Multi-Modal Traffic Signal Design under Safety and Operations Constraints

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ABSTRACT

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Behzad Rouhieh

Currently, most transportation agencies design signal timing plans for intersection with the main objective of minimizing vehicular traffic delay while ensuring compliance with basic safety guidelines. Often times along urban roadways where automobiles share the space with large volumes of non-motorized users (i.e. pedestrians and cyclists), reaching a balance between delays and safety of all road users is a challenging task. In this thesis, different approaches are presented to address potential improvements on traffic operations and safety of intersections serving more than one mode of transportation.

The impact of tunnels on the pedestrian operations and the effect of applying different signal timing plans on the performance of an isolated intersection are being studied. A methodology is proposed to reach a desired compromise between the safety and efficiency of either an isolated intersection or a corridor of independent/coordinated intersections. An integrated delay-safety (*DS*) indicator is used in combination with a neural network based tool. The proposed methodology was applied to a real-world urban arterial in downtown Montreal, along which a bicycle path was recently built. The study area was evaluated using VISSIM, a microscopic traffic simulator, by coding traffic signal timing plans along the arterial to perform independently, or coordinated. The objective is to advance with minimum delay a specified transportation mode (i.e. automobiles or bicycles).

A Multi-Layer Perceptron (MLP) neural-network was built to identify what type of signal timing plan yields the best tradeoff between automobile delay and safety of non-motorized users. Based on traffic data collected from real-world and from simulations, a large date set of input/output pairs was used to train and test the MLP neural network. It was found that for 99.8% of the tested cases the neural network identifies correctly the configuration of signal timing plan that yields the optimal *DS* value.

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LIST OF SYMBOLS

Symbol	Description
α	Safety weight factor for vehicle-to-vehicle conflicts
β	Safety weight factor for vehicle-to-bicycle vehicle conflicts
γ	Safety weight factor for vehicle-to-pedestrian conflicts
λ_0	Arrival rate of opposing through traffic [veh/sec]
d_v	Average vehicle control delay [sec]
d_b	Average bicycle control delay [sec]
d_p	Average pedestrian control delay [sec]
DS_v	Delay and Safety Index for Vehicles
DS_b	Delay and Safety Index for Bicycles
DS_p	Delay and Safety Index for Pedestrians
g_b	Bicyclist green time [sec]
g_f	Non conflict green time period, starting when signal turns green until arrival of first left turning vehicle [sec]
g_p	Pedestrian green time [sec]
g_q	The portion of permitted green time that is blocked by opposing through traffic [sec]
g_u	The amount of green time used by turning vehicles to drive through opposing traffic [sec]
OCC_b^g	Average bicyclist occupancy of the conflict zone during bicycle green time [bicycles]

Symbol	Description
OCC_b^r	Average bicycle occupancy of conflict zone [bicycles]
OCC_b^u	Average bicycle occupancy of conflict zone, after the queue of opposing through movement clears [bicycles]
OCC_p^g	Average pedestrian occupancy of the conflict zone during green time [pedestrians]
OCC_p^r	Average pedestrian occupancy of conflict zone [pedestrians]
OCC_p^u	Average pedestrian occupancy of conflict zone, after the queue of opposing through movement clears [pedestrians]
P_{nc}	Probability of having no conflict, due to small headway of opposing through flow
P_{PC}	Probability of potential left turn conflict
PC_v	Expected number of vehicles with potential conflicts [veh]
PC_b	Expected number of bicycles with potential conflicts [bicycles]
PC_p	Expected number of pedestrians with potential conflicts [pedestrians]
PC_{LT}	Number of left turning vehicles with potential conflict [veh]
PC_{OT}	Number of opposing through traffic with potential conflicts resulting from left turning movement [veh]
t_l	Lower limit of potential conflict gaps that could result in potential left turn conflicts [sec]
t_g	No-conflict gap [sec]
t_{LT}	Turning time for a left turning vehicle [sec]

Symbol	Description
t_u	Upper limit of potential conflict gaps that could result in potential left turn conflicts [sec]
V_v	Total vehicle volume [veh/h]
V_b	Total volume of bicycles [bicycles/h]
V_p	Total number of pedestrians [pedestrians/h]
V_{LT}	Volume of left turning vehicles [veh/h]
V_p^g	Pedestrian volume during pedestrian green time [pedestrian/h]
V_b^g	Bicycle volume during bicycle green time [bicycle/h]
V_{OT-g_u}	Volume of opposing through traffic during green period of g_u

LIST OF ABBREVIATIONS

Abbreviation	Stands for
ANN	Artificial Neural Network
EB	East Bound
HCM	Highway Capacity Manual
LOS	Level of Service
LT	Left Turn
MLP	Multi-Layer Perceptron
MVP	Machine-Vision Processor
PSU	Portland State University
QC	Quebec
SGW	Sir George Williams
SLOS	Safety Level of Service
TDM	Transportation Demand Management
WB	West Bound

CHAPTER 1

INTRODUCTION

1.1 Background and Problem Definition

Traffic signals play an important role in the transportation network. A primary objective of signal timing settings is to move people through an intersection safely and efficiently. Achieving this objective requires a plan that allocates the right-of-way to various users and accommodates fluctuations in demand. One of the most used design criterion for signalized intersections is minimizing vehicular traffic delay. However, in urban environments with large volume of pedestrians and cyclists, transportation professionals should design the operating traffic signals to balance between delays of all road users with respect to their safety. Proper signal timing design becomes more critical to address for intersections within or around an urban university campus. The challenge is to accommodate high interactions between a large number of users, both motorized and non-motorized. The population of an urban university campus is heterogeneous due to the proximity of commercial and residential activities and increase in demand for relatively short time intervals such as breaks between classes. This usually means a significant amount of interactions between motor vehicles, pedestrians and bicyclists using the intersections.

One way to account for the effect of user interactions at the intersections is simulation. Traffic simulation models are becoming an increasingly important tool for traffic control. Simulators are needed to generate scenarios, optimize control and predict network behavior at the traffic operations level. They can give the traffic engineer overall information about the traffic conditions and the ability to assess current problems and project possible solutions. Computer simulation models provide the most detailed objective operational analysis technique available for evaluating design and traffic control features (Clark and Daigle 1997). Among the studies that use simulation software to analyze signal phasing design, to date, only a limited number consider multi-modal simulation, i.e. applying automobiles/pedestrians/bicyclists behavior. Due to advancements in computer systems, the simulation programs can process more efficiently large-scale networks with high level of details. Moreover, new algorithms are able to provide realistic simulation of pedestrian flows and their interactions with motorized vehicles and bicycles. (PTV America 2009).

1.2 Objectives and Scope of Work

The objective of this thesis is to study the potential improvements on traffic operations and safety at signalized intersection that serve motorized and non-motorized transportation modes. A methodology is proposed to reach a desired equilibrium between delays and safety of all road users for intersections with coordinated signal controllers or isolated intersection. In order to achieve the study objective, the following procedure has been identified:

1. Collect and process real-world traffic data for a particular study area.
2. Develop and calibrate a computer model of the study area in VISSIM, microscopic simulator software.

3. Propose a methodology to identify the signal plan that optimizes safety of non-motorized users and motor vehicles' delay. The method deploys a combined delay and safety measure in a neural network based adaptive tool.
4. Perform three analytical tasks to investigate:
   i. The impact of tunnels on the pedestrian operations: The current usage of the intersection is compared with alternative scenarios. The purpose is to devise a sensitivity analysis of the effect of re-routing pedestrian flows through underground tunnels that connect major buildings within the study area.
   ii. The effect of signal timing plans: In this task, the effect of applying different signal timing plans on the performance of an isolated intersection of study area is evaluated by using vehicle delay and pedestrian trip length as performance measures.
   iii. The effect of signal coordination: This task investigates if operational and safety performance of the major arterial in the study area can be improved by setting the signal controller of all intersections to operate in one of the three modes: (I) independent, (II) coordinated to promote automobile traffic and (III) coordinated for progression of bicycle flows.

1.3 Organization of the Thesis

This research work is organized in six chapters. The first chapter provides a brief introduction and presents the objective and scope of this thesis. Chapter 2 presents a literature review of the previous studies relevant to this research work. Chapter 3 describes the methodology used in this study. Chapter 4 introduces the research area and the data collection method. Chapter 5 discusses different experimental analyses performed in this study. Chapter 6 includes the conclusions drawn from this research work and potential research extensions.

CHAPTER 2

LITERATURE REVIEW

2.1 Transportation within University Campuses

One of the common features of universities' operations and planning offices is the effort to address the complex problem of road-users interactions under a continuous growth of student enrollment within their campuses. An overview of recent studies identifies various solutions that are used to alleviate safety and traffic operations effects of the increase in campus traffic and parking demand (Haines et al. 1974; Guyton 1983). For example, Shang et al. (2007) presented a case study of the campus parking problem at the Beijing University. They analyzed the inflow and outflow of vehicles, parking lots location and drivers' parking behavior and found some problems that according to the authors commonly exist in other Chinese universities (i.e. (i) Many vehicles park in the zone for public activities; (ii) Current parking lots utilize the ground spaces around buildings; (iii) The on-street parking has caused severe traffic congestion; (iv) Safety hazard for pedestrians and multitude of daily passing vehicles through the campus).

Daggett and Gutkowski (2003) documented the types of transportation and parking policies, demographics, and land use characteristics and the relationship between them in 23 university campuses. Balsas (2003) investigated how college campuses encouraged modal shift from cars to bicycling and walking to make the campuses more sustainable communities from the bicycle and pedestrian planning point of view. His findings showed active promotion of alternative transportation modes in college campuses. The author recommended consideration of seven measures to have more bicycle and walking friendly campuses (i.e. transportation demand management (TDM) strategies, organization, planning, facilities, promotion, education, and enforcement).

Most of the existing research focuses on safety and operations efficiency within campuses that have limited interaction with users outside the university perimeter. For example, Rodriguez et al. (2008) investigated pedestrian crosswalk safety issues and measures used to improve pedestrian safety in the top ten big universities in the United States. The authors identified various traffic demand management techniques as well as traffic supply and enforcement strategies. Another study by Isler et al. (2005) presents alternative parking management policies within campuses. For example, implementing restrictive parking policies, such as prohibiting undergraduates from bringing vehicles to campus or making residents within a particular radius of the campus ineligible for a parking permit. The authors suggest that universities that plan to devote campus land to academic facilities rather than parking lots may want to direct their resources towards the transportation aspects of the surrounding area rather than providing additional on-campus housing to students.

Lawson (2001) analyzed the impact of the Transit Pass program at Portland State University (PSU) as a TDM strategy. In preparation to provide incentives for students and employees to find alternative forms of transportation, PSU implemented a combination strategy that included raising the price of parking and providing a transit subsidy program. Their findings indicate that the length of stay is an important factor in mode choice, both for employees and students. The financial structure of many TDM programs results in cross-subsidizing those who ride transit by those individuals who drive.

Other recent studies are concerned with pedestrian behavior inside university campuses. Schroeder et al. (2009) explored pedestrian compliance behavior along an urban arterial corridor separating a major university campus from an urban business district. His study showed evidence of frequent pedestrian non-compliance, both in terms of utilization of the crosswalks and the WALK phase at signalized crossings. Based on his findings, non-compliance at both signals and midblock locations were related to signal phase indications and expected wait times of pedestrians.

Medina et al. (2008) evaluated the effects of different types of crosswalk signing and marking treatments on pedestrian safety by analyzing pedestrian-vehicle interactions and conflicts at 24 crosswalks in the University of Illinois, Urbana-Champaign campus area. To document perceptions and preferences, they performed two opinion surveys, one for pedestrians and one for drivers. Results indicate that pedestrian crossing signs are perceived by both pedestrians and drivers as significantly safer than other pedestrian signs, but only 50% of them correctly understand the meaning of the signs. The other half has different degrees of misunderstanding that may create false sense of security, thereby increasing the potential for pedestrian-vehicle conflicts.

Akin and Sisiopiku (2007) investigated pedestrian crossing compliance (signal and spatial) characteristics at signalized crossings in a downtown campus of Michigan State University. The authors found that signalized intersection crosswalks in their study site attract pedestrians as crossing points as they are highly visible and strategically located at intersections to where major pedestrian paths lead. According to their observation, signal timing and/or phasing schemes failed to convince the majority of pedestrians to cross during the pedestrian WALK interval. Authors believe that low vehicular volumes during some periods of the day or improper signal timing design could be an explanation for this non-compliance behavior.

2.2 Operational and Safety Performance of Signalized Intersections

Two main factors that should be considered in designing traffic signals are operational and safety performance. One major design criteria for signalized intersections is to minimize the delay for vehicular traffic. However, in urban environments with large volume of pedestrians and cyclists, there should be a balance between delays of all road users with respect to their safety. The Highway Capacity Manual (HCM 2000) provides level of service (LOS) measures for all modes crossing at signalized intersection, based on estimates of delay they experience while attempting to cross the street.

Day et al. (2009) extended the Highway Capacity Manual's (HCM) intersection saturation metric and Webster's single ring formulation for cycle length and introduced a model for dual ring operation. The authors recommended a tool for evaluating the effectiveness and efficiency of cycle length at a signalized intersection. Their framework identified periods of time when cycle length could be substantially shortened or increased to provide some improvements. It also identified periods of the day when cycle length is adequate and capacity problems are best addressed by split adjustments.

There are several studies for evaluating the trade-offs between comfort and safety of road users in signalized intersections by using LOS concept. For example, Landis et al. (2003) described an intersection LOS model for bicycle through movement. Steinma and Hines (2004) developed a methodology to assess features affecting pedestrians and bicyclists crossing signalized intersections. This evaluation is based on the influence of comfort and safety on non-motorized road users and includes: crossing distance, roadway space allocation for crosswalks/bike lanes, corner radius dimension and characteristics of traffic signal. Dowling et al. (2008) presented a method for multimodal assessment of the quality of service for four different types of users: auto drivers, transit passengers, bicycle riders and pedestrians. They developed four level-of-service models for each mode based on the street cross section, intersection controls and traffic characteristics.

Ishaque and Noland (2007) used a micro-simulation model to study the effects of signal cycle timings on delay and travel time costs for both vehicles and pedestrians in various pedestrian phasing scenarios. They applied various multi-attribute weighting criteria to different components of travel delay to examine cost trade-offs between pedestrians and vehicles. Their results showed that the policy selection when considering pedestrians may differ from that when just considering vehicular traffic.

Zhang and Prevedouros (2003) introduced a methodology, based on HCM (2000), that quantifies potential conflicts between left-turning vehicles and opposing through vehicles and pedestrians. They developed a model that combines delay and safety as an index, denoted DS, to evaluate the LOS. The authors used this measure in a case study for two intersections. The authors used safety factor weights to include the vulnerability of pedestrians in their interactions with other transportation modes (i.e. vehicles and bicycles). Their results showed that if potential conflict is not considered, the signal timing plan with permitted left turn improves LOS as opposed to the timing plan with protected left turns. However, if potential conflict is considered, the estimated LOS under protected left-turn phasing is better than under permitted left-turn phasing based on DS, only when the safety weight factors exceed a certain value.

