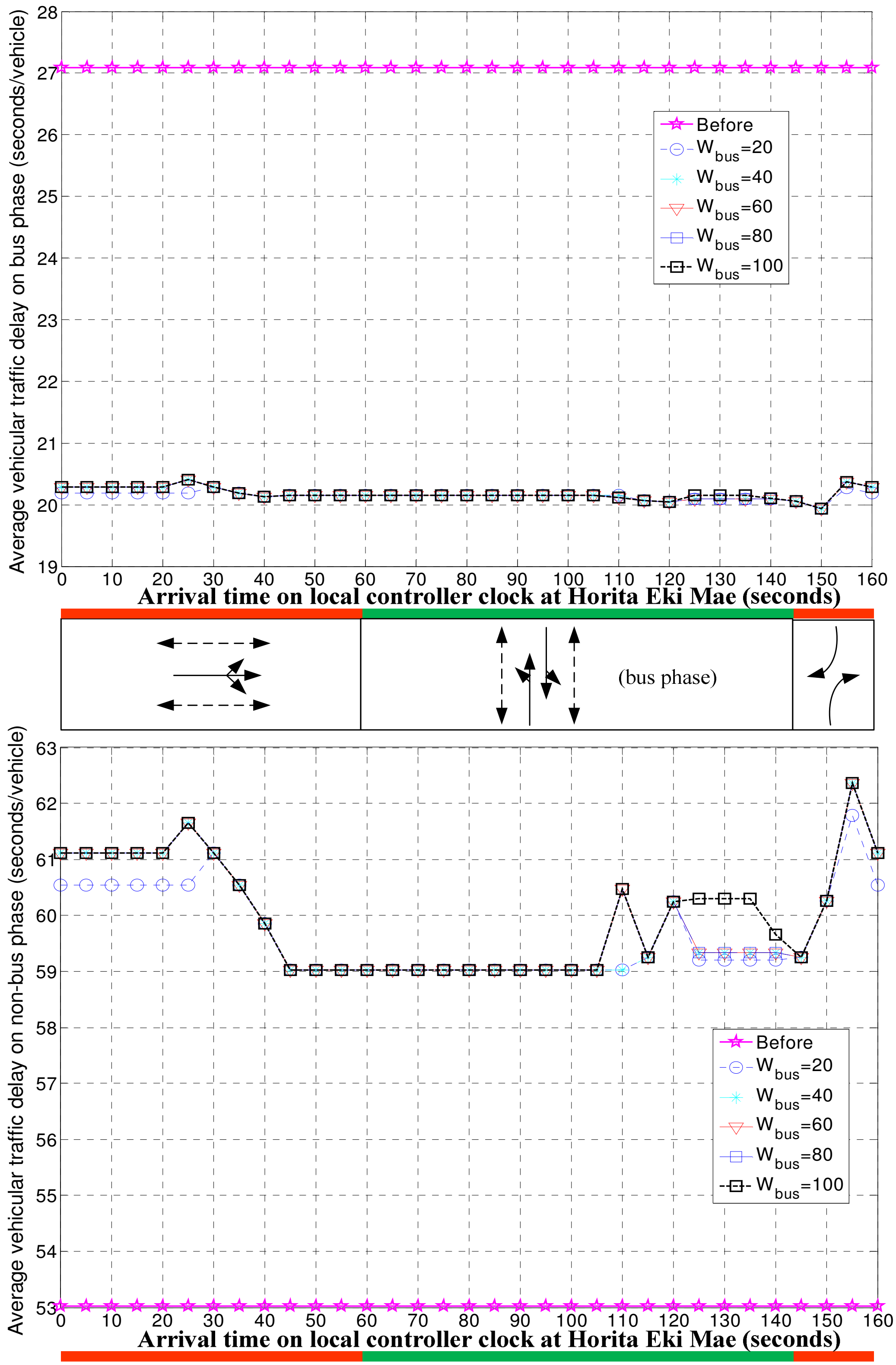


Figure 5-23 Average vehicular traffic delay versus weighting factors on BSD

Table 5-3 Model performance under various weighting factors on bus

Scenario	Before	After				
Weighting factor on BSD	N/A	20	40	60	80	100
BTT (sec)	133.4	90.5	85.7	85.6	85.6	84.9
Change (sec)	N/A	-42.9	-47.7	-47.8	-47.8	-48.5
Change (%)	N/A	-32.16%	-35.76%	-35.83%	-35.83%	-36.36%
BSD (sec)	76.6	35.4	30.7	30.6	30.6	30.0
Change (sec)	N/A	-41.2	-45.9	-46	-46	-46.6
Change (%)	N/A	-53.79%	-59.92%	-60.05%	-60.05%	-60.84%
BNS	1.44	0.88	0.84	0.81	0.81	0.81
change	N/A	-0.56	-0.6	-0.63	-0.63	-0.63
Change (%)	N/A	-38.89%	-41.67%	-43.75%	-43.75%	-43.75%
AVD(B) (sec/veh)	27.1	20.1	20.1	20.1	20.1	20.1
Change (sec/veh)	N/A	-7	-7	-7	-7	-7
Change (%)	N/A	-25.83%	-25.83%	-25.83%	-25.83%	-25.83%
AVD(NB) (sec/veh)	53.0	59.6	59.8	59.8	59.8	60.0
Change (sec/veh)	N/A	6.6	6.8	6.8	6.8	7.0
Change (%)	N/A	12.45%	12.83%	12.83%	12.83%	13.21%
AVD (sec/veh)	34.2	30.9	31.0	31.0	31.0	31.0
Change (sec/veh)	N/A	-3.3	-3.2	-3.2	-3.2	-3.2
Change (%)	N/A	-9.65%	-9.36%	-9.36%	-9.36%	-9.36%
APD (sec/ped)	36.7	35.7	35.7	35.7	35.7	35.7
Change (sec/ped)	N/A	-1	-1	-1	-1	-1
Change (%)	N/A	-2.72%	-2.72%	-2.72%	-2.72%	-2.72%
APRD (sec/per)	35.1	31.7	31.8	31.8	31.8	31.8
Change (sec/per)	N/A	-3.4	-3.3	-3.3	-3.3	-3.3
Change (%)	N/A	-9.69%	-9.40%	-9.40%	-9.40%	-9.40%