Several research studies have been recently performed on safety issues of non-motorized users at intersections. For example, Fuquan et al. (2008) presented the concept of safety level of service (SLOS). First, the authors developed a model of SLOS for signalized intersections based upon vehicle conflicts, intersection geometry, signal phasing, pavement markings; signage and pavement condition. Then they combined the existing performance measure of LOS with the risk factor of SLOS to develop the delay and safety index that accounts for the safety of intersection.

Carter et al. (2007) introduced a macro-level Bicycle Intersection Safety Index (Bike ISI) using data on traffic volume, number of lanes, speed limit, presence of bicycle lane, parking, and traffic control to give a rating for an intersection approach according to a six-point scale. Authors recommend the Bike ISI to be used by practitioners to prioritize intersections based on the relative likelihood of safety for bicyclist. They can also target the most hazardous sites for conducting a more detailed review on how to improve their safety.

Zegeer et al. (2006) presented a similar approach to identify the level of risk for pedestrian at intersections by calculating the Pedestrian Intersection Safety Index (Ped ISI). Ped ISI is a cross-walk based tool to prioritize a group of pedestrian crossings at intersection based for safety improvements. The authors recommended FHWA's PEDSAFE (Harkey and Zegeer 2004) as an assistant tool to select appropriate countermeasures and safety treatments to improve the pedestrian safety.

Chi et al. (2009) studied the results of a before-after observational evaluation of two low-volume, high-pedestrian intersections in inner Portland, Oregon where marked crosswalks were installed. Video recordings were used to evaluate pedestrian and motorist behaviors. They concluded that marked crosswalks had mixed results in changing behaviors that would promote safer crossing conditions or increased pedestrian or driver attentiveness, thereby reducing the risk for potential pedestrian-vehicular crashes.

2.3 Traffic Signal Coordination

Several traffic studies (see for example Castro-Neto et al., 2006 and Skabardonis et al., 1998) showed that improved operations of closely spaced intersections in urban downtown areas can be achieved if implemented signal timing plans account for some kind of signal synchronization. Signal coordination along a roadway is more efficient whenever traffic demand along that particular road is significantly larger than the demand along the crossing roads. Signal coordination is preferred for major arterials or collector roads, and its effectiveness in promoting traffic largely depends on the travel speed, the critical intersection (i.e. the intersection with highest flow to saturation flow ratio) and the spacing between crossing roads. Signal coordination systems can be implemented to run independently over select corridors, or can be integrated in area wide signal adaptive systems such as Sydney Coordinated Adaptive Traffic System (SCATS), Split Cycle, Offset Optimization Technique (SCOOTS), Optimized Policies for Adaptive Control (OPAC) etc. (Lee et al., 2005).

Most of the recent studies on signal coordination attempt to identify the most appropriate tools and strategies in adaptive signal systems. For example, Rakha et al. (2000) investigated potential benefits of coordinating traffic signals along corridors that cross adjacent jurisdictions. The authors showed that optimizing the location of the break in traffic signal coordination can impact the efficiency of travel (i.e. reduced travel time), the environment (i.e. reduction of gas emissions and fuel consumption occurred due to reduction in delay) and safety (i.e. severity of vehicle crashes). Other studies are concerned with real-time modeling of coordinated signals by automatic adjustment of signal offsets using either traditional analytical tools (Abbas et al., 2001) or soft-computing techniques such as genetic algorithms (Castro-Neto et al., 2006).

Automatic adjustment of signal offsets may require specific treatment because it has to accommodate fluctuations in traffic flows and oversaturated intersections. For example, Girianna and Benekohal, (2002) proposed an algorithm to solve signal coordination problem on two-way arterial networks with oversaturated intersections. The algorithm can be implemented in either one-way or two-way progression modes. Another study by Wilson et al. (2006) evaluated coordinated adaptive signal timing strategies using a microsimulation framework. The authors investigated the benefits of coordinated adaptive strategies of the SCATS algorithm using Paramics.

In general, most of the existing studies are concerned with mono-modal vehicle progression along busy corridors, due to the fact that urban trips are heavily vehicle-based. It is believed that designing for multi-modal progression can contribute to a more sustainable transportation system, especially, if it encourages travelers use non-motorized transportation modes such as bicycles and pedestrians.

For example, Virkler (1998) described three techniques to determine appropriate signal offsets to benefit pedestrians. The author either explored the possibility that pedestrians are able to keep a certain average pace, or accommodated a tradeoff between pedestrian and vehicular delay. This study indicated that the platoon effect due to upstream signals can either increase or decrease pedestrian delay, depending on the offsets of the downstream signals. For signals with low green time to cycle length ratios, the platoon effects on delay are greater than those used in the HCM for the worst and best vehicle platooning situations. In order to estimate the effects of upstream signal platooning, the author suggested using field measurements of the arrival pattern on the approach to a signal. He believed this can be used to modify delay results calculated from delay equation that assumes pedestrians arrive randomly.

Bicycles have been used for many years heavily in high-density urban areas of Asian developing countries. However, only recently large North-American cities started to investigate the feasibility and impact on sustainable development of this 'active' and 'green' transportation mode, while trying to learn from the European practice (Pucher and Buehler, 2008). A recent study by Shladover et al. (2009) showed the way to accommodate the needs of bicyclists for adequate green time to cross wide arterials at signalized intersections. Authors made observations of the timing of bicyclists' intersection crossing maneuvers. Video recordings were made of bicyclists' crossings and the video images were processed to extract the bicyclists' trajectories. These were synchronized with video images of the traffic signals so that the timing of the bicyclists' maneuvers could be determined relative to the signal phases. The authors presented the detailed measurement of bicycle crossing time as base of signal timing design. They parameterized the measurements in terms of starting offset time and final crossing speed so that the results could be generalized for intersections with arbitrary width.

Another study by Taylor and Mahmassani (2000) investigated signal coordination to provide progression for bicycles on shared facilities. The authors present a framework that emphasized one-way progression design and does not account for actuated signals, pedestrian crossing or turning traffic. The results showed that, because of speed variability, there will be less benefit in long street segments with widely spaced intersections. However, if negative impacts to automobiles are minimal, short sections with closely spaced intersections are most likely to produce less delay and fewer stops for bicycle users.

Currently, traffic practitioners and researchers seek solutions to reduce the significant costs associated with the delay and traffic congestion due to lost productivity, negative environmental impact and energy waste. On the other hand, in recent years more and more transportation agencies started to recognize that a mono-modal surface transportation approach is not economically sustainable, especially for busy central-business districts of urban areas.

For example the city of Montreal (Ville de Montreal, 2008) started to promote bicycle use as alternative transportation mode for short trips and is currently investing in its bicycle network to expand it from 400 to 800 km. However, bringing more non-motorized users on the new and existing facilities has to be complemented by adequate safety measures and policies.

Recently, several studies attempted to investigate the safety and operations implications of designing for more bicycle and pedestrian friendly facilities. Jutaek et al. (2008) developed prediction model for bicycle crashes at signalized intersections using numerous potential variables related to bicycle crashes by conducting field survey at 151 intersections in Inchon, Korea. The authors found Poisson regression as the most suitable model to estimate bicycle crashes at intersections. They believe that the levels of safety for bicycle crossing intersections can be estimated through bicycle crash prediction models. Another study by Demetsky and Natarajan (2009) developed a four-component framework for administering the bicycle and pedestrian safety and similar programs. In this framework, analysis procedures were identified for each component that can be used for identifying hazardous locations, determining causal factors, establishing performance measures, and determining potential countermeasures. The framework was then applied for selecting an appropriate safety treatment and for prioritizing a set of safety projects requested for funding. The authors believe that the levels of safety of bicycle travels at currently existing or future intersections can be estimated through bicycle crash prediction models and efficient countermeasures can be implemented to decrease crash rates and reduce socio-economic loss.

2.4 Traffic Simulation Models

Several modeling techniques are available to evaluate the safety and efficiency of operations of various transportation facilities. Using simulation in traffic modeling is an effective approach to identify the benefits and limitations of different design alternatives. Computer simulation has become a widely used tool in transportation engineering with a variety of applications from scientific research to planning, training and demonstration. Traffic simulation packages are frequently used by researchers and practitioners for the analysis of traffic. One of the analysis methods used with simulation models is first, to develop a calibrated base model of existing conditions, next, to extend the model to include the design alternatives and finally, to make conclusions on the basis of the modeling results.

Traffic simulation models vary by the desired level of analysis (planning, design or operation) of the real world network. Traffic simulation models are grouped by the level of details into microscopic, macroscopic or mesoscopic (a mixture of first two types). Macroscopic models assume that traffic flow can be modeled as one-dimensional continuous fluid and place more emphasis on the aggregate behavior and characteristics of the traffic stream. Macroscopic models simulate traffic flow, by calibrating macroscopic parameters (i.e. speed, flow, and density). On the other hand, microscopic models are capable of tracing the movements of individual vehicles in time and space within the traffic network. Each vehicle advances through the network at every simulation unit according to the physical characteristics of the vehicle (e.g. length, acceleration and deceleration rate), the kinematic laws (e.g. acceleration times time equals velocity, velocity times time equals distance) and driving behavior models (e.g. car following, lane changing, etc.).

A third category simulation models are mesoscopic models that combine the properties of both microscopic and macroscopic simulation models to model movement of platoons of vehicles. Mesoscopic models can handle the higher level of detail for large study areas by simulating individual vehicles, while describing their interactions based on aggregate (macroscopic) relationships.

VISSIM (PTV America, 2009) is a microscopic, time-step and behavior-based simulation model developed to analyze the full range of functionally classified roadways and public transportation operations. VISSIM can model integrated roadway networks found in a typical corridor as well as various modes consisting of general-purpose traffic, buses, light rail, heavy rail, trucks, pedestrians, and bicyclists. In order to develop a model, the user begins by importing an aerial photo or schematic drawing of the study area into the simulator. Next, additional network elements can be added and network's specific attributes are defined (e.g., lane widths, speed zones, and priority rules). The basic element of the street network is a link, which is a physical representation of a transportation facility and it may have one or more lanes promoting traffic in the same direction. The network is composed of links and connectors. A connector attaches two adjacent links and allows vehicle movements between two links. In VISSIM, signal control is modeled by placing the signal heads at the location of the stop lines. Vehicle or pedestrian detectors measure the traffic for the signal control (i.e. gap, occupancy, presence) and they are used for microscopic and macroscopic measurements (i.e. speeds, volumes and travel times).

The latest available version of the simulator, VISSIM 5.2, integrates a recently added feature, a pedestrian add-on module. This pedestrian module is based on the social-force model (see for example Helbing and Molnar 2005 and Johansson et al. 2007). This module features the ability of modeling pedestrian along various facilities (i.e. tunnels, ramps, building stairwells, etc.) and allows for more realistic interactions between pedestrian and motorized vehicles.

2.5 Artificial Neural Network Modeling in Transportation Engineering

Artificial Neural Network (ANN) models have been used to solve various transportation problems, such as planning, operation and control. If properly trained, ANNs exhibit good generalization properties and can be used in applications to perform function approximations, pattern recognitions or classification and clustering. Alecsandru and Ishak (2004) conducted a study to seek optimal settings that maximize the performance of soft computing techniques in short-term traffic prediction of speed on freeways. Saito and Fan (1999) applied artificial neural network to evaluate LOS for isolated intersections, based on past experience. They considered several factors affecting vehicle delay as input. These factors were grouped in three categories based on traffic, geometric and signalization conditions. The pedestrian effect was accounted in by using the number of conflicting pedestrians. Dougherty et al. (1993) and Smith and Demetsky (1994) utilized a backpropagation neural network to forecast short-term traffic volumes. Gilmore and Abe (1995) also applied a neural network model to forecast network traffic volumes by using data from a simulation model. Kwon and Stephanedes (1994) developed two models: Kalman filter based adaptive model and backpropagation neural network; then compared them with the UTCS-2 model. Abdelwahab and Abdel-Aty (2002) studied some of the traffic safety issues related to toll plazas by using two artificial neural networks paradigms: the Multi-Layer Perceptron (MLP) and Radial Basis Functions (RBF) neural networks. Abdelwahab and Abdel-Aty (2001) also investigated the use of artificial neural networks in predicting injury severity at signalized intersections.

CHAPTER 3

METHODOLOGY

Transportation professionals designing traffic signal timing plans for signalized intersections attempt to reach a tradeoff between users delay and safety. To study the operational and safety performance of an urban intersection, one needs a combined measure that accounts for both motor vehicles' delay and non-motorized users' safety. In this section, first such a performance measure is presented and then a methodology for evaluating the effect on performance of coordinating signal controllers of adjacent signalized intersections is proposed.

3.1 Performance Measures

In Highway Capacity Manual (2000) the effect of pedestrian and bicycles on turn movements is addressed by adjusting the saturation flow rate at the intersection. However, safety hazards of these users are not explicitly modeled. Zhang and Prevedouros (2003) developed a method that combines collision risk and delay in a single performance measure, which can be used in level of service (LOS) assessment. The authors introduced a methodology that accounts for potential conflicts between left-turning vehicles and opposing through vehicles and pedestrians. Basically, for any given intersection, a delay and safety index (DS) is calculated by using one combined measure. This measure incorporates the perception of inconvenience, by measuring delay for both motorized and non-motorized road users, and risk factor, by estimating possible conflicts between the road users.

The proposed DS index is being used for evaluating the effect of signal coordination on the study area in this thesis. Equations 1- 4 summarize the calculation of DS:

$$DS = \frac{(DS_v \times V_v) + (DS_b \times V_b) + (DS_p \times V_p)}{V_v + V_b + V_p} \tag{1}$$

$$DS_v = d_v \times \left[1 + \alpha \times \frac{PC_v}{V_v}\right] \tag{2}$$

$$DS_b = d_b \times \left[1 + \beta \times \frac{PC_b}{V_b}\right] \tag{3}$$

$$DS_p = d_p \times \left[1 + \gamma \times \frac{PC_p}{V_p}\right] \tag{4}$$

Where,

DS_v= Delay and Safety Index for Vehicles

PC_v= Expected number of vehicles with potential conflicts [veh/h]

V_v= Total vehicle volume [veh/h]

DS_b= Delay and Safety Index for Bicycles

PC_b= Expected number of bicycles with potential conflicts [bicycles/h]

V_b= Total bicycle volume [bicycles/h]

DS_p= Delay and Safety Index for Pedestrians

PC_p= Expected number of pedestrians with potential conflicts [pedestrians/h]

V_p= Total pedestrian volume [pedestrians/h]

d_v= Average vehicle control delay [sec]

d_b= Average bicycle control delay [sec]

d_p= Average pedestrian control delay [sec]

α= Safety weight factor for vehicle-to-vehicle conflicts

β=Safety weight factor for vehicle-to-bicycle conflicts

γ= Safety weight factor for vehicle-to-pedestrian conflicts

The approach introduced by Zhang and Prevedouros (2003), presented in equations 1-4, allows for adjusting the importance of risk or convenience in the calculated DS measure through its safety weight factors: α, β, and γ. This helps in estimating DS indices sensitive to the characteristic of the study area. For example, some authors (Kim 2000), showed that vehicle-pedestrian crashes are more severe than vehicle-vehicle crashes. This can be accounted for by setting a higher value to the pedestrian safety weight factor. The procedure to calculate the potential conflicts for each approach in the intersection $(PC_v, PC_p \text{ and } PC_b)$ is detailed hereafter.

3.1.1 Potential vehicle-to-vehicle conflicts

The model for the vehicle-to-vehicle conflicts is depicted in Figure 3.1. For illustration purposes, the details are provided in this methodology for one set of conflicts, in movements from the EB-WB approaches. However, the method applies similarly for all four pairs of conflicts in a typical 4-way intersection.

In Figure 3.1, the conflict between LT and opposing through vehicles occurs only during a portion of the EB-WB green phase. There are two intervals, hereafter are referred to as no-conflict periods, during which there is no interaction between LT and opposing traffic. When the EB-WB signal indication becomes green, the first conflict occurs as soon as the first left turning (LT) vehicle on WB approach arrives at the intersection. The first no-conflict period, g_f; starts from the beginning of green phase and continues until first LT vehicle arrives at intersection. For exclusive LT lanes, $g_f = 0$.

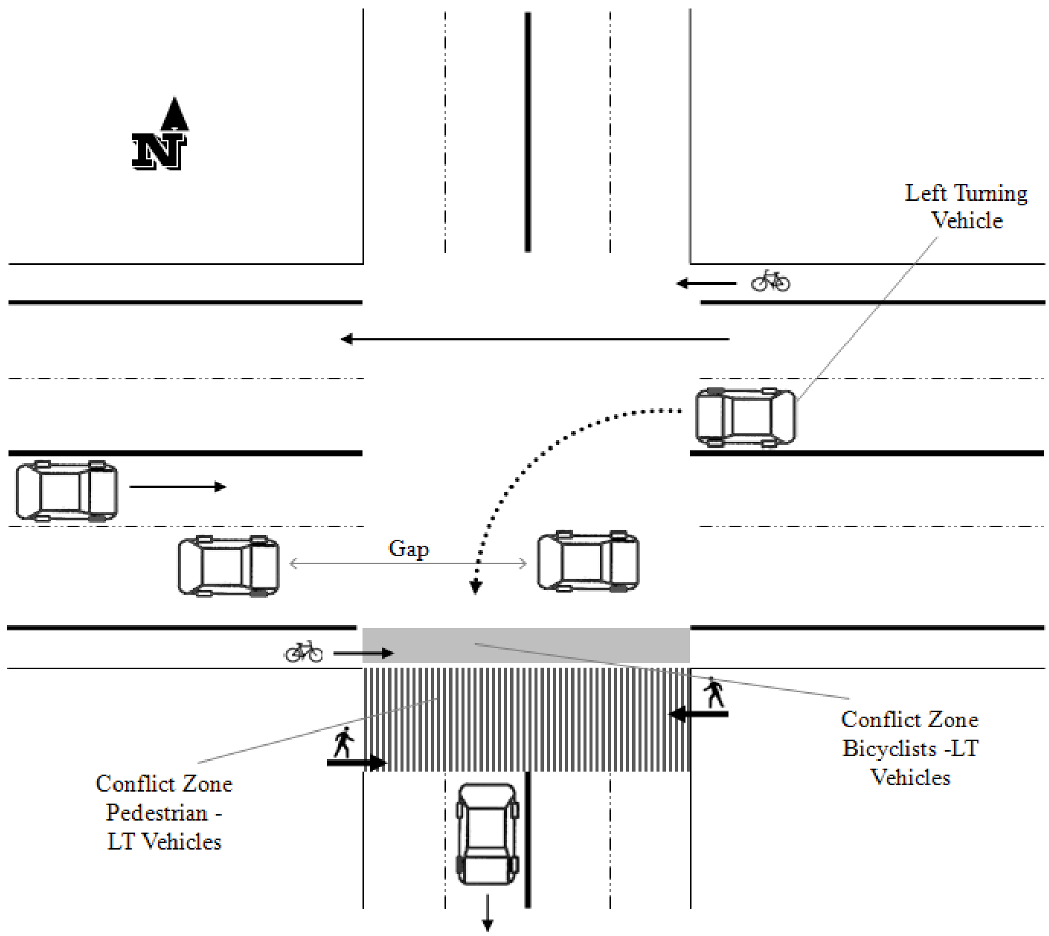

Figure 3.1: General intersection layout for potential conflict between vehicles, pedestrians and bicycles

The second no-conflict period, g_q; occurs when a queue of vehicles in the opposing approach discharge at the saturation flow rate and there is virtually no acceptable gap for LT vehicles on the WB approach to complete the maneuver. Hence, no vehicle-to-vehicle conflict may happen until the opposing flow rate drops beyond the saturation flow.

Considering the two periods mentioned above, the amount of green time that is needed by LT vehicles to drive through opposing traffic, g_u; is estimated by using the following equation:

$$g_u = \begin{cases} g - g_q & when\ g_q \geq g_f \\ g - g_f & when\ g_q < g_f \end{cases} \tag{5}$$

By calculating the turning time for a left turning vehicle, t_{LT}, and assuming the average driver's reaction time of δ seconds, the total maneuver time for a LT vehicle to clear the intersection is: $t_{LT} + \delta$ seconds. Therefore, potential conflict gaps in opposing traffic can be defined as ranging between t_l and t_u, calculated as shown in equations 6a and 6b. In other words, any opposing vehicle arriving with headway within [t_l , t_u] range is considered as a conflict to LT traffic. Gaps smaller than t_l or greater than t_u are not considered in conflict calculation.

$$t_l = t_{LT} + \delta - 2 \tag{6a}$$

$$t_u = t_{LT} + \delta + 2 \tag{6b}$$

Where:

t_u= upper limit of potential conflict gaps that could result in potential LT conflicts [sec]

t_l= lower limit of potential conflict gaps that could result in potential LT conflicts [sec]

t_{LT}= turning time for a left turning vehicle [sec]. It can be derived from computer simulation results.

The headway of arriving opposing traffic is assumed to be distributed based on Poisson distribution, which is a commonly accepted assumption for lightly congested traffic conditions (Mannering et al., 2005). Then probability of observing headway h between t_l and t_u on opposing approach is:

$$P_{PC} = P\,(\,t_l \leq h \leq t_u\,) = e^{-\lambda_0 t_l} - e^{-\lambda_0 t_u} \tag{7}$$

Where:

P_{PC}= Probability of potential LT conflict

λ_0= Average arrival rate of opposing through traffic [veh/sec]

The expected number of vehicles with potential conflict can be calculated as:

$$PC_v = PC_{LT} + PC_{OT} \tag{8}$$

$$PC_{LT} = PC_{OT} = \begin{cases} V_{LT} \times P_{PC} & when\ V_{LT} \leq V_{OT-g_u} \\ V_{OT-g_u} \times P_{PC} & when\ V_{LT} > V_{OT-g_u} \end{cases}$$

Where:

PC_{LT}= Number of potential conflict for LT vehicles

PC_{OT}= Number of potential conflicts for opposing traffic resulting from LT movement

V_{LT}= Volume of LT vehicles [veh/h]

V_{OT-g_u}= Volume of opposing through traffic during green period of g_u [veh/h]

3.1.2 Potential pedestrian conflict

In order to calculate the potential pedestrian conflicts, one needs to estimate the number of pedestrians occupying the crosswalk during the green time. Zhang and Prevedouros (2003) used HCM (2000) method of adjusting saturation flow rate, to estimate the potential conflicts between crossing pedestrians and left turning (LT) vehicles. A conflict zone is defined on the crosswalk where the most interactions between pedestrians and vehicles occur (Figure 3.1). The HCM (2000) method, which is based on a study by Milazzo et. al. (1998), proposes a linear model to estimate the occupancy of pedestrians (OCC_p^g) inside the conflict zone during pedestrian green time (g_p) as below:

$$OCC_p^g = \begin{cases} V_p^g \div 2{,}000 & when V_p^g \leq 1{,}000 \\ V_p^g \div 10{,}000 + 0.4 & when\ V_p^g > 1{,}000 \end{cases} \tag{9}$$

$$V_p^g = V_p \times (g_p / C)$$

Where:

OCC_p^g= Average pedestrian occupancy of the conflict zone during pedestrian green time [pedestrian]

V_p^g=Pedestrian volume during pedestrian green time [pedestrian/h]. It is calculated by equation 11:

V_p= Pedestrian flow rate [pedestrian/h]

g_p= Pedestrian green time [sec]

C= Cycle time [sec]

Drivers turning left will have to find proper gaps in the opposing traffic. Therefore, pedestrians crossing the conflict area are not vulnerable to conflicts with turning vehicles during whole period of green time (g_p). Milazzo et. al. (1998) recognized that pedestrians are protected under two circumstances: first, the time period during which the vehicles queued on the opposing approach clear the intersection; and second, when the opposing vehicles arrive with small headways that are not safe enough for LT movements. These two time periods are calculated with equation 10 and 11:

$$OCC_p^u = OCC_p^g \times \left[1 - 0.5(g_q/g_p)\right] \quad (10)$$

$$OCC_p^r = OCC_p^u \times P_{nc} \quad (11)$$

$$P_{nc} = e^{-\lambda_0 t_g} \quad (12)$$

Where:

OCC_p^u = Average pedestrian occupancy of conflict zone, after the opposing queue clears (Assuming the uniform arrival of LT vehicles) [pedestrian]

g_q = The portion of permitted green time that is blocked by opposing traffic [sec]

OCC_p^r = Average pedestrian occupancy of conflict zone [pedestrian]

P_{nc} = Probability of having no conflict, due to small headway of opposing flow

λ_0 = Arrival rate of opposing traffic [veh/sec]

t_g = No-conflict gap for opposing through vehicles flow [sec]

When the opposing traffic arrive with headway less than t_l, there is not enough time for LT vehicles to perform the movement. Thus, pedestrians could benefit from this blockage and cross by avoiding interaction with turning vehicles. Under this circumstance, no-conflict duration can be set equal to t_l, and P_{nc} represents the probability of having opposing flow with minimum headway of t_l.

The potential vehicle-pedestrian conflicts can be estimated by using the equation below:

$$PC_p = V_p \times OCC_p^r \tag{13}$$

3.1.3 Potential bicycle conflict

The potential bicyclist conflicts can be calculated with the same method as for pedestrians. The equations presented in previous section can be rewritten as following:

$$OCC_b^g = \begin{cases} V_b^g \div 2{,}000 & when\ V_b^g \leq 1{,}000 \\ V_b^g \div 10{,}000 + 0.4 & when\ V_b^g > 1{,}000 \end{cases} \tag{14}$$

$$V_b^g = V_b \times (g_b/C)$$

Where:

OCC_b^g = Average bicyclist occupancy of the conflict zone during bicycle green time [bicycle]

V_b^g =Bicycle flow rate during green time [bicycle/h]

V_b = Volume of bicycles [bicycles/h]

g_b = Bicyclist green time

Bicyclists, similar to pedestrians, are protected during the period when the queue on the opposing approach clears; and during the period when the opposing vehicles arrive with small headways not suitable for LT movements (equation 15).

$$OCC_b^u = OCC_b^g \times [1 - 0.\ 5(g_q/g_b)] \tag{15}$$

$$OCC_b^r = OCC_b^u \times P_{nc}$$

$$P_{nc} = e^{-\lambda_0 t_g}$$

Where:

OCC_b^u= Average bicycle occupancy of conflict zone, after the opposing queue clears (Assuming the uniform arrival of LT vehicles) [bicycle]

g_q= The portion of permitted green time that is blocked by opposing traffic [sec]

OCC_b^r= Average bicycle occupancy of conflict zone [bicycle]

P_{nc}= Probability of having no conflict, due to small headway of opposing flow. It can be estimated as following:

λ_0= Arrival rate of opposing traffic [veh/sec]

t_g= No-conflict gap [sec]

The potential vehicle-bicycle conflicts can be estimated by using the equation below:

$$PC_b = V_b \times OCC_b^r \tag{16}$$

3.1.4 Special case: One-way streets

The methodology presented in the previous section can be used for traffic operations and geometric design conditions with appropriate modifications. For example, if the major arterial is a one-way street there is no need to account for vehicle-to-vehicle conflict on LT movements. Similarly, there is no vehicle-to-vehicle conflict for right turning vehicles at intersection. Under these circumstances, pedestrian and bicyclists do not benefit from the protection caused by opposing traffic blocking the LT drivers. Therefore, $g_q = 0$ & $P_{nc} = 1$ and PC_p and PC_b can be estimated by using the modified equations 17-20:

$g_q = 0$ & $P_{nc} = 1$:

$$OCC_p^r = OCC_p^u = OCC_p^g \tag{17}$$

$$PC_p = V_p \times OCC_p^r \tag{18}$$

$$OCC_b^r = OCC_b^u = OCC_b^g \tag{19}$$

$$PC_b = V_b \times OCC_b^r \tag{20}$$

3.1.5 Performance evaluation

In order to evaluate the operational and safety performance of an intersection one needs to first calculate the potential conflicts for each approach (j) within the intersection as described in equations 21-23:

$$PC_v = \sum_j PC_{LT(j)} + PC_{OT(j)} \tag{21}$$

$$PC_p = \sum_j PC_{p(j)} \tag{22}$$

$$PC_b = \sum_j PC_{b(j)} \tag{23}$$

Equations 1- 4 can be subsequently used to calculate delay and safety factor (DS) of each approach and by combination of the whole intersection.

3.2 Implementation Procedure

The performance measures described above can be used to investigate different solutions to address potential improvements on traffic operations and safety of intersections serving more than one mode of transportation. This kind of evaluation can be performed for an isolated intersection or an urban corridor with several intersections.

This section identifies a general procedure that can be used to evaluate the performance of a two-way arterial that intersects several minor two-way streets. The procedure is summarized by a flow chart at the end of the chapter. For this corridor it is assumed that the signal controllers are operated in a pre-timed mode at each intersection and a bicycle lane exists on each side of the main arterial.

3.2.1 Network modeling

The network model is created and tested in a microscopic simulation environment, for example VISSIM. The signal plan for each intersection is evaluated by using a simplified version of HCM 2000 approach (Roess et. al. 2004). For independent intersections, signal plan for bicycles will be the same as for pedestrians. The performance measure (*DS*) values, as defined in the previous section, will be calculated for all types of users and each intersection of the arterial. The required data will be collected from field survey and simulation results.

To investigate the operational and safety performance of the corridor, the effect of using coordinated signals will be studied by employing alternative signal plans for the intersections. Applying signal coordination through the arterial requires a common cycle length for all signal controllers. Thus the largest cycle time among the signal plans for individual intersections will be chosen as the common cycle time. The effective green and red times for each intersection have to be adjusted accordingly.

Two alternative signal timings scenarios will be studied. The first scenario assumes that all signal controllers will be coordinated for motor vehicle traffic along the corridor. The second scenario assumes that a coordinated signal plan for bicycle progression will be calculated and applied in the simulation model. In both cases the same performance measure (*DS*) for motorized and non-motorized users has to be estimated based on the simulation results.

In this evaluation, the safety weight factors (α, β and γ) can quantify different levels of severity of vehicular crashes for bicycles and pedestrians, respectively. For example during the cold season a very small number of bicycles travel on the roads, hence β can be modified accordingly which according to equations 1-4 will impact the DS values. In addition signal coordination affects directly vehicle delay. Consequently DS may also change, should intersections along the major approach have different offsets even if input flows and signal timing plans stay the same. To investigate the effect of signal coordination on DS, a classification tool will be developed and used to identify the kind of signal coordination that yields optimum value of DS. Figure 3.3presents a flow chart summarizing the procedure described above.