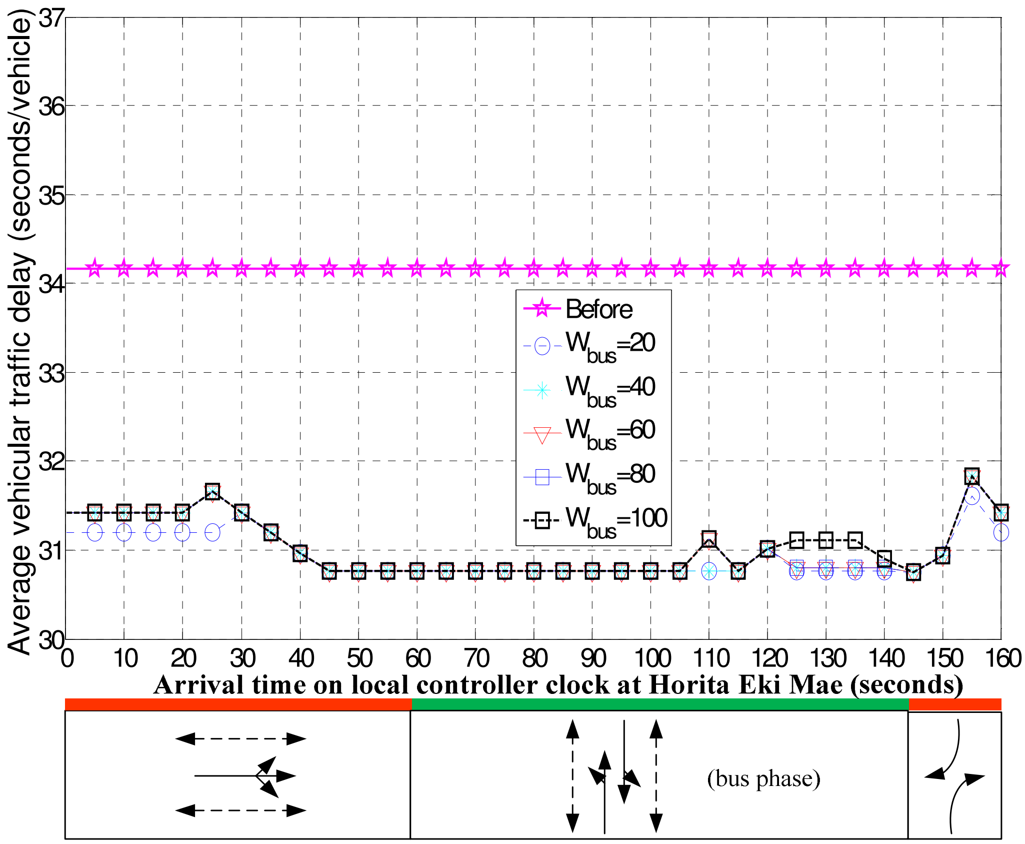


Figure 5-24 Average vehicular traffic delay versus weighting factors on BSD

For most of other arrival times, there is no difference in bus delay even the weighting factor is changed from 20 to 100. In other words for such time slots, the difference in weighting factor is not significant enough to provide much more priority because the incurred impacts on other traffic would surpass the weighted benefits.

Figure 5-22 illustrates the difference on number of bus stops when changing weighting factors. Only with arrival time at local clock 25 at signal #1, there is a difference between weighting factor 20 and higher weighting factors. The difference is one stop per bus trip.

Figure 5-23 presents the impacts on vehicular traffic delay on bus phase (top) and that on non-bus phase (bottom). Comparing with the "before" scenario, the AVD(B) (top figure in **Figure 5-23**) was reduced while the AVD(NB) (bottom figure in **Figure 5-23**) was increased by the TSP. It is because the priority on bus movement can also help on the vehicular traffic on the same direction. Similarly with the results on bus delays, there are some differences on average vehicular traffic delay for the arrivals between local clock -5 and 25. However, the differences are very small and actually less than one second for both AVD(B) and AVD(NB).

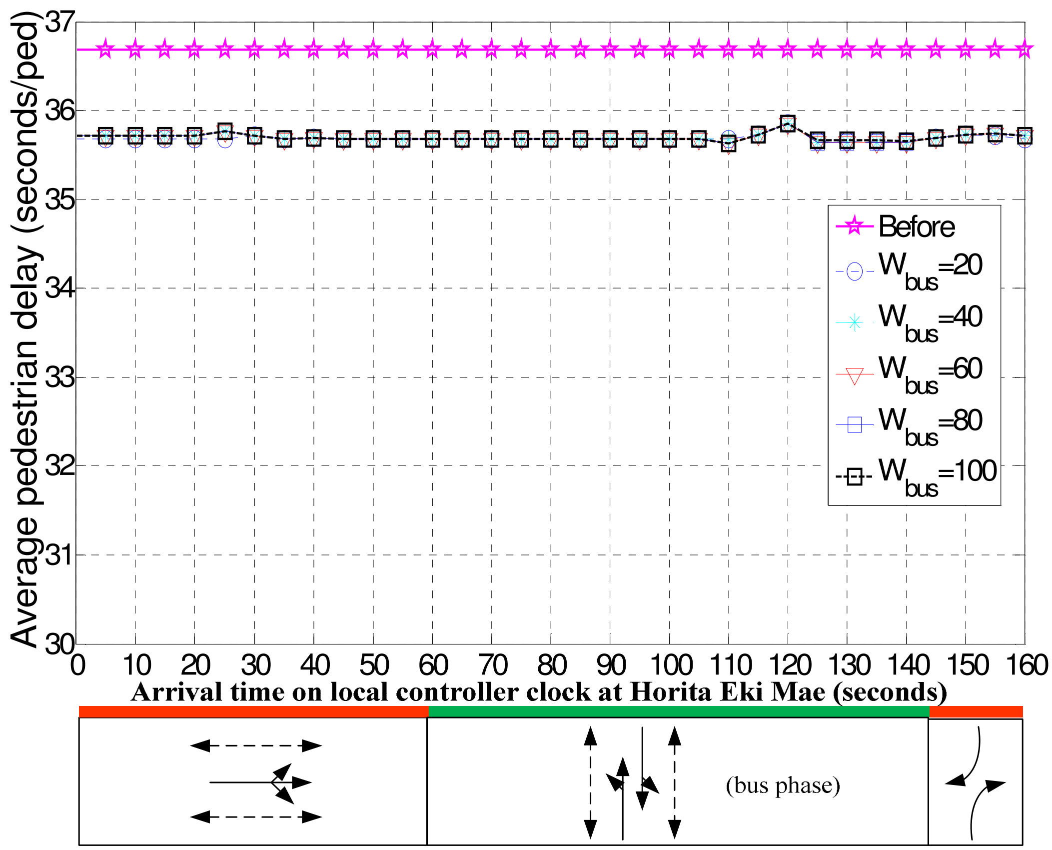


Figure 5-25 Average pedestrian delay versus weighting factors on BSD

Figure 5-24 presents the system performance for average AVD for all approaches. It is noted that the AVD with priority is lower than that for the "before" case for any bus arrivals. It is because the existing timings are not optimum given the observed traffic condition. The proposed model can also adapt the TSP requests based on traffic demand information, which can either be from real-time data collections or from latest traffic surveys on different time of day.