3.2.2 Decision tool calibration

The proposed methodology incorporates large set of data regarding the study area. This includes traffic volume of motorized and non motorized users and safety weight factors used to evaluate the delay and safety DS values. Since these parameters provide a spectrum of data variation, there is a need for a tool that learns and adapts itself, as more data become available.

In the present study, a Multi-Layer Perceptron (MLP) adaptive network is used. It consists of three types of layers: input, hidden, and output (Figure 3.2) and is trained with the backpropagation algorithm, which is based on minimizing the sum of squared errors between the desired and actual outputs.

The adaptive network used in this study is defined on the basis of the following seven input variables: vehicular flows, pedestrian flows, cycling flows, safety weight factors and potential conflicts for pedestrians and bicycle conflicts, respectively. For a given set of input values three traffic simulations were run corresponding to the assumption that signals at each of the four intersections function either independently or synchronized (i.e. for vehicle or bicycle promotion). The output is a symbolic variable representing the type of signalization that based on the simulation results, is connected to the optimum DS value.

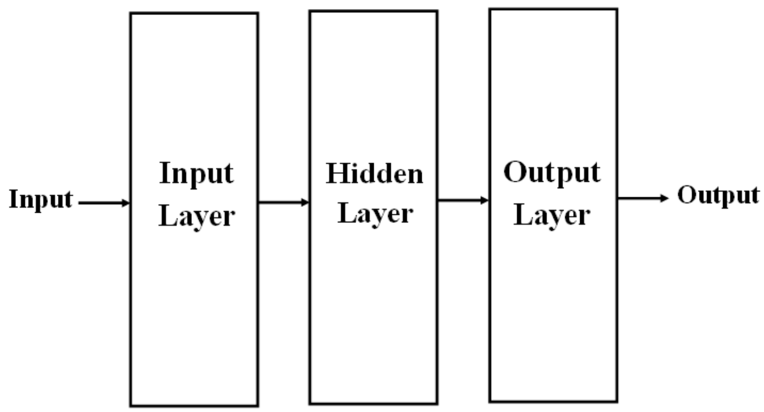

Figure 3.2: General layout of Multi-Layer Perception Network

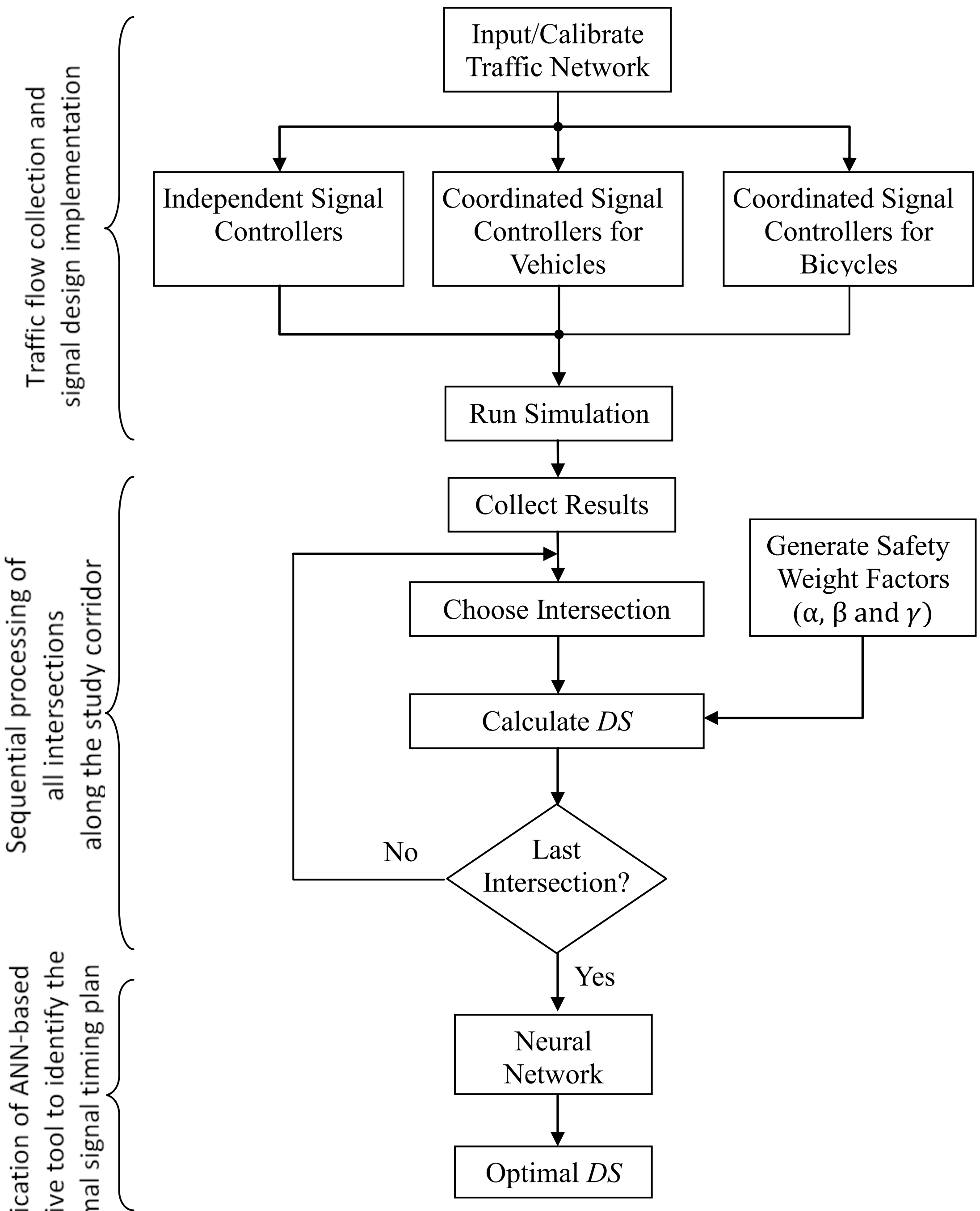

Figure 3.3: Implementation flowchart

CHAPTER 4

STUDY AREA AND DATA COLLECTION

4.1 Study Area

In order to test the proposed methodology, a particular study area has been chosen and used based on the previously described implementation procedure. This study area was used to evaluate potential improvements on traffic operations and safety at an isolated intersection and for a corridor of closely spaced intersections. The study area is located on a corridor between three major universities in downtown of Montreal, Quebec (i.e. UQAM, McGill, and Concordia University). A one-way, three-lane street with on street parking facilities, Maisonneuve Boulevard (henceforth referred to as the major approach) crosses four local streets (minor approaches) each spaced at approximately 100 meters. The first minor approach, de la Montagne, is a two-lane street that has on-street parking spaces. The other three approaches (i.e. Crescent, Bishop and MacKay) are one-way north-bound or south-bound streets with one lane and on street parking on both sides. Recently a bicycle path was built and it replaced the left-side parking on the major arterial (Figure 4.1).

The last intersection of study area, MacKay, is located within the perimeter of Concordia University and is referred to as the critical intersection due to highest level of interactions between motorized and non-motorized users. This intersection is between the four largest buildings of Concordia University's Sir George Williams (SGW) campus (i.e. GM, EV, H and LB as shown in Figure 4.2). The university has most of its facilities grouped in two different locations, SGW Campus in the downtown core of Montreal and Loyola Campus in a residential area at west of Montreal. The SGW campus is located in an open access neighborhood with intense commercial and residential activity and hosts mostly teaching, research and office facilities for students of the four largest academic units; the business, engineering, visual art and science faculties. The open access characteristic of the SGW campus results in significant interactions between vehicles and pedestrians crossing inside intersection. Field observations show abrupt increase in both motorized and non-motorized traffic flows for relatively short time intervals, usually coinciding with university class break periods. Consequently, there is a legitimate concern of traffic safety due to the significant amount of interactions between vehicles, bicycles and pedestrians using the intersection (Figure 4.2).

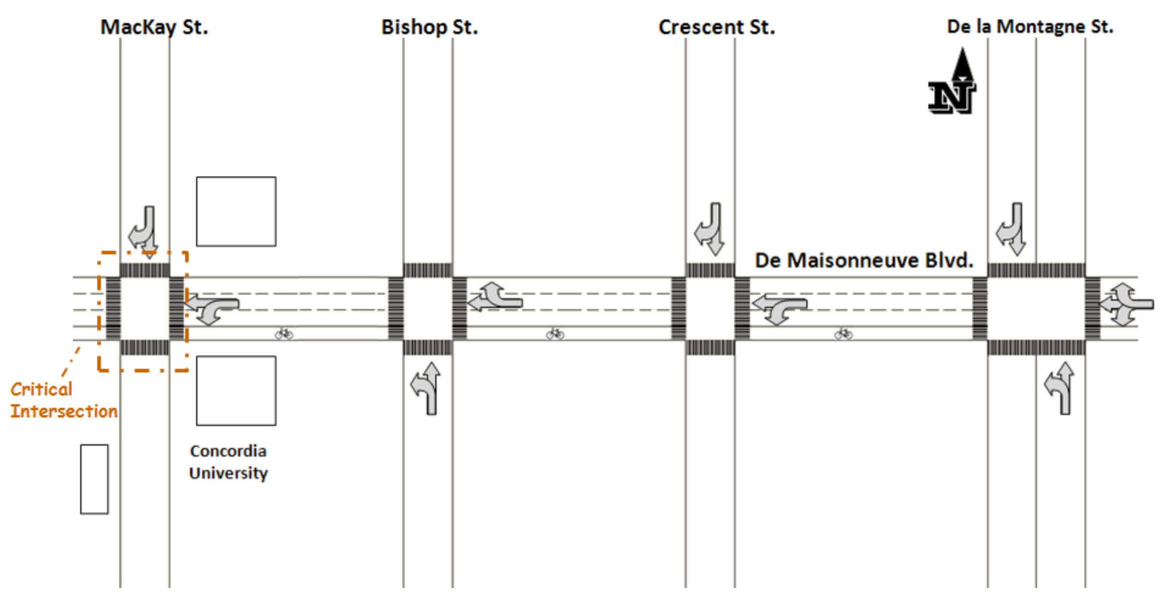

Figure 4.1: Layout of the study area

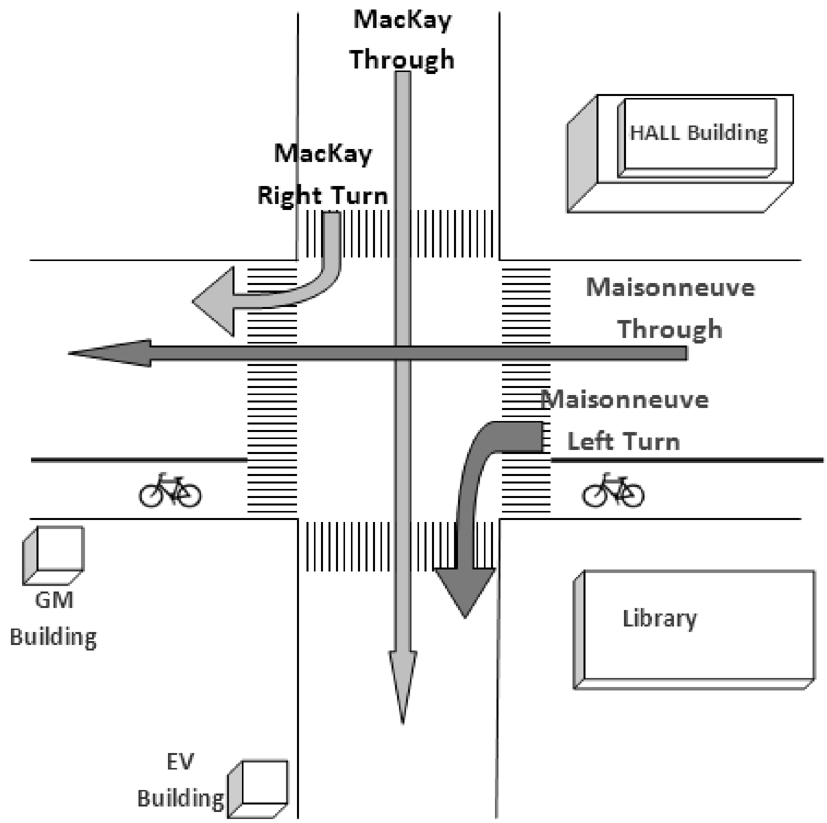

Figure 4.2: Layout of critical intersection & vehicle movements

Currently one single underground tunnel is functional between two major buildings in the campus, a 12-story teaching facility and the university library. This tunnel can be used by university students and personnel to bypass a five-lane wide large boulevard to access one building from another. However, major pedestrian generators/attractors (engineering, art/science and business faculties) are across the street from this tunnel (Figure 4.3). There is also a new underground tunnel, currently under construction, that connects the GM building to Hall and Library buildings (Karren 2008).

Due to geographical location of Montreal, with high snowfall accumulations the capacities of pedestrian pathways and vehicle roads are directly impacted for durations that may extend several days (Labelle et al. 2002).

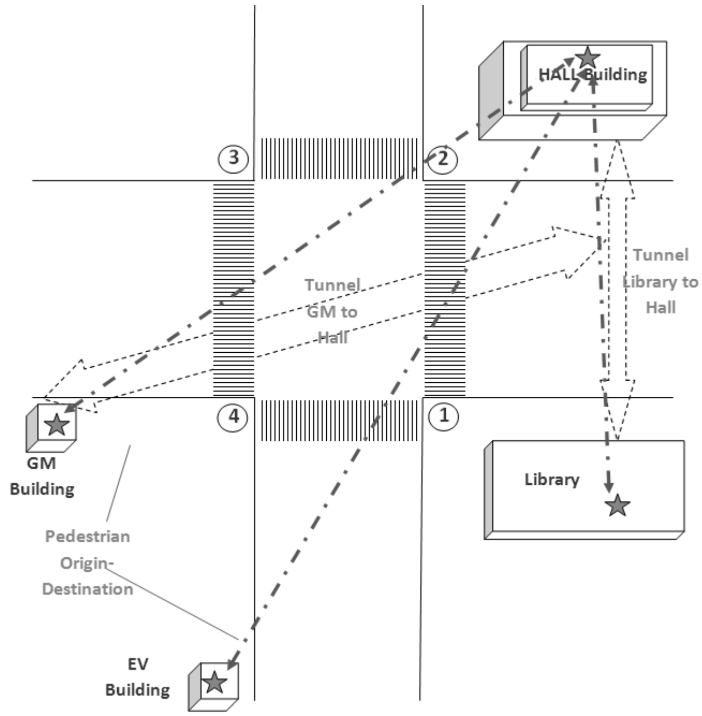

Figure 4.3: Layout of Pedestrian Crosswalks

4.2 Data Collection

Traffic data were collected using a digital camcorder and analyzed for the critical intersection using the Autoscope® machine-vision processor (MVP). One hundred hours of digital video recordings were used to determine traffic flows for three hours during morning and afternoon rush hours.

The Autoscope system processes video input from a traffic scene in real time and extracts the required traffic data, including vehicle presence, counts, speed, length, time occupancy (percent of time the detection zone is occupied), average headway (time interval between vehicles) and flow rate (vehicles per hour per lane). For the purposes of this study speed detectors that include the count detector functionality as well, were used for data collection following time stamped information: vehicle speed, count and length measurements. The speed detectors were placed in such a manner as to capture the front part of the hood of a vehicle. This ensures the most accurate measurements of speed and length. Speed detectors are the rectangular section seen in the center and right hand shoulder lane in Figure 4.4.