Figure 5-25 illustrates that the impacts on pedestrian delay is also not very sensitive with the weighting factor from 20 to 100. The largest difference is within 1 second per person. Finally, **Figure 5-26** presents the average person delay for all the three intersections within the two control cycles. Here we assume the number of passengers on bus is 20. Similarly with the results for AVD, the differences of average person delay are insignificant for all bus arrival times.

It is noted the changes in weighting factor might not necessarily change the optimization results because the objective function is not continuous function. **Figure 5-28** illustrates the trip#1 case with bus arrival in red at Horita Eki Mae with local clock 16th

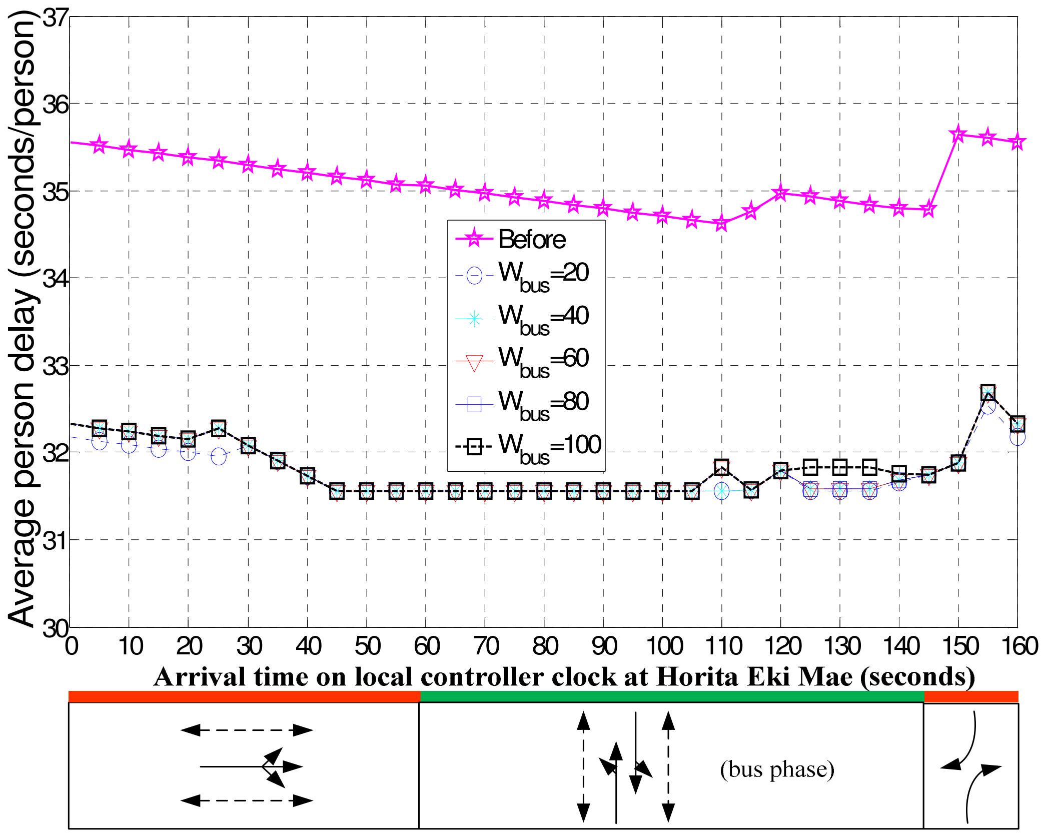


Figure 5-26 Average person delay versus weighting factors on BSD

second. The optimal results changed when the weighting factor on BSD increases from 0 to 20 and from 20 to 40. When weighting factor keeps increasing from 40 to 100, there is no change in the optimal solution. **Figure 5-27** illustrates trip#2 case with bus arrival in green at Horita Eki Mae with local clock 131st second. The optimal solution changes when the weighting factor on BSD increases from 20 to 40 and from 80 to 100. For other changes on the weighting factor, the optimal solution stays. The results are consistent with the turning points shown on **Figure 5-20.**

Specifically for the case study, it is reasonable to select relative high weighting factor such as 100 to save more bus delay without introducing significant delay to other traffic. However, there is no global optimum for the selections of weighting factors. The selection of weighting factor can be political, policy and circumstance dependent. For example, higher weighting factors on bus delay/stop should be chosen when sustainable transportations are being considered for the national or regional transportation planning and management. Or when it is like any typical metropolitan areas with highly congested traffic but limited or no space to broaden or improve existing street systems, the proposed TSP system with relatively high weighting factors on bus delays can potentially relieve

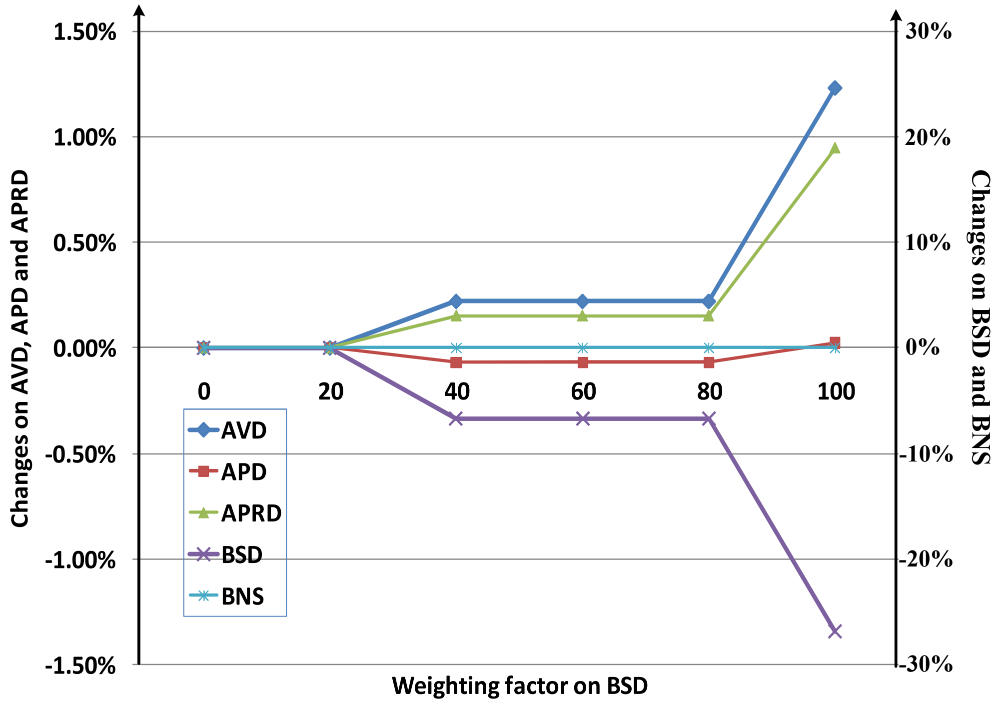


Figure 5-27 Model performance with various weighting factors on BSD (Trip#2)

such traffic problems by improving transit services and thus attract more travelers to switch their transportation model from driving to riding.

Other than the impacts from politics and policies, many site and control specific factors, such as vehicular and pedestrian demand levels, demand ratios between bus phase and non-bus phase, cycle length and coordination design, should be considered when choosing the weighting factors. The relationship of such factors with weighting factors can be discovered by well designed sensitivity analysis in the future.

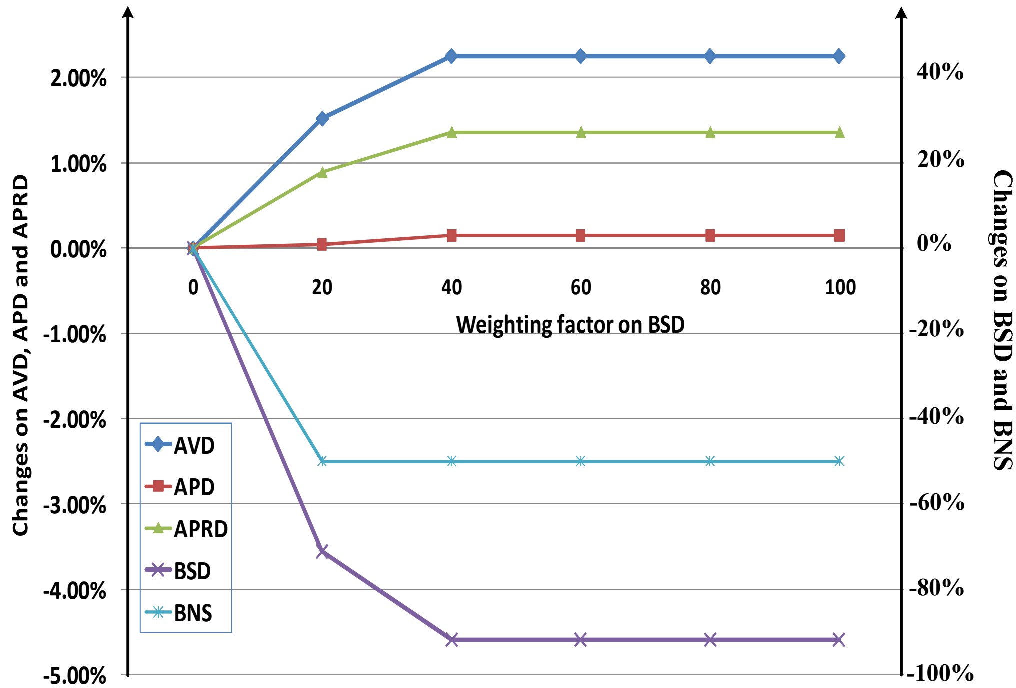


Figure 5-28 Model performance with various weighting factors on BSD (Trip#1)

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Although prevailing active TSP systems are efficient in granting priority to buses, they might incur noticeable delays to the minor-phase traffic, which has raised concerns among traffic engineers and thus has impeded the wide-scale acceptance and deployment of TSP systems. ***The methodologies and analysis results from this study make the concept and implementation of adaptive TSP possible for the state-of-practice traffic signal control systems, i.e. fixed-time and actuated control systems.*** The findings of the study provide transportation authorities with three cost-effective ways to achieve adaptive TSP upon the widely deployed traffic signal control systems. More specifically, it provides quantitative models to explicitly balance the benefits and impacts of TSP. According to the results from the numerical case studies, microscopic traffic simulations, and the field operational tests, the developed model demonstrated significant benefits on bus movement while minimizing the impacts to other vehicular traffic and pedestrian traffic.

There are some major contributions of this study. First of all, it is the first ATSP study will develops the quantitative models with limited traffic detection inputs and constraints from state-of-practice signal control systems. Second, this study considers the TSP impacts on pedestrian flows, specifically the delay on sidewalk and on crosswalk. For a transit oriented study, it is necessary to consider the highly correlated pedestrian flows. Third, this study considers TSP coordination crossing multiple intersections, which can guarantee that the priority and the associated impacts on other traffic would not be wasted. Finally, the results of sensitivity analysis on the key design factors can help designers choosing the right numbers given various policy preferences and characteristics of geometry and transit services.

The first ATSP model developed in ***Chapter 3*** utilizes GPS-based AVL systems to continuously monitor bus movements. The resulting historical and online bus data are used by a bus arrival time predictor to predict bus arrival times to signalized intersections. Given the bus arrival information together with real-time traffic and signal status data obtained from the closed-loop signal control system, a delay-based ATSP optimization model aims to minimize the objective of weighted delays through manipulating the green splits of signal phases for two consecutive cycles at one intersection. The model objective is the weighted bus delay together with total traffic delays in the period of two control cycles. A set of system constraints were set up to protect the safety requirements, to maintain the logic of dual-ring actuated signal control, and to make the best use of the dynamic information from bus AVL systems, signal controllers, traffic loop sensors, and pedestrian push buttons. The numerical case studies were conducted for a medium-congested scenario and a highly-congested scenario. In both of the two scenarios, the proposed model demonstrated a significant delay reduction (up to 100%) for transit vehicles while the impacts on other vehicular traffic varied from 4.4% to 13.2%. The weighting factor on bus delay is sensitive with the impacts on other traffic, particularly in the highly-congested scenario. At the end, a field operational test has been conducted along a two-mile-long signalized arterial which consists of seven signalized intersections. The results show a promising performance in the field environment. At the most congested intersection, the bus delays and traffic delay along bus phase have been reduced by 43% and 16%, respectively, while the traffic delay on minor phases was increased by 10%. All the changes were statistically significant.