The larger lines at the end of each speed detector represent the presence of count detectors. The count detector portion of a speed detector is located on the downstream side of the speed detector. Speed and length are calculated when the vehicle leaves the detection zone of the speed detector. The presence of the vehicle is triggered at this time by both the speed and count detectors (Figure 4.4). The raw data produced by Rackvision are stored in text files. These files were imported into Excel for further data processing and to generate summary statistics and plots.

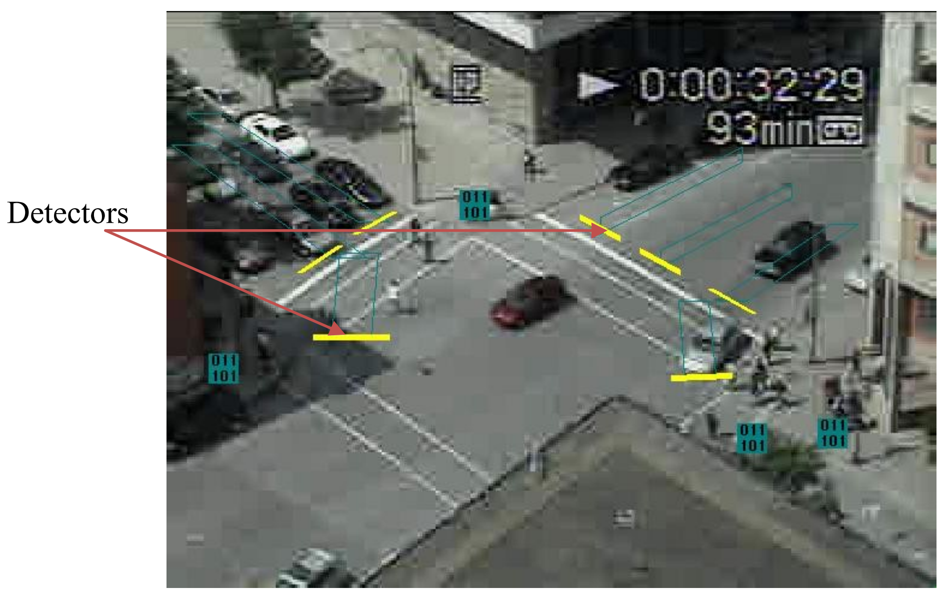

Figure 4.4: Defining detectors for Autoscope

Pedestrian flows were determined by visual post-processing from the same video recordings and they were adjusted in Vissim to reproduce the observed 15-min peak flow rates of nearly 1200 pedestrians crossing the intersection. Since the bicycle path was still under construction at the time of data collection, a different source of bicycle demand was identified. According to Velo-Quebec (Jolicoeur 2005), an estimated maximum flow of 300 cyclists per hour was expected to occur on this section for each direction, and this value was used in the study. All the data regarding vehicle, bicycle and pedestrian flows was used to conduct the experiments presented in the next chapter. A sample of this data is shown in Table 4.1 and Table 4.2.

Table 4.1: Sample vehicle data

Approach	Number of Lanes	Movement	Average Speed (Km/h)	Vehicle Count	Average Headway (Sec)
Maisonneuve	3	Left Turn	8	42	17
		Through	16	92	22
MacKay	2	Right Turn	8	26	24
		Through	10	14	25

Table 4.2: Sample pedestrian data

Crosswalk (Figure 4.3)	Crosswalk Width (m)	Pedestrian Count
1↔ 2	3.0	192
2↔ 3	3.0	248
3↔ 4	3.0	175
4↔ 1	3.0	238

The calibration of the MVP of the Autoscope® was needed to accurately estimate the intersection vehicular traffic. During the recording period, a probe vehicle was driven with a known constant speed through the intersection three times. The parameters of the MVP (i.e. camera height, focal length of the camera, and the width of the analysis area) were adjusted such that the speed output of the MVP matched the known speed of the probe vehicle. This was necessary to ensure that all the video data processed by MVP results in an accurate output of vehicle flows approaching the study area. Furthermore, automatically detected vehicle counts was confirmed at random by manual counts from the video recordings..

CHAPTER 5

Experimental Work and Analysis

This chapter presents the experiments performed to study the potential improvements of operational and safety performance of signalized intersections located within the downtown campus of Concordia University. The study area includes a one-way three-lane street with on street parking facilities, Maisonneuve Boulevard (referred to as the major approach) that crosses four local streets (minor approaches) each spaced at approximately 100 meters. The last intersection with MacKay St., which is located within the perimeter of Concordia University, is referred to as the critical intersection. Three different tasks have been conducted to achieve the thesis's objective: (i) Study the impact of underground tunnels on pedestrian operations, (ii) investigate the effect of different signal timing plans and (iii) study the effect of signal coordination. The analysis performed in each task is described in the following sections:

5.1 Effect of underground tunnels on pedestrian operations

In the first analytical task of the thesis, the impact of adverse weather conditions on vehicle delay and pedestrian trip length at the critical intersection was assessed. In order to achieve this goal, several performance measures are compared under two scenarios. The first scenario assumes all pedestrian flow to occur on surface pathways. In the second scenario, a variable proportion of the pedestrian flow is redirected through underground tunnels.

Field observations indicated that currently very few users utilize the existing tunnel between Hall and Library buildings. Therefore, a base case scenario is considered to approximate the real-world situation in which pedestrians do not use the existing underground tunnel. In this case all pedestrian demand measured through the intersection during peak periods, 4800 ped/h, is distributed only through the surface pathways interconnecting the four buildings. In addition, it was assumed that 10% of the total pedestrian flow users are not directly related to campus activities that will never use the underground tunnels. If the percentage of pedestrians with off-campus activity changes, necessary adjustment needs to be done in defining alternative scenarios that assume some pedestrians use the tunnels.

In order to account for the effect of snow accumulation, the sidewalk width is reduced by 50%; that is from currently 3 m to 1.5m. It is expected that narrowing the sidewalks leads to faster and more frequent pedestrian crowding. According to the collected data a total vehicle flow of 600 veh/h is estimated to travel along the Maisonneuve, major approach (Table 5.1)

The intersection is currently designed to operate with a pre-timed controller with a 70 sec cycle and two phases. The first phase corresponding to the major approach is 40 seconds long, while the second phase for the Mackay, minor approach, is 30 seconds long (Figure 5.1)

Table 5.1: Vehicle input volumes

Approach	**Total Vehicle Flow (Veh/h)**	**Route (Figure 4.2)**	**Ratio (% of total Flow)**
Maisonneuve	600	Left Turn	30 %
		Through	70%
Mackay	200	Through	30%
		Right Turn	70%

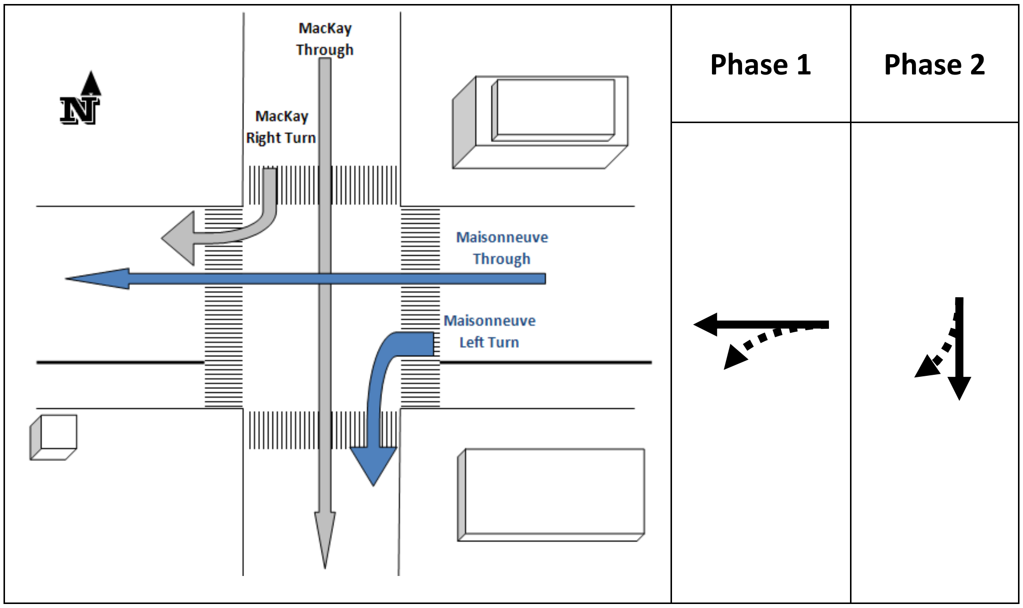

Figure 5.1: Signal plan for critical intersection

Since it is expected that by spring of 2010 the new tunnel will provide direct access to Hall and Library buildings from GM and EV buildings and vice-versa, four more scenarios are modeled using the same network. In each of these scenarios the total pedestrian and vehicle flows remain unchanged, but a variable fraction of the pedestrians is re-routed to use the available underground pathways to reach their destination. The four scenarios correspond to the assumptions that 25%, 50%, 75% and 90%, respectively, of all pedestrian demand is re-routed through the tunnels, as shown in Table 5.2. Each simulation scenario was ran 30 times, assuming the same random seeds, as the random seed used in base case, to account for stochastic variations in the model.

Table 5.2: Pedestrian rerouting scenarios

Scenario	Input Volume (Ped/h)	Proportion of Tunnel Users (%)
Base Case	2400	0
Case 1	2400	25
Case 2	2400	50
Case 3	2400	75
Case 4	2400	90

Average vehicle delay was estimated for each movement in the intersection. It can be seen from Figure 5.2 that the average vehicle delay of the base case decreases for each movement on both approaches when compared with each of the four alternative scenarios. For example, it can be seen that by rerouting 25% of the estimated pedestrian demand during peak period through tunnels, the delay on the major approach is reduced by more than 50%. This decline can be explained by the reduction in the pedestrian flows crossing the intersection, and consequently the reduction in the time the turning vehicles have to yield to crossing pedestrians.

The output of the conducted simulations represents averages of estimated delays for each vehicle in the network. The average vehicle delay calculated from each of the 30 scenarios runs can be considered to be normally distributed assuming the central limit theorem holds true. The central limit theorem (CLT) states that while sampling from a population that has an unknown probability distribution, the sampling distribution of the sample mean will be approximately normal (Montgomery and Runger 2007).

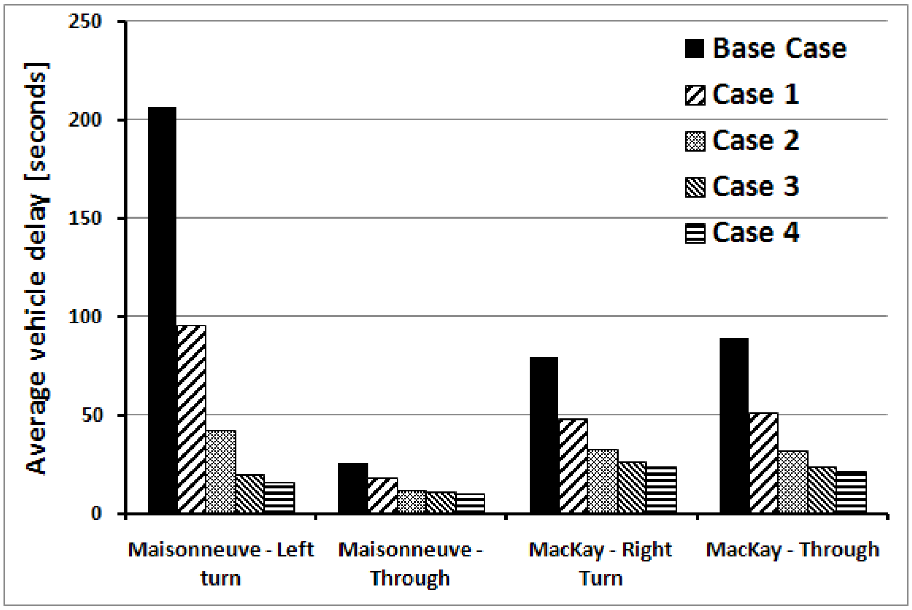

Figure 5.2: Effect of alternative pathways on the vehicle delay

To test for statistically significant difference between the average vehicle delays of the base case and alternative scenarios, several T-tests were conducted. Table 5.3 shows the results of the tests that compare average vehicle delay of the base-case (μ_0) and the average vehicle delay of each of the four alternative cases (μ_i, where $i = 1,2,3,4$). The null hypothesis tested is that the two average values are not significantly different ($H_0: \mu_0 - \mu_i = 0$) at 95% confidence. It can be seen from Table 5.3 that most of the tests yield statistically different average vehicle delays at 95% confidence. Based on the test results, it was found that for vehicles turning left from Maisonneuve the reduction in average vehicle delay varies between 110 and 190 seconds at 95% confidence, corresponding to the case 1 and case 4, respectively. These values correspond to a relative reduction in average delay of 50% and 90%, respectively. Hence, it can be conducted that for the observed hourly volume of 200 vehicles on this movement there is a potential saving of 6.1 to 10.5 vehicle-hours in total vehicle delay.

Table 5.3: Results of T-tests comparison for average vehicle delay

	T-test ($H_0: \mu_0 - \mu_i = 0; i = 1..4$)			
Vehicle movement	Case 1	Case 2	Case 3	Case 4
Maisonneuve - Left turn	5.70*	10.08*	11.67*	11.93*
Maisonneuve - Through	1.49	2.98*	3.20*	3.35*
MacKay - Right Turn	5.06*	8.37*	9.74*	10.09*
MacKay - Through	5.29*	8.69*	10.09*	10.41*

* denotes statistically different means at 95% confidence

Another performance measure evaluated in this analysis was the pedestrian travel time. Using two origin-destination pairs, EV and Hall, and GM and Hall buildings, the travel times for pedestrian were analyzed (Figure 5.3). Figure 5.4 shows that availability of the new underground tunnel leads to total pedestrian travel time savings in the peak fifteen minutes that may reach 90 pedestrian-minutes (case 2). It can be seen that the most advantageous scenario, identified by case 2, re-routes 50% of the pedestrian traffic. This may be explained by the fact that as more and more pedestrians are using the underground pathways; crowding conditions are likely to occur inside the tunnels. Under these assumptions, the average pedestrian travel time saving, that ranges between 1 and 9 seconds for various scenarios, is almost the same when all campus pedestrian activity is re-routed through tunnels. In this case, operational benefits are minimal, however safety benefits are expected to increase as the campus users are not exposed to possible conflicts with vehicular traffic when traveling and moving equipment between the four buildings.