Chapter 4 expands the discrete ATSP model to a centralized ATSP system for transit vehicles. As the "brain" of the system, the PRG adopts a three-scheme conditional priority control strategy. Scheme I, which applies to late transit vehicles, features a timing optimization model. With the randomness of transit vehicles' running time in mind, the MIQP control model could minimize the expected delay for transit vehicles while with only limited impacts on other traffic. A case study, based on San Diego Trolley system, demonstrates that an enormous intersection delay saving is as much as 89.5%, or 25.3 sec/train for late trains after applying the proposed scheme I strategy, meanwhile the impact on other traffic in the priority cycle is only 4.4 second per vehicle. For scheme II and III when no priority is needed, traffic delay savings are 32.5% and 52.0%, respectively. A simulation model coded in PARAMICS not only confirms the benefits of the proposed model but also validates the practicality of the centralized ATSP system.

Chapter 5 summarized the findings and experiences from the previous two ATSP models and developed an integrated delay-based model for a centralized ATSP system. In this chapter, the optimization model not only considers the bus delay and all vehicular traffic delay but also considers pedestrian delay as an important factor of traffic signal operation. System constraints were set up to guarantee the safety of operation and the logic of traffic signal control. The proposed model has been evaluated by a numerical case study. The case study was based on Key Route Bus System in Nagoya, Japan. The test site consists of three signalized intersections. Two typical bus trip trajectories were collected by GPS devices and applied by the proposed system. The testing results for the two types of trips were promising. The bus delays were reduced by 86% and 46%, respectively. The average vehicular delay on bus phase was reduced by about 26% while vehicular delay on non-bus phase was increased by about 13%. The average pedestrian delay was reduced by about 3%. Overall, the average person delay was reduced by about 10%. Finally, a sensitivity analysis was conducted for the weighting factor on bus delay. The weighting factors from 20 to 100 were testified. For the test site, the weighting factors below 100 do not make much difference on the system performance for all the eight MOEs except for BSD. When bus arrival time at signal #1 is between -5 to 25 on the local clock, the bus signal delay can be further reduced by 20 seconds after raising the weighting factor from 20 to 100. But for average vehicular delay, average pedestrian traffic delay, average person delay, the changes are less than 1 second. Therefore, it is reasonable to select a relatively high weighting factor such as 100 to save more bus delay without introducing significant delay to other traffic. With weighting factor for bus delay is 100, the average bus delay for all bus arrivals can be reduced by about 47 seconds and 61%, meanwhile the average traffic delay on non-bus phase has been increased by 7 seconds per vehicle and 13%. The delays for vehicular traffic along bus phase and for pedestrian traffic decreased by 9% and 3%, respectively. Overall, the average person delay has been reduced by 3 seconds per person and 9%.

6.2 Comparisons of ATSP development in Japan versus in U.S.

6.2.1 Transit Recognition

The transit recognition is significantly different in Japan and in U.S. In Japan, population density in the urban areas is much higher than in U.S, particularly for the medium- and large-size cities. Except for the super-size city like Tokyo, Japanese live closer to the urban areas than Americans. Most Japanese citizens take public transportation as their first choice when travelling. However in U.S, people always prefer driving partially because they typically live in suburban areas. Furthermore, driving has already been part of the American life style. Such preference is not very sensitive to the congestion and gas price. In most of states in U.S. including some metropolitan areas, existing transit services suffer from very low occupancy. Even worse as a vicious circle, transit agencies have to cut more services and sacrifice service quality to sustain, which further jeopardizes the desire of travelers to use transit services.

Comparing with the U.S., the improvement of transit services in Japan can immediately impact on people's daily life. With higher recognition of transit services, the policy makers, city planners, and transportation engineers in Japan can have higher motivation on improving existing transit services and thus seriously consider TSP as a solution.

6.2.2 Other Institutional Issues

TSP can only be implemented through a solid partnership of the transit and traffic agencies. This requires a continuous dialogue and solid working relationship. In U.S., the regional transportation planning is typically managed by the local metropolitan planning organization (MPO), council of government (COG), traffic agency or other regional authorities. With such authorities, regional transportation goals and regional ITS architecture can be accordingly realized.

In Japan, the traffic operation and control are under National Police Agency (NPA). Unfortunately, it is too common to observe a total lack of communication between NPA and transit agencies and between NPA and transportation institutes. There are many reasons behind it. One of the most important one is that the focus of NPA is mainly on national security and public safety but not much on operational efficiency for the transportation systems. It makes them to be very conservative on making such changes in traffic signal control to improve transit services. Therefore, a lot of efforts are still needed on such institutional issues in order to successfully implement an ATSP system in Japanese cities.

6.2.3 Technology Issues

Japan and the United States are the two countries with most advanced technologies. Regarding to the technologies on public transportation particularly on buses, neither of the two countries is the leader of the world. However, more and more transit services in the two countries have already or started installing AVL systems on all the fleet vehicles. The AVL together with advanced communication system (ACS) provides a good infrastructure foundation for potential implementations of the ATSP systems described in Chapter 3 to Chapter 5.

6.2.4 TSP Model Development

As described in previous chapters, the TSP model development highly depends on the type of traffic signal control system. In Japan, a high percentage of traffic signals are under TOD fixed-timing control. The centralized ATSP model described in Chapter 4 and the integrated multi-modal ATSP model developed in Chapter 5 can be good candidates for implementations. Furthermore, Japanese signalized intersections are generally characterized by unreasonable long cycles (140sec~200sec) regardless of the size, complexity or vehicle demand, which impose high delays on all users. Such long cycles are referred to the high vehicle demand, however at some signalized intersections where vehicle demands are not high, still cycle lengths are very long. Long cycle creates some difficulties for TSP development. First, fixed-timing control in Japan needs about one cycle to prepare for the implementation of a TSP request. Such long lead time requires the arrival time predictor (ATP) to accurately predict buses' arrival times when they are still far from intersections. Second, a TSP request needs another cycle as the transition time to compensate the priority impacts on other traffic. Long cycle length will also increase the duration of transition period. As a result, the ATSP system needs very long time to complete transition and get ready to serve the next request. Because the high recognitions and demands on transit services in Japan, the service frequency is much higher than that in U.S. Therefore, the TSP systems in Japan have to be more selective or conditional due to such short gaps between two service buses. For example, only buses which are running behind their schedules more than 5 minutes can be served by TSP. Other buses would have to be blocked due to the conflicts of long cycle lengths and high service frequency.

In the United States, about 90% of existing traffic signals are under either actuated or semi-actuated control. The typical signal control settings and traffic detection layouts are described in Chapter 3. For such control systems, the discrete ATSP model described in Chapter 3 and the integrated ATSP model described in Chapter 5 can be good candidates for implementations. Furthermore, most traffic signals in U.S. have reasonable cycle lengths which make TSP implementations easier than those in Japan.

Last, urban Japanese signalized intersections are often characterized by medium to high pedestrian demands, which is much higher than those intersections in U.S. Thus the proposed multi-modal ATSP model which considers pedestrian waiting and crossing delays can be more significant in Japan than in U.S.

6.3 Future Works

6.3.1 Model Assumptions and Parameters

Given a specific traffic situation, a cost-benefit analysis could be conducted to determine a weighing factor for the optimization models. In future studies, detailed sensitivity analysis should be conducted in order to understand the relationships among weighting factors, bus arrivals, and traffic coordination. Furthermore, the weighting factor could be a function of factors such as maximum allowed vehicular and pedestrian traffic delays, longest vehicular queues, number of transition cycles, transit headways, or schedule adherences. In other words, the ATSP algorithm can work with these factors instead of ambiguous weighting factors.

Moreover, the assumption of deterministic traffic arrival pattern in traffic delay calculation can be relaxed using the data-driven model (Li et al. 2009; Yin et al. 2007) based on the detections system upon closed-loop actuated control system. In this approach, the distribution of traffic arrival within each cycle is studied. Newell (1965) and Asano et al. (2004) proposed a method to estimate the delay due to the stochastic arrivals, which can be borrowed for this study to evaluate the system performance considering stochastic delays. It is also found that the stochastic delay is comparably less than deterministic delay when traffic streams are under-saturated.

Although the current model considers the TSP impacts on pedestrian traffic, it does not consider some details of pedestrian behaviors. For example, the interaction between turning vehicles and pedestrian has not been considered. This interaction actually relates to the signal phasing scheme and pedestrian crossing scheme. If all the turning phases are protected phase but not permitted phase, there won't be such interactions.

Finally, the sensitivity analysis on how the accuracy of the model inputs, e.g. bus arrival time and short-term traffic flow, and the communication latency would impact on the final system performance will be conducted.

6.3.2 ATSP Model Development

A PRS manages and prioritizes priority requests generated by the PRG, and sends one or more service requests to signal controllers for execution. For a large-scale implementation, the PRS plays an important role in achieving system-wide benefits. This study will improve the current PRS, which is heuristic, by integrating the PRS and the PRG. Specifically, the priority timing strategy will be determined by considering the needs of multiple buses, thereby resulting in a balance between the delay of an individual bus (a very late bus would have the highest weight) and system-wide traffic delay.

6.3.3 Coordination of Pedestrian and Transit Services

There is strong relationship between pedestrian and public transportation services. Improved transit services, e.g. BRT services, aim to attract more and more passengers to shift their transportation modes from driving to riding. With more transit users, pedestrian demands would definitely grow. Thus it is worthwhile to study the coordination of TSP with pedestrian flows at or close to signalized intersections. As the future sustainable transportation system, multi-modal system will be transit oriented. With the continuous efforts by transportation researchers, planners, and engineers, we believe the traffic signal control will also be transit oriented in the near future. I imagine that a story like this can happen to our daily life in some days:

Just before an AVL equipped BRT bus approaches to a station, the traffic signal control center receives a predicted bus arrival time and the requests from those pedestrians around the area who want to take the incoming bus. Thus a special pedestrian phase will be designed and served to help them reach the bus station in time. Once the bus finishes loading passengers, it can go smoothly to the next stop without any delay because the signal priority has been designed appropriately at all signals before the bus's arrival at intersections. All these transit-oriented traffic signal operations are based on the real-time information to minimize the impacts from the priority services. At the end, the efficient and attractive transit service becomes the most dominant transportation modes and also significantly reduces the traffic demands and congestions.

References

AASHTO/ITE/NEMA (2008). *National Transportation Communications for ITS Protocol: Objective Definitions for Signal Control and Prioritization.* NTCIP 1211, V01.

Abkowitz, M.D. and Engelstien, E. (1983) *Factors affecting running time on transit routes*. Transportation Research 17A (2): 107-113.

Alhajyaseen, W. and Nakamura, H. (2009) *A Methodology for Modeling Pedestrian Platoon Discharge and Crossing Times at Signalized Crosswalks.* Proceedings of the 88th Transportation Research Board Annual Meeting, Washington, D. C., 2009.

Alhajyaseen, W. and Nakamura, H. (2009). *Estimating the Minimum Required Width of Signalized Crosswalks Considering Bi-directional Pedestrian Flow and Different Age Groups.* Journal of the Eastern Asia Society for Transportation Studies (EASTS), Volume 8. / Proceedings of the EASTS 2009, Surabaya, Indonesia, November 2009.

Asano, M., Horiguchi, R. and Kuwahara, M. (2004) *Adaptive Traffic Signal Control Using Real-time Delay Measurement (Consideration of Stochastic Delay).* ITS World Congress, Nagoya, Japan, 2004.

Baker, R.J. et al., (2004) *An Overview of Transit Signal Priority*, ITS American, published July 2002, Revised and updated 2004.

Bayley, J.M. (1966) *Pedestrian and traffic control.* Traffic Engineering and Control 8, 1966, pp. 311-312.

Bretherton, R.D., (1996) Current Developments in SCOOT: Version 3, Transportation Research Record 1554, National Research Council, Washington, D.C.

Celniker, S. and Terry, E.W. (1991) *Trolley Priority on Signalized Arterials in Downtown San Diego*, Paper prepared for presentation at the National Light Rail Transportation Conference

Chien, S. I., Ding, Y. and Wei C. (2002) *Dynamic bus arrival time prediction with artificial neural networks*. Journal of Transportation Engineering 128 (5): 429-438

Cho, H., and Rilett, L.R. (2004) *Improved Transitional Preemption Strategy for Traffic Signals at Intersections Near Highway-Railway Grade Crossings*. Transportation Research Board 83rd Annual Meeting.

Courage, K. G. and Wallace, C.E. (1977) *Evaluation of some bus priority strategies on NW 7th avenue in Miami*. Transportation Research Record. 626: 32-35.

Dion, F., Rakha, H., and Kang, Y.S. (2004) *Comparison of delay estimates at under-saturated and over-saturated pre-timed signalized intersections.* Transportation Research Part B 38 99-122

Energy Information Administration (EIA) (2008) website www.eia.doe.gov.iea. Projection: EIA, World Energy Projections Plus 2008

Evans, H. and S Skiles, G. (1970) *Improving public transit through bus preemption of traffic signals.* Traffic Quarterly 24 (4): 531-543.