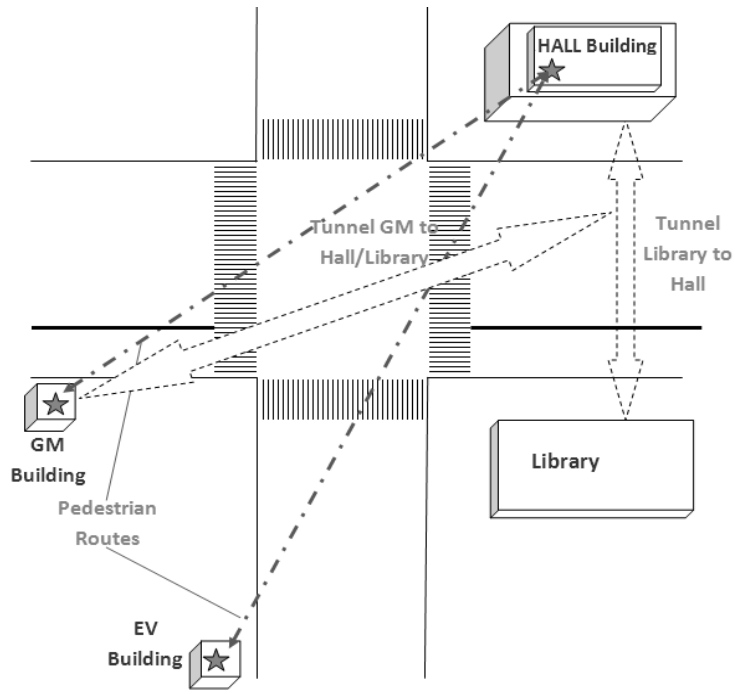

Figure 5.3: Pedestrian routes between main university buildings

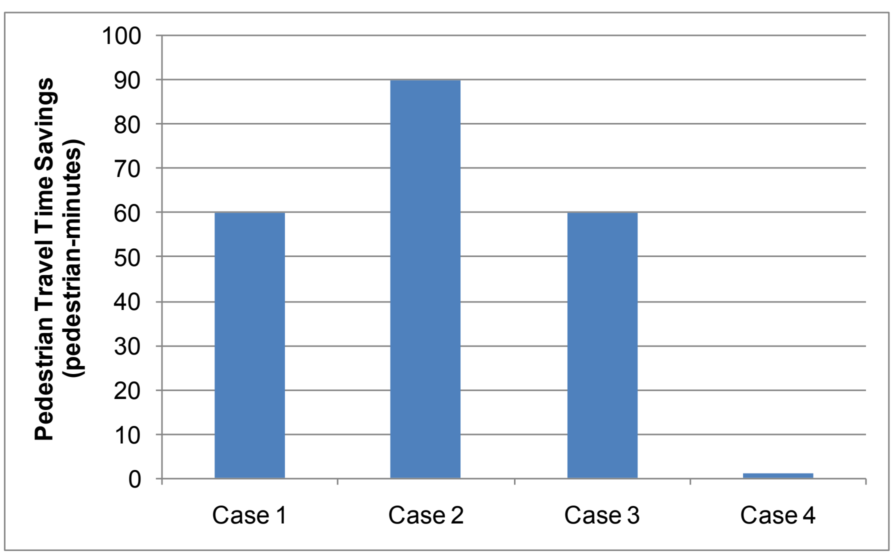

Figure 5.4: Potential pedestrian travel time savings under various scenarios

5.2 Effect of alternative signal timing plans

The second analytical task of the thesis evaluates the performance of critical intersection based on the current signal timing plan and three alternative timing plans using vehicle delay and pedestrian trip length as performance measures. The traffic signal controller of the intersection presently operates in a pre-timed mode with a 70-second cycle length and two phases. The phase promoting traffic on the major approach, Maisonneuve, is 40 seconds long, while the phase of the minor approach, Mackay, is 30 seconds long. Pedestrians/cyclists have a 10-second exclusive crossing interval at the beginning of each phase during which only through vehicle movements are allowed. For the remaining of the effective green time vehicular traffic is allowed to turn in permitted mode, providing they can find sufficient gaps within conflicting pedestrian/cyclist flows.

All the above mentioned parameters were defined in VISSIM. In addition, to account for realistic pedestrian/vehicle behavior, the signal timing plan in VISSIM was coded such that during the last three seconds of the effective green time in each phase pedestrian are prohibited to cross. This feature was coded for all scenarios and allows emulating an often observed behavior of pedestrians entering the crosswalk at the end of their corresponding green phase. The signal timing plan identified above is used as the base scenario. In addition, three alternative scenarios were considered as follows:

Scenario 1: Vehicles are allowed a 10-second protected turn movement at the end of each phase (during which pedestrians are prohibited to cross). This scenario also eliminates the 10-second protected crossing for pedestrians/cyclists at the beginning of the phase.

Scenario 2: Left turn movements from all approaches are protected for the first 10 seconds of each phase. In addition, pedestrians/cyclists have a 10-second protected crossing at the end of the phase.

Scenario 3: The last alternative allocates 10 seconds protected vehicle turn movement at the beginning of each phase, no protected crossing for pedestrians/bicycles.

All scenarios were tested with a 70-second cycle time and no change in vehicle and pedestrian flows. Figure 5.5 summarizes the phasing plans corresponding to each scenario. Each scenario was simulated for 20 minutes using the same 30 distinct random seeds, to account for stochastic variations in the model and allow for statistical analysis. Average vehicle delay and average pedestrian travel times were calculated using the last 15 minutes data for each simulated scenario. Vehicle delay due to yielding the right of way to pedestrians and bicycles was estimated by using the Node Evaluation feature in VISSIM on the areas close to crosswalk and bicycle path where vehicles are stopping.

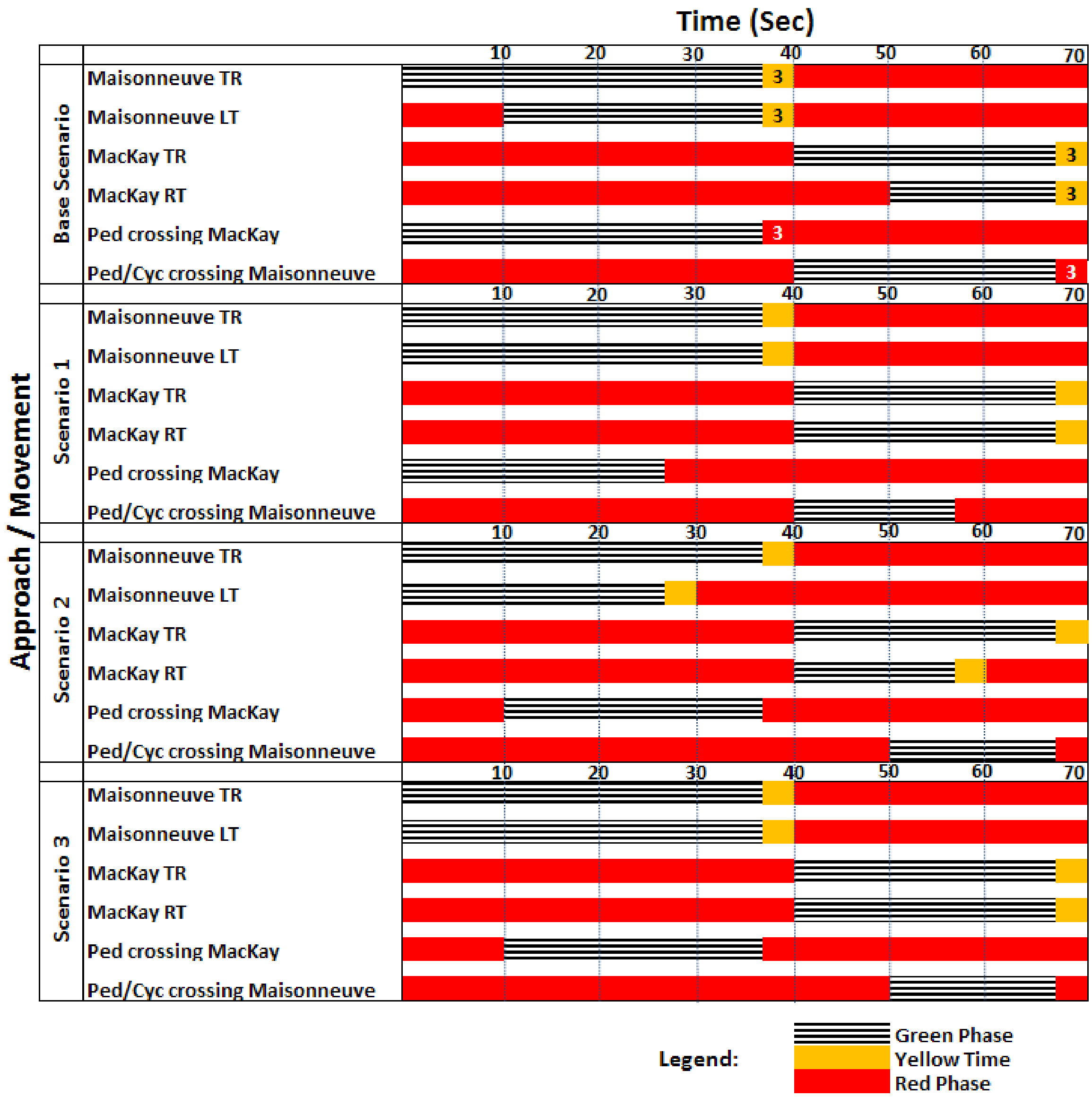

Figure 5.5: Signal timing plan scenarios

Video data recordings were processed with the Autoscope® MVP and average vehicle flow of 600 veh/h and 200 veh/h was evaluated for Maisonneuve and MacKay approaches, respectively (See Table 5.1). The turn ratios shown in Table 5.1 represent approximately the vehicle movements from the analyzed video traffic data. It was found out that 15-min peak flow rate of nearly 1200 pedestrians cross the intersection. This evaluation was done by off line processing of the pedestrian counts. Similarly to the first task it is assumed that all the pedestrians are using only the surface pathways surface pathways interconnecting the four buildings.

For each simulated scenario average vehicle delays were calculated for all movements within the intersection. From Figure 5.6 it can be seen that the average vehicle delay varies between 20 and nearly 200 seconds. Of the overall intersection delay, more than 76% occurs for left turning movement from Maisonneuve. High delay values encountered by left turning vehicles can be explained in the base scenario as follows. During the first 10 seconds of the green time for each phase, only pedestrians are allowed to cross. However, the high level of pedestrian flows and the effect of the crowd dispersion, limits considerably the opportunity for vehicles to turn left at this intersection. It was observed that in most instances only one or two vehicles are able to turn at the end of the phase, due to the fact that they are already engaged in the turning maneuver and they have to clear the intersection. Under these circumstances, high percentage of vehicles will wait more than two cycles to turn left from Maisonneuve.

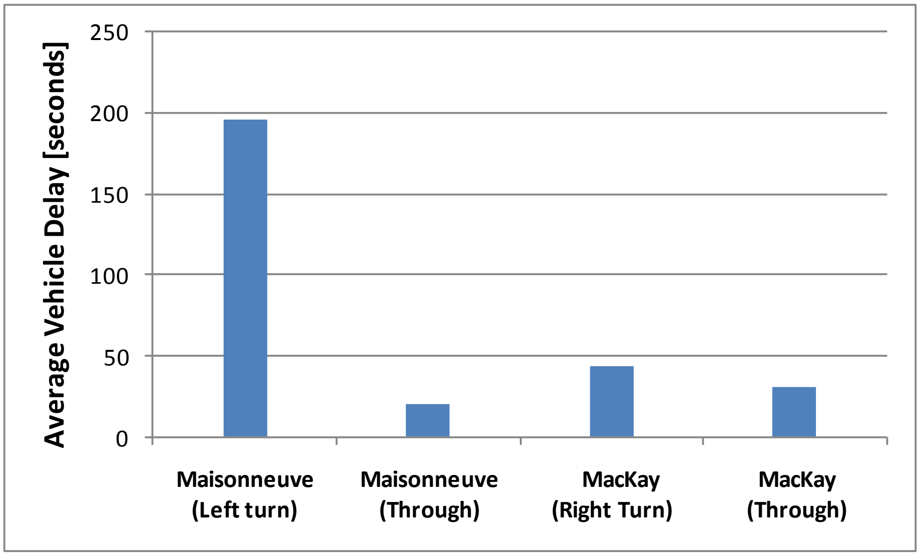

Figure 5.6: Base scenario average vehicle delay for each movement

The analysis indicates that almost 90% of the average vehicle delay for left turn movement on major approach is due to time spent in queue, while only 10% comes from yielding the right of way to pedestrians and cyclists, as shown in Figure 5.7. Consequently, more aggressive drivers might try to force their way through narrow gaps in pedestrian flows to avoid waiting for the green signal indication in the next cycle. This behavior is expected to negatively impact the safety of pedestrians crossing at the end of the phase.

By comparing all approaches it can be seen that the intensity of interactions between left turning vehicles and pedestrians/bicycles on the major approach deems this movement critical for the intersection's safety and efficient operations. The average delays for other movements through this intersection are less than the signal cycle length and they are not considered critical. To improve the operations and safety of vehicular and pedestrian flows, all three alternative scenarios are tested in this study for the left turn movement from Maisonneuve.

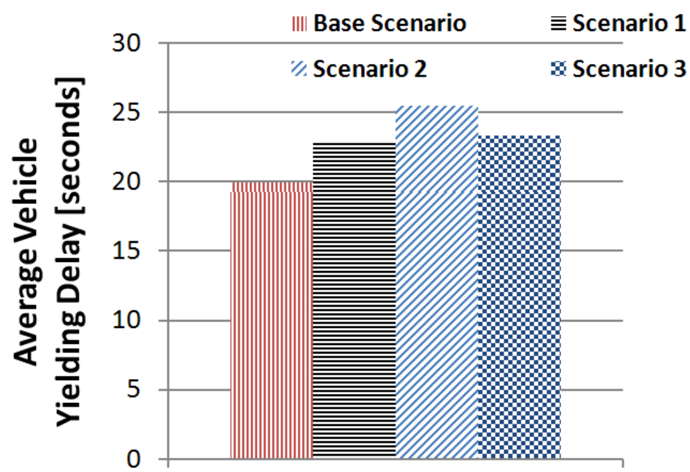

Figure 5.7: Effect of yielding maneuver on vehicle delay

It can be seen from Figure 5.8 that each scenario leads to some reduction in the average vehicle delay. The most effective signal timing plan is the one simulated in scenario 3 that reduces the vehicle average delay by 40%, to less than 2 minutes. However, it can be seen in Figure 5.7 and Figure 5.9 that there is 10-20% increase in the delay and stopped time due to yielding maneuver. This is explained by the fact that reducing the effective green time for pedestrians will lead to more compact crossing flows due to accumulation, which in turn will offer fewer appropriate gaps in the pedestrians and cycle flows for the turning vehicles. However, assuming the conditions of the scenario 3 for example, the average delay is reduced by more than 40% due to the protected left turn interval at the beginning of the phase. Under these circumstances, it is believed that the remaining drivers that were not able to turn during the protected phase could accept more easily the 3 seconds increase in yielding delay (Figure 5.10), since their overall delay for this approach is reduced by more than 80 seconds. This behavior should lead to safer crossing conditions for pedestrians and cyclists.