Fehon, K., Jarzab, J., Emoto, C. and Dagang, D. (2004) *Transit signal priority for Silicon Valley bus rapid transit. DKS Associates,* http://www.dksassociates.com/, Accessed July.

FHWA (2003) *Manual on Uniform Traffic Control Devices for Streets and Highways.* FHWA, U.S. Washington, D.C.

Garder, P. (1989) *Pedestrian safety at traffic signals: a study carried out with the help of a traffic conflicts technique.* Accident Analysis and Prevention 21, 1989, pp. 435-444.

Gifford, J., Pelletiere D., and Collura J. (2001) *Stakeholder Requirements for Traffic Signal Preemption and Priority in the Washington D.C. Region*. Preprint CD-ROM of Transportation Research Board 80th Annual Meeting, 2001, Washington, D.C.

Gettman, D., Shelby, S.G., Head, L., Bullock, D. M. and Soyke, N. (2007) *Data-driven algorithms for real-time adaptive tuning of offsets in coordinated traffic signal systems.* Transportation Research Record, 2035, 1-9.

Golani, A. and Damti, H. (2007) *Model for Estimating Crossing Times at High Occupancy Crosswalks.* Proceedings of the 86th Transportation Research Board Annual Meeting, Washington, D. C., 2007.

Hayashi, K., Sugimoto, M., (1999) *Signal Control System (MODERATO) in Japan,* Intelligent Transportation Systems, Proceedings. 1999 IEEE/IEEJ/JSAI International Conference.

Head, L., Gettman D., and Wei, Z.P. (2006). *Decision Model for Priority Control of Traffic Signals*. Transportation Research Record, no. 1978: 169-177.

Hunt, P.B., Robertson, D.I. and Bretherton, R.D. (1981) *SCOOT: A Traffic Responsive Method of Coordinating Signals.* TRRL Laboratory Report 1014. Transportation and Road Research Laboratory, Crowthorne, Berkshire, U.K.

Institute of Urban Traffic Research (1999) *ITS Developed by Japanese Police*, Japan Traffic Management Technology Association, Japan

Intelligent Transportation Society of America (2004*) An Overview of Transit Signal Priority*, Washington, D.C.

Ishaque, M.M., Noland, R.B. (2005) *Micro-simulation of vehicle and pedestrian signal timings: minimizing multi-modal travel times.* In Transportation Research Record, No. 1939, Transportation Research Board of the National Academics, Washington, D.C.,, 2005. pp.107–122.

Ishaque, M.M., Noland, R.B. (2007) *Trade-offs between vehicular and pedestrian traffic using micro-simulation methods.* Transportation Policy 14, 2007, pp. 124-138.

Janos, M. and Furth, P.G. (2002) *Bus Priority with Highly Interruptible Traffic Signals: Simulation of San Juan's Avenida Ponce de Leon,* Transportation Research Record*,* no. 1811: 157-165.

Japan Society of Traffic Engineers (2006) *Manual of Traffic Signal Control***.** Japan Society of Traffic Engineers.

Kimpel, T.J., Strathman, J., Bertini, R., Bender, P., and Callas, S. (2004) *Analysis of Transit Signal Priority using Archived TriMet Bus Dispatch System Data.* 83rd Annual Meeting of the Transportation Research Board*,* Washington, D.C.

Li, J.Q., Song, M.K., Li, M., Zhang, W.B. (2009) *Planning for Bus Rapid Transit in a Single Dedicated Bus Lane*. Journal of the Transportation Research Record, Washington, D.C., January, 2009

Li, M., Wu, G., Li, Y., Bu, F., and Zhang, W.B. (2007) *Active Signal Priority for Light-Rail Transit (LRT) at Grade-Crossings*, Journal of the Transportation Research Record, No. 2035

Li, M., Song, M.K., Wu, G.Y. (2009) *An Online Performance Measurement Method based on Arterial Infrastructure Data.* 87th Transportation Research Board Annual Meeting, Washington, D.C., January, 2009

Li, M., Yin, Y.F., Zhang, W.B., Zhou, K., Nakamura, H. (2010) *Modeling and Implementation of Adaptive Transit Signal Priority on Actuated Control Systems,* Journal of Computer-Aided Civil and Infrastructure Engineering (passed the first round of review and the second review is in progress).

Li, M., Alhajyaseen, W., and Nakamura, H. (2010) *A Traffic Signal Optimization Strategy Considering both Vehicular and Pedestrian Flows*, Journal of the Transportation Research Record, Washington, D.C. (passed the first round of review and the second review is in progress)

Li, M., Song, M.K., Zhou, K., and Zhang, W.B. (2009) *Measuring arterial performance using Bus Rapid Transit (BRT) vehicles as traffic probes*, 16th World Congress on ITS, Stockholm, Sweden

Li, M., Zhang, W.B., Zhou, K., (2007) *Parsons Traffic and Transit Laboratory*. 14th World Congress & Exhibition on ITS, Beijing, China

Li, M., and Yin, Y.F., (2005) *Field Evaluation of VTA Line 22 Bus Signal Priority System*, 13th World Congress & Exhibition on ITS, San Francisco

Li, M., Yin, Y.F., and Zhang, W.B., (2005) *Modeling adaptive transit signal priority on actuated control systems*. INFORMS, San Francisco.

Liu, H., Li, M., Alex, Skabardonis, and Zhang, W.B. (2004) *Development And Application of A Simulation Tool for Transit Signal Priority*. Proceedings of 83rd

Transportation Research Board Annual Meeting, Washington, D.C.

Li, M., Yin, Y.F., and Zhang, W.B. (2005) *Adaptive Transit Signal Priority on Actuated Signalized Corridors*, Proceedings of the 84th Transportation Research Board Annual Meeting, Washington, D.C.

Li, M., Wu, G.Y., Johnston, S., and Zhang, W.B., (2007) *Analysis Toward Mitigation of Congestion and Conflicts at Light Rail Grade Crossings and Intersections*, California PATH Research Report.

Li, M., Zhou, K., Zhang, W.B., and Li, Y., (2007) *Toward Deployment of Adaptive Transit Signal Priority System*, California PATH Research Report.

Li, M., Zhou, K., Zhang, W.B., and Li, Y. (2009) Field Operational Testing of Adaptive Transit Signal Priority System", California PATH Research Report.

Link, K. and Shalaby A. (2003) *Automated Transit Headway Control via Adaptive Signal Priority*. Journal of Advanced Transportation 38, no. 1: 45-67.

Liu, H., Alex, Skabardonis, and Li, M. (2006) *Simulation of Transit Signal Priority Using the NTCIP Architecture*. Journal of Public Transportation.

Liu, H., Li, M., Alex, Skabardonis, and Zhang, W.B. (2004) *Optimal Location of Detectors for Transit Signal Priority*. Journal of in Transportation Research Record, No. 1867, p. 144-150, 2004

Li, Y., Bu, F., Li, M., Wu, G., Zhang, W.B., and Zhou K., (2007) *Application of Advanced Detection Data in Development of Active Signal Priority System*, proceedings of 86th Transportation Research Board Annual Meeting, Washington, D.C.

Li, Y., Koonce, P., Li, M., Zhou, K., Li, Y.W., Beaird, S., Zhang, W.B., Hegen, L., Hu, K., Skabardonis, A., and Sun, Z.S., (2006) *Transit Signal Priority Research Tools*, Federal Transit Administration and California PATH Research Report.

Lowrie, P.R. (1982) *The Sydney coordinated adaptive traffic system (SCATS) – principles, methodology, algorithm*. Proceeding of International Conference on Road and Road Traffic Signaling, London.

Mirchandani, P., Head, L., Knyazyan, A., and Wu, W. (2001) *An approach towards the integration of bus priority and traffic adaptive signal control.* Preprint CD-ROM of Transportation Research Board 80th Annual Meeting, Washington, D.C.

Newell, G.F. (1965) *Approximation methods for queues with application to the fixed-cycle traffic light. SIAM Rev.* No. 2, pp. 223-240, 1965.

Nichols, A. and Bullock, D. (2004) *Planning Procedures for Estimating an Upper Bound on Bus Priority Benefits.* In Proceedings of the Eighth International Conference on Applications of Advanced Technologies in Transportation Engineering, May 26, 2004 – May 28, 2004, 169-174.

Noland, R.B. (1996) *Pedestrian travel times and motor vehicle traffic signals.* In Transportation Research Record: Journal of the Transportation Research Board, No. 1553,Transportation Research Board of the National Academics, Washington, D.C., 1996, pp.28-33.

Rakha, H. (2004) *Sensitivity analysis of transit signal priority impacts on operation of a signalized intersection.* Journal of Transportation Engineering, Vol. 130, No. 6, 796-804.

Takeshita, H., Kato, H., Hayashi, Y., and Shimizu,K., (2009) *Evaluating Bus Rapid Transit System in Nagoya City*, 88th Annual Meeting of the Transportation Research Board, Washington, D.C.

Wall, Z. and Dailey, D.J. (1999) *An algorithm for predicting the arrival time of mass transit vehicle using automatic vehicle location data.* 78th Annual Meeting of the Transportation Research Board, Washington, D.C.

Smith, B. L., Scherer, W. T., Hauser, T. A., Park, B. B. (2002) *Data-driven methodology for signal timing plan development: a computational approach.* Journal of Computer-Aided Civil and Infrastructure Engineering, 17, 387-395.

Song, M.K., Li, M., and Nakamura, H. (2010) *Real-time Arterial Performance Measurement using Signal Timing Data and Bus Rapid Transit (BRT) as Probes*. Proceedings of 88th Transportation Research Board Annual Meeting, Washington, D.C.

Tan, C.W., Park S.S., Liu, H.C., Xu, Q. and Lau, P. (2008) *Prediction of Transit Vehicle Arrival Time for Signal Priority Control: Algorithm and Performance.* IEEE Transactions on Intelligent Transportation Systems 9, no. 4: 688-696.

Tan, C.W., Li, M., Park, S., Lau, P., Liu, H. and Zhang, W.B. (2007) *Analysis of Communication Channel Establishment in a Transit Signal Priority System*, International Conference on Multimedia and Ubiquitous Engineering, Seoul, Korea

Tanaka, R., Takeuchi K., Masuyama, Y., and Maeoka, A. (2007) *Trial Operation of a New Public Transportation Priority System Using Infrared Beacons for Two-Way Communication*, Universal Traffic Management Society of Japan (UTMS Japan), 1998

Teknomo K. (2006) *Application of Microscopic Pedestrian Simulation Model.* In Transportation Research, Part F 9, 2006, pp. 15-27.

Turksma, S. (2001) *An overview of UTOPIA-SPOT development in Northern Europe.* Paper Presented at 8th ITS World Congress, Sydney, Australia.

United Kingdom (1998) *A New Deal for Transport: Better for Everyone*, The Government's White Paper on the Future of Transportation

Urbanik, T., Z. Tian, and R. Engelbrecht. (2000) *Pedestrian Timing with Split Phasing Operations.* In Proc., 70th ITE Annual Meeting, Nashville, Tenn., Aug. 6–9, 2000.

U.S. Department of Transportation (2008) *Fixed Route Buses Equipped with Automatic Vehicle Location: 2006 National Summary*.
http://www.itsdeployment.its.dot.gov/Results.asp?year=2006&rpt=M&filter=1&ID=376

Vincent, R.A., Cooper, B.R., and Wood. K. (1978) *Bus-actuated Signal Control at Isolated Intersections.* Report 814. Crowthorne, UK: Transportation and Road Research Laboratory.

Wang, X., Tian, Z., Ohene, F. A. and Koonce, P. (2009) *Pedestrian Delay Models at Signalized Intersections Considering Signal Phasing and Pedestrian Treatment Alternatives.* Proceedings of the 88th Transportation Research Board Annual Meeting, Washington, D. C., 2009.

Webster, F.V. (1958) *Traffic signal settings. Road Research Technical*, Paper no. 39. Transport Research Laboratory, Berkshire.

Weerasooriya, G.N., Bajwa, S.I., Kuwahara, M., and Sarvi, M. (2008) *An Improved Bus Signal Priority Model*, SEISAN-KENKYU, Vol. 60 No. 4, p. 59-63, Japan

Yamashiro, Z., Sakakibara, H., Mashiyama, Y. (1999) *Priority Control in Japan.* 1999 Mid-year traffic signal committee meeting, Minneapolis, MN, U.S.

Yin, Y.F., Li, M., and Skabardonis, A. (2007) *An Offline Offset Refiner for Coordinated Actuated Signal Control Systems*, Journal of Transportation Engineering

Zhou, K., Li, M., Yin, Y., Zhang, W.B., and Skabardonis, A. (2004) *Development of Adaptive Transit Signal Priority Systems*, University of California, Berkeley: Institute of Transportation Studies, California PATH Program, PATH Research Report *UCB-ITS-PRR-2004*