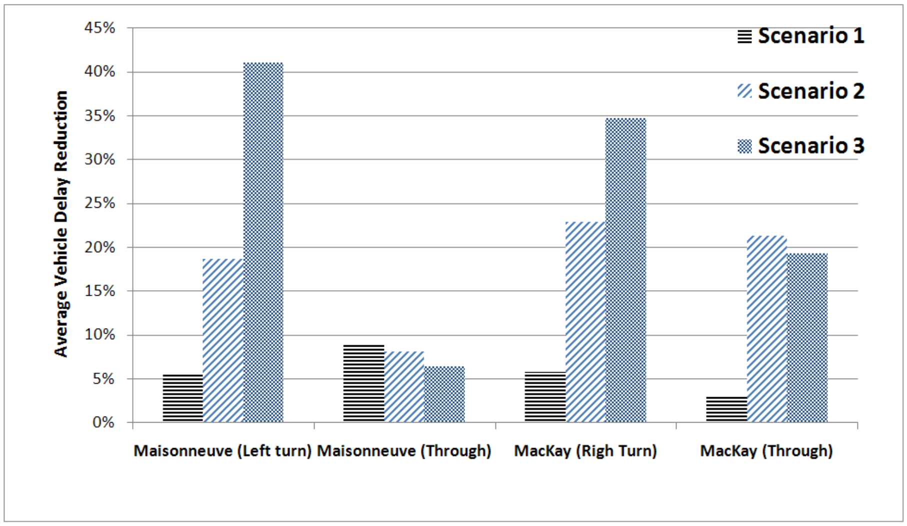

Figure 5.8 : Reduction in average vehicle delay for the alternative signal timing plans

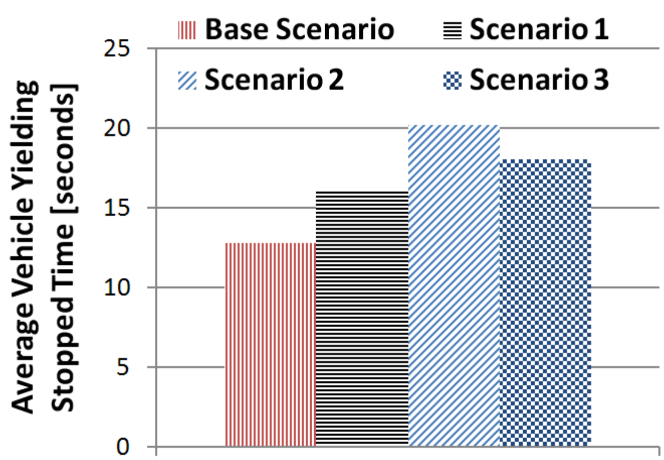

Figure 5.9: Effect of yielding maneuver on vehicle stopped time

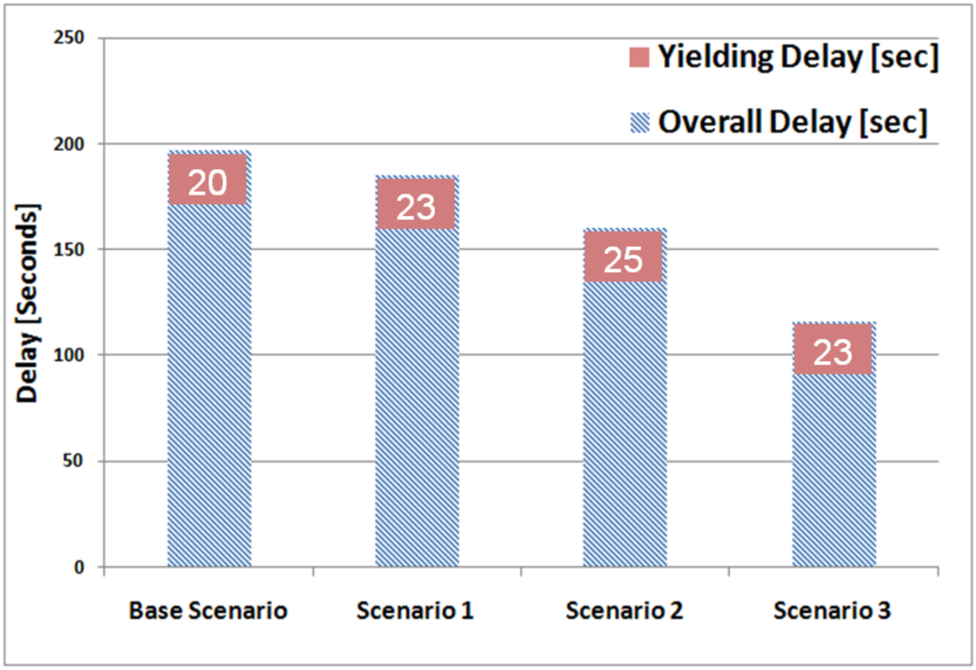

Figure 5.10: Vehicle delay vs. yielding delay

The average pedestrian travel time is used to evaluate the impact of the proposed alternative scenarios on the pedestrian flows. It was found that there is no statistically significant difference in average pedestrian travel times along the surface pathways connecting the four major buildings of the university.

Assuming that CTL holds true, the average delays and travel times estimated from 30 scenarios can be considered to be normally distributed. Therefore, T-test analysis was conducted to determine if the improvements shown by all three alternative scenarios are statistically significant. Table 5.4 shows the results of the tests that compare average vehicle delay of the base scenario (μ_0) and the average vehicle delay of each of the three alternative cases (μ_i , where i= 1..3). The null hypothesis tested is that the two average values are not significantly different (H_0: μ_0- μ_i = 0) at 95% confidence. It can be seen that for most of the tests, the null hypothesis can be rejected, which demonstrates statistically different average vehicle delays at 95% confidence.

Table 5.4: Results of the T-test analysis

	T-test (H_0: μ_0-μ_i = 0, i=1..3)		
Vehicle movement	**Scenario 1**	**Scenario 2**	**Scenario 3**
Maisonneuve - Left turn	1.0	8.4*	3.2*
MacKay - Right Turn	3.7*	10.7*	6.4*
Yielding Delay (Maisonneuve LT)	-4.5*	-6.9*	-7.4*

* denotes statistically different means at 95% confidence (t-critical = 1.7)

5.3 Effect of signal coordination

The last analytical task of this thesis identifies signal timing plans that optimize for the safety and the delay of both motorized and non-motorized users. A case study investigates if, depending on the volume of motorized and non-motorized flows, operational and safety performance of the major arterial depicted in Figure 4.1 can be improved by setting the controllers of all intersections to function in one of the three modes: (I) independent, (II) coordinated for vehicle flows, and (III) coordinated for bicycle flows. The signal timing diagrams corresponding to the three signal operating modes are shown in Figure 5.11, Figure 5.12 and Figure 5.13. Dotted lines in each of these figures represent the throughput bandwidth. The number of vehicles that can pass through all the intersections without stopping is called bandwidth capacity and is calculated based on saturation headway.

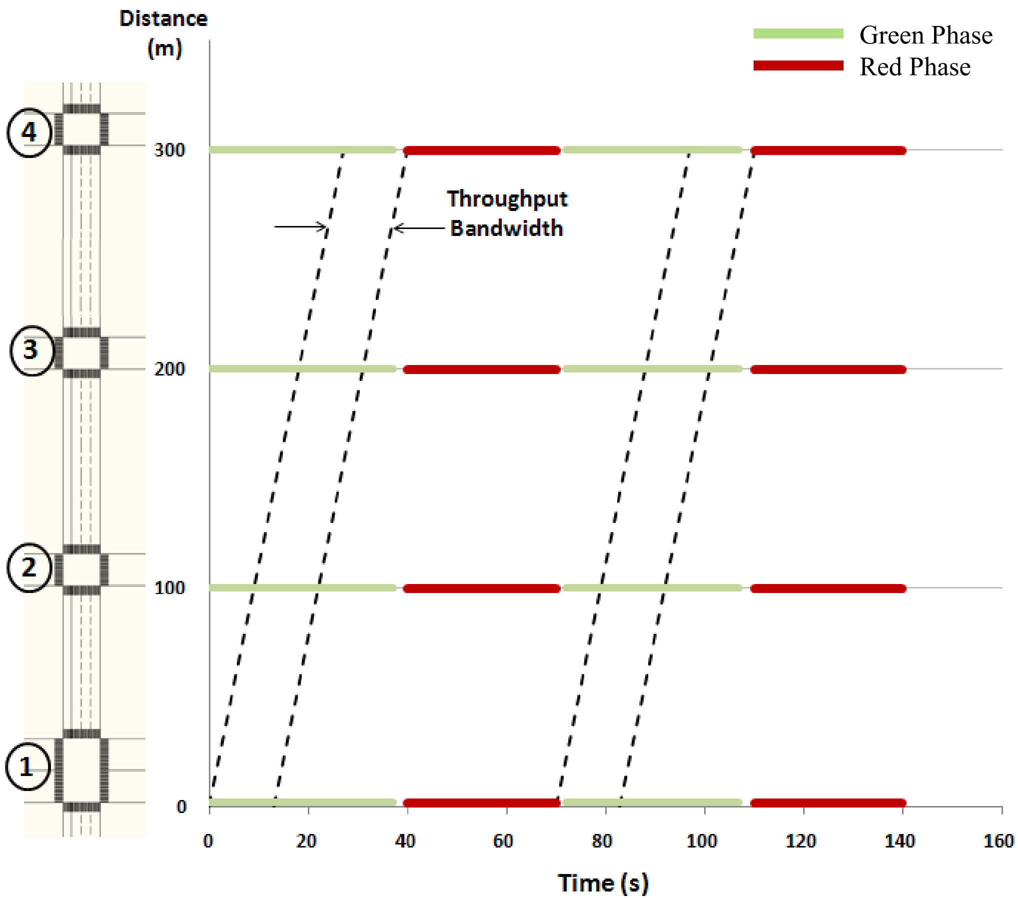

Figure 5.11: Independent signal timing plans along 4-intersection corridor

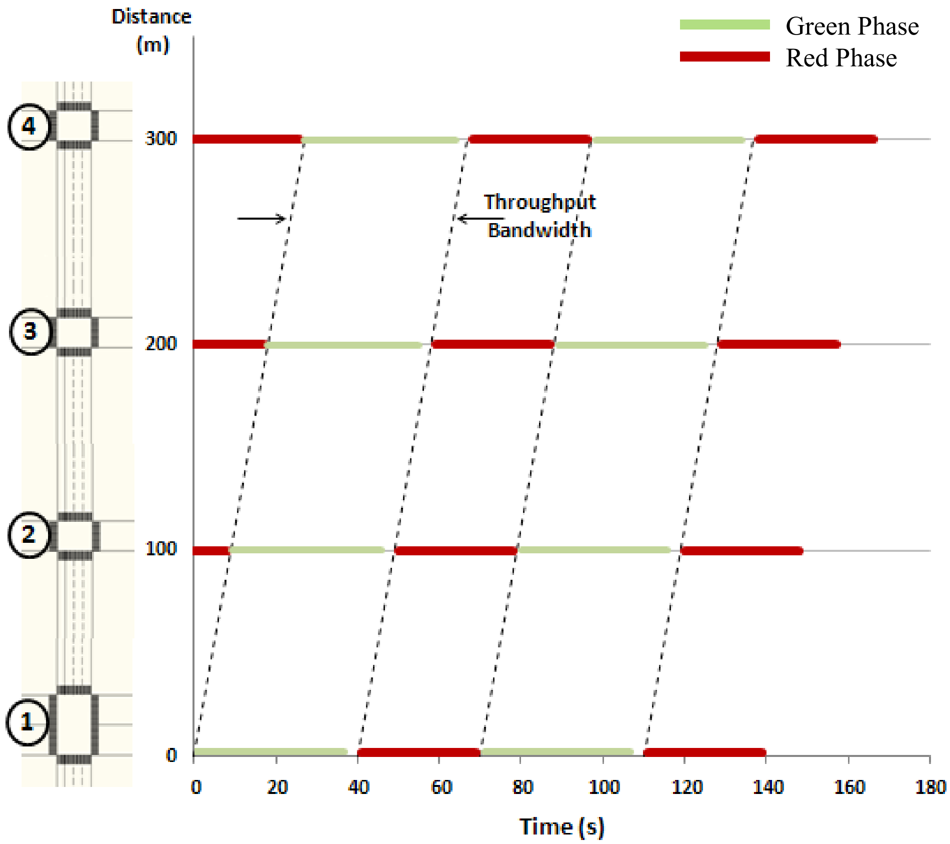

Figure 5.12: Signals coordinated to promote vehicle progression along 4-intersection corridor

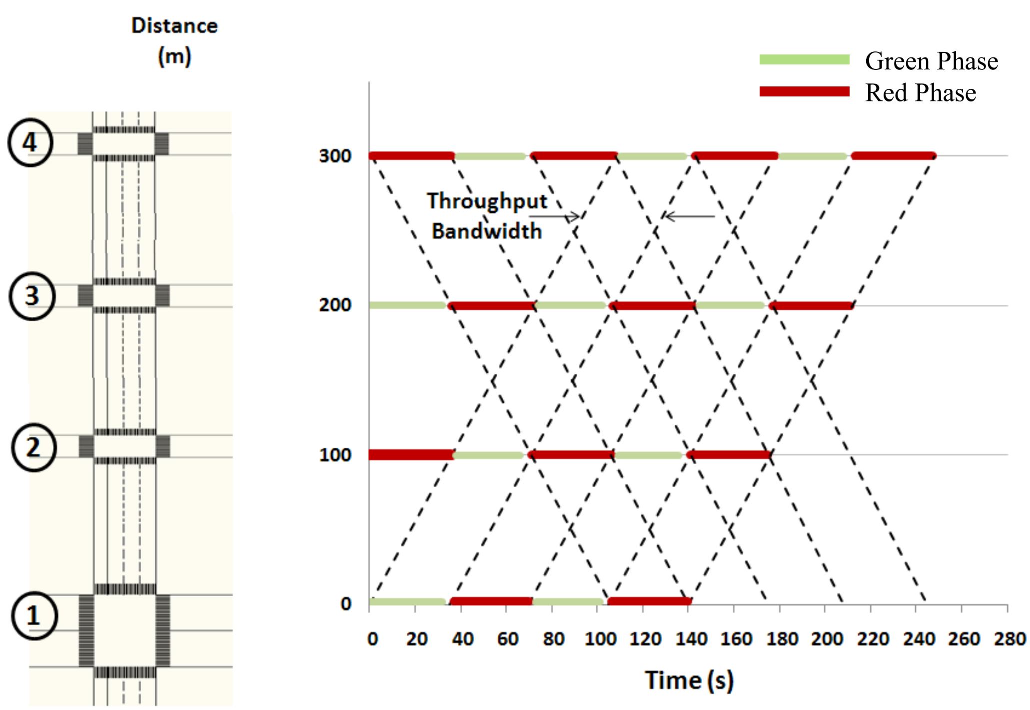

Figure 5.13: Signals coordinated to promote bicycle progression along 4-intersection corridor

Table 5.5 summarizes the offsets between intersections under each coordination plan. Calculations are based on 70 seconds cycle time and the design speed of 40 km/h and 10 km/h for vehicles and bicycles, respectively.

Table 5.5: Signal coordination offsets

Intersection No.	Offsets [sec]	
	Vehicles	Bicycles
2	9	36
3	18	72
4	27	108

Currently, all intersections along this corridor operate in pre-timed mode with a 70-second cycle and two phases. The phase corresponding to the major approach is 40 seconds long, while the phase of the minor approaches is 30 seconds long. The yellow time for each phase is 3 seconds. These features were implemented in VISSIM for all intersections of the study area. In addition, the signal timing plan in VISSIM was coded such that during the last five seconds of the effective green time in each phase pedestrian are prohibited to cross. This allows emulating an often observed behavior of pedestrians entering the crosswalk at the end of their corresponding green phase (See Figure 5.14).

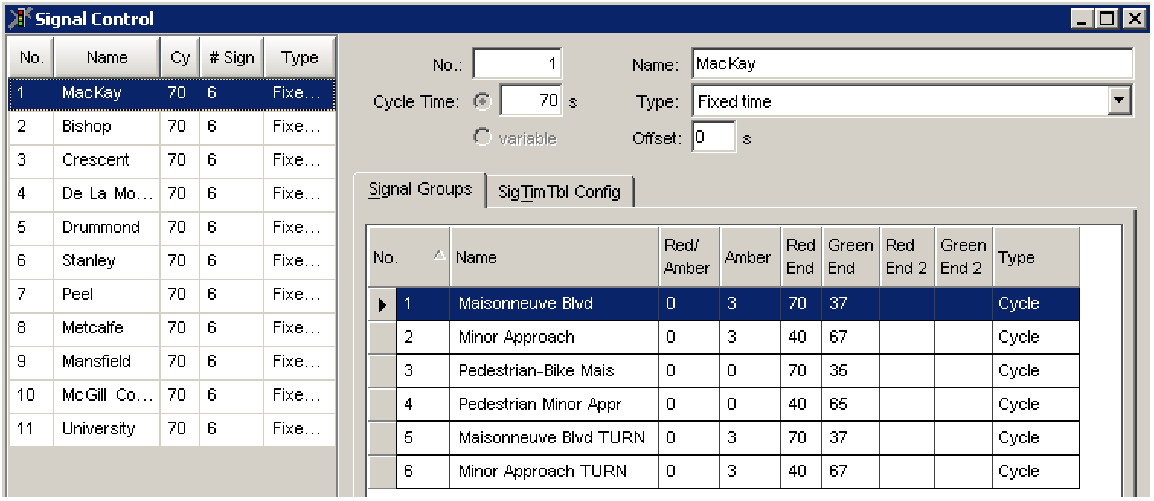

Figure 5.14: Implementation of Signal Controllers in VISSIM

To evaluate the effect of input flows on delay and safety for each type of signal controller along the major arterial, DS was estimated using arbitrary values for the safety weight factors of bicycles and pedestrian (β and γ) ranging between 1 and 20. Since the major arterial in this case study is a one-way street, there is no conflict between through and left turning vehicles and safety weight factor for vehicle (α) will not be used in the estimation of DS. Moreover, the equations presented in section 3.1.4 of chapter 3 can be used in calculation of delay and safety indices.

In order to model the interactions between all road users, the pedestrian flows in the model are generated from two opposite corners of each intersection and travel over crosswalks toward the other corner (Figure 5.15). It is not necessary to model pedestrian behavior outside the crossing area since this modeling approach is concerned with the interactions between vehicles and non-motorized road users around intersection and their impact on delay and safety.

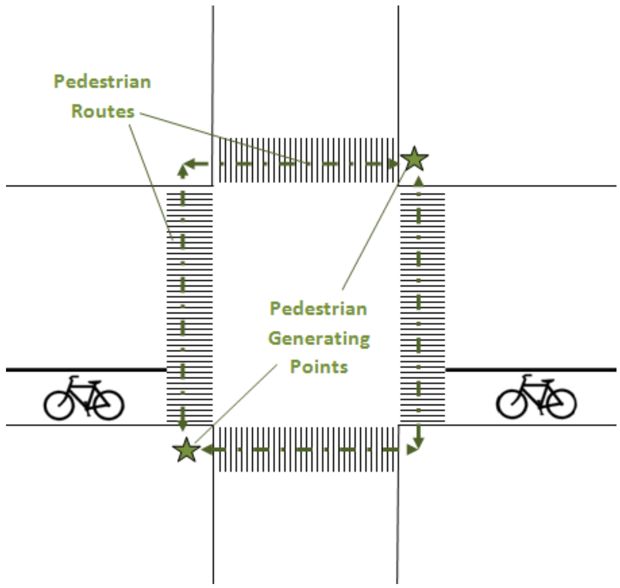

Figure 5.15: Pedestrian routes at intersections

The analysis of traffic video data collected from the critical intersection shows relatively limited variation of traffic parameters. However, pedestrian flows as high as 4800 ped/h were observed for short periods of time. The study area was simulated under different combinations of traffic conditions by assuming four levels of demand volumes for each of the three types of traffic, vehicles, bicycles and pedestrians, as shown in Table 5.6. The traffic volume on all minor approaches was assumed 200 veh/h, as observed from collected data of critical intersection. The number of pedestrians at the three upstream intersections, (De la Montagne, Crescent and Bishop), was assumed at a relatively low level, 500 ped/h. At each intersection it was assumed that 30% of the vehicles diverging onto the minor approaches.

Each combination of the inputs was simulated considering three possible cases of signal operation (i.e. independent, coordinated to promote automobile traffic and coordinated for progression of bicyclists). In total, 192 (64*3) simulation scenarios were run. To account for stochastic variations in the model, each scenario was simulated for 20 minutes using the same 30 distinct random seeds, to account for stochastic variations in the model and allow for statistical analysis. The following measurements were aggregated excluding the first five minutes, considered as the simulation warm-up period: average vehicle delay for vehicles travelling on the major approach (d_v), average bicycle delay (for both directions) (d_b), and average pedestrian delay at the critical intersection (d_p). They are used in equations 2-4 for calculating the performance measure values, as detailed in the methodology section presented in Chapter 3.

Table 5.6: Demand volumes

Vehicle demand on major approach (vph)	Bicycle demand (bicycles/h)	Pedestrian demand at critical intersection (ped/h)
600	100	1,000
800	200	2,000
1,000	400	4,000
1,200	600	6,000

For each simulation scenario, DS was calculated for the critical intersection using each pair of input data and the corresponding simulation output. Table 5.7 presents a sample of DS measures calculated for three different scenarios. Potential conflicts for pedestrian and bicycle flows, PC_p and PC_b, are calculated using equation (6). For example, given the conditions of the simulation scenario 1 the optimal (DS is the smallest) operation conditions are when signals are coordinated for vehicles progression (II). On the other hand, under the assumptions of input of simulation scenario 31, it is optimal if signals work independently (I).

Table 5.7: Sample of DS calculations for critical intersection

	Parameters	Scenario 1	Scenario 31	Scenario 50
Input	V_v (vehicles)	600	1200	600
	V_b (bicycles)	100	200	600
	V_p (pedestrians)	1000	4000	2000
	β	3	10	15
	γ	7	15	20
	PC_b (bicycles)	0.7	2.9	26.3
	PC_p (pedestrians)	125	1867	500
Output DS [sec]	Independent Intersections **(I)**	**35.9**	**188.6**	**139.7**
	Coordination for Vehicles **(II)**	**32.3**	**190.8**	**128.9**
	Coordination for Bicycles **(III)**	**57.1**	**321.5**	**118.5**
	Optimal Signal Plan	**II**	**I**	**III**

In this study a two-hidden layer Multi-Layer Perceptron (MLP) was used as classification tool. The structure of the network is shown in Figure 5.16.

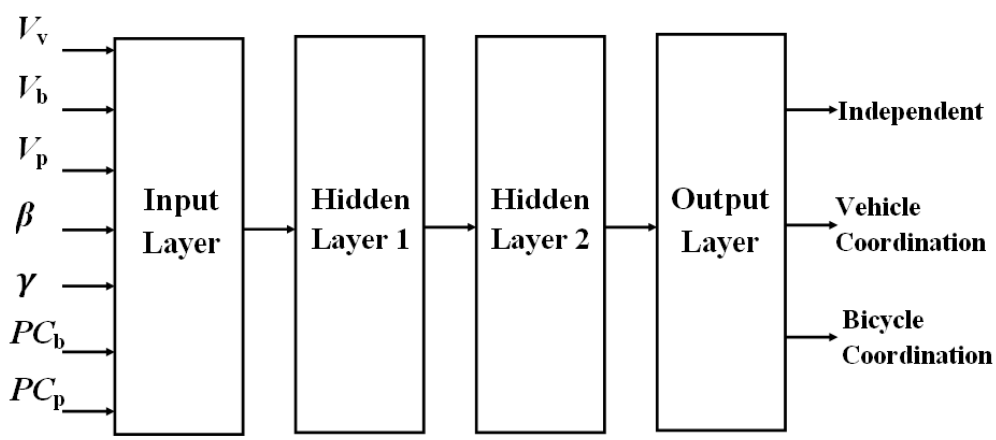

Figure 5.16: A two hidden layer MLP

For each of the seven different inputs, one neuron is used in the input layer. Similarly, three neurons were used in the output layer, corresponding to the three types of signal coordination. The number of neurons corresponding to the first and second hidden layers was arbitrarily selected as fifteen and seven, respectively.

Using all simulation results and the corresponding input values a large pool of data was build to train and test the performance of the MLP. Training of the neural network was performed using NeuroSolutions (Lefebvre, 2001). In total 25,600 (20*20*64) combinations of input/output values were generated corresponding to the range of values the two safety weight factors, β and γ, and the distinct number of scenarios. All records were randomly shuffled and the network was trained by using 40% of total data (10,240 records) and cross validation was done by using another 40% of data. Training was terminated when the mean square error for the cross-validation set does not decrease for 100 consecutive training cycles, a common procedure to prevent overtraining. The performance of the network was tested using the remaining 20% of the data set. Out of 5,120 cases presented to the network only 40 were incorrectly classified by the trained network, this corresponds to a success rate of 99.8%.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Concluding Remarks

In general, all universities, and in particular urban universities have to address various problems related to safety, security and operations of activities occurring within the perimeter of their campuses. The complexity of the problem increases especially for campuses located in an open access urban area such as Concordia University in Montreal. In this research work three different approaches, each organized as an individual task, have been applied to investigate the potential improvements of operational and safety performance for such intersections. Vehicular and pedestrian data was collected at one study intersection. This data was used to calibrate a microscopic simulation model, VISSIM, capable of modeling vehicle-pedestrian interactions.

The first task of the thesis evaluates potential benefits of building a new underground tunnel in the downtown campus of Concordia University. During the cold season in the Montreal region, there are significant snowfalls that lead to a significant reduction in pathways width. The effect of snow accumulation on pedestrian sidewalks was coded in the simulation model as 50% reduction in the width of the available sidewalks. Vehicle delay and pedestrian travel time information were collected from a base case simulation scenario that represents normal conditions (i.e. all pedestrians use all available surface pathways). Four alternative scenarios are simulated using the same input data, but assuming that a fraction of the pedestrian activity is re-routed through one underground tunnel (i.e. 25%, 50%, 75%, and 90%, respectively, and the available sidewalks width is reduced to half). All simulations were run with 30 different random seeds. A comparison of the base case with the alternative scenarios shows clearly the operational and safety benefits of using the underground tunnel.

The statistical analysis conducted in this task was performed using the T-test at 95% confidence, to investigate for statistical significance in the average pedestrian travel time and in the average vehicle delay. It was shown that the average delay of vehicles turning left from the major approach (Maisonneuve), that have to yield to the high volumes of crossing pedestrians may be reduced by up to 190 seconds when most of the pedestrians are re-routed through the tunnel. Similarly, all movements through the intersection were shown to have statistically significant lower delays when a fraction of the pedestrian activity is using the underground pathways.

In addition to vehicle related benefits, it was shown that pedestrians (mostly university users) can benefit as well. For example, it was found that total pedestrian travel times can be reduced by 90 minutes with the peak 15-minute interval. Maximum benefits are achieved in this case when half of the pedestrian activity is rerouted through the tunnel. This can be explained by the fact that as more and more pedestrians are using the tunnel crowding conditions may occur and the advantage of not waiting at the intersection crossing is significantly diminished. In general, it was found that the availability of the underground pathways has operational and safety benefits, by minimizing pedestrian-vehicle interactions and providing a more convenient environment for pedestrian activity within the campus perimeter.

The second task of the thesis conducts a study on the effect of different signal timing plans on delay and safety for the study intersection. Total vehicle delay, pedestrian travel time and yielding stopped time information were collected from a simulating a base scenario that represents current conditions. One particular movement, vehicles turning left from Maisonneuve onto McKay, was identified as critical, due to high vehicle delay levels and high risk of pedestrian safety degradation. Three alternative scenarios implementing different signal timing plans were developed to address the safety and operational issues of the critical movement. All scenarios were simulated using the same input data and cycle length as the base scenario. Each scenario was simulated using the same 30 distinct random seeds. Using statistical inference it was found with 95% confidence that vehicle delay for the critical movement can be reduced by as much as 40%. It is expected that this reduction in total delay leads to safer crossing conditions for non motorized users.

The last task of the thesis presents a methodology to optimize signalization along arterial roads located within study area with significant demand for both motorized and non-motorized traffic. A methodology is proposed to employ an integrated intersection delay and safety performance measure into an artificial neural network framework to create a signal timing plan decision tool.

A case study of four intersections along a one-way major arterial in downtown Montreal, Quebec was analyzed. This network was simulated in VISSIM under a large range of input traffic demand (i.e. vehicle flows, cyclist flows and pedestrian flows). The last intersection along the study area was considered the same critical intersection investigated in the previous two tasks. The same traffic data collected from video recordings taken at this intersection was used in this task. From all simulation scenarios average delay values for all road users were estimated and used in determining the integrated performance measure, DS. In calculating DS it was necessary to allocate different weights to conflicting movements at intersections. This was done through corresponding safety weight factors for conflicts between vehicular and pedestrian flows, β, and vehicular and bicycle flows γ, respectively. It was found that DS is changing with the type of signal coordination should the set of input flows do not change. The type of synchronization that yields the smallest DS value is considered optimal, since it is associated with the least impact on delay and on potential conflicts between the road users.

To assist transportation agencies with real-time management of coordinated intersections systems, a neural network classification tool was developed. The role of the neural network is to anticipate what type of signal synchronization, if necessary, is most suitable given a certain set of input parameters. In this study a two-hidden layer MLP network was trained and tested using the simulation results of 192 different simulation scenarios. It was found that in 99.8% of the tested cases the neural network identified correctly the optimal signal plan (i.e. independent intersection, intersection coordinated to promote vehicle flows, or intersection coordinated to promote bicycle flows).

6.2 Recommendations for Future Work

The work presented in this study establishes a long term project in identifying real-work applications for safety and operations within the high density urban districts. It is anticipated that more development and calibration work will be performed in the future. For example, the safety weight factors used to estimate the delay and safety indices have direct effect on calculation of DS and need to be calibrated with real-world data. Since non-motorized users are more vulnerable in accidents, it is expected that their corresponding safety factors might have more significance. One possible way to identify these values is to use the crash history of the site. Furthermore, the effect of additional parameters on the weight factors needs to be investigated. For example: the effect of vehicular delay on drivers' behavior and proportion of non-complying users. In addition, the currently estimated demand for cyclists (300 bicycles per hour) should also be updated based on filed observations from the study area.

The neural networks are capable of generalization, however it is not necessary that a network trained at one location can be successfully used on a different location. Additional training may be necessary when the geometric configuration of the study area changes. Future work will investigate the transferability of adaptive network.

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