Evaluation of Traffic Operations and Safety of Reserved-Lanes

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ABSTRACT

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This study investigates the safety and operations of reserved lane facilities, with multiple interactions between vehicles. Currently, there are a limited number of studies that investigated the effects of various geometric designs impact on traffic operations along reserved-lanes, especially the specific factors that control for frequent opportunities of merging/diverging and crossing maneuvers. In this study, a VISSIM simulation model has been developed to model vehicular interactions of reserved-lanes facilities, along an arterial with interrupted traffic setup and along an uninterrupted highway segment, both located in the Montreal metro area. The model was used to evaluate the safety and traffic operations along the selected corridors by comparing the status quo with some proposed alternative design and assuming the prevailing traffic conditions. The simulation model was calibrated with real-world vehicle headways and the generated vehicle trajectories were used in a Surrogate Safety Assessment Model (SSAM). An improvement of the SSAM model was achieved via a binary matrix calibration methodology, in order to identify the vehicle conflicts more accurately. This improvement helps traffic analysts to identify the potential traffic operations measures that could contribute to a reduction of vehicular conflicts. The results show that traffic operations along the corridor can be significantly improved if a different geometric alignment is used, one that would reduce the number of interaction opportunities. For example, it is shown that a 30-meter weaving section along the analysed arterial and a 50-meter merging section at the end of the highway bus-on-shoulder segment leads to improvements vehicles' travel time as well as improvements in traffic safety.

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To the most beautiful woman – Mrs. Chunxia Zhao

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AADT: Annual Average Daily Traffic

AASHTO: American Association of State Highway and Transportation

BoS: Bus on Shoulder

CITL: Le Conseil Intermunicipal de Transport des Laurentides

CPI: Crash Potential Index

DOT: Department of Transportation

DRAC: Deceleration Rate to Avoid a Crash

FHWA: Federal Highway Administration

GP: General Purpose

HOT: High-occupancy Toll

HOV: High-occupancy Vehicle

ISS: Injury Severity Score

ITS: Intelligent Transportation System

MTQ: Ministère des Transports du Québec

MUTCD: Manual on Uniform Traffic Control Devices

PDO: Property Damage Only

PET: Post Encroachment Time

RIRO: Right-in / Right-out

SSAM: Surrogate Safety Assessment Model

SSD: Stopping Sight Distance

TCRP: Transit Cooperative Research Program

TCT: Traffic Conflict Technique

TRB: Transportation Research Board

TTC: Time to Collision

TTI: Texas Transportation Institute

VMT: Vehicle Miles Traveled

Chapter 1.

Introduction

1.1 Background

Several studies showed that the geometric design and traffic operations along reserved-lanes and/or High-Occupancy Vehicle (HOV) lanes have significant impact on roadway traffic safety. The design considerations include various elements: the type of cross-section (e.g. buffer-separated vs. barrier-separated roadway cross-section), types of access points (e.g. ingress/egress), the buffer width, and the shoulder width, etc. Jang, Kang, Seo, and Chan (2012) evaluated the impacts of cross-sectional design for safety performance and recommended a set of design threshold values which could reduce the number of accidents. The authors have developed different accident prediction models for different injury categories (property damage only collision and injury collision) based on historical accident data, geometric design characteristics and AADT. A case study of San Francisco Bay area has been evaluated by applying the proposed crash prediction model into different cross-sectional design conditions (contiguous HOV lane vs. buffer-separated HOT lane). Under the same total width, the author adjusted the geometric variables, such as buffer width, HOV lane width, and shoulder width. The optimization function has also been given in order to find the minimum number of crashes under the two constrains: a fixed total width and an adjustable width of HOV lane between 11 ft (3.35 m) and 13 ft (3.96m). Finally, the author suggested different widths of buffer, shoulder and HOV lanes for three study segments based on quantitative prediction of crashes. Apparently, geometric design has significant safety impact for reserved-lane facility, each local authorities should determine their desired geometric thresholds in order to improve safety performance.

Reserved bus-lanes are one category of HOV lanes and they are promoted as a method to improve the operations of public transportation and discourage the use of private vehicles in highly congested areas. This is possible mainly because it allocates a separate right-of-way as a dedicated space for public transit movement permanently or only during specified congestion periods. One method to implement reserved-lanes is via Bus-on-Shoulder (BoS) facilities – which allow public transit vehicles to use sufficiently wide highway shoulders especially during peak hours. However, while reserved-lanes allow maintaining a reliable schedule, the design and implementation guidelines have to be considered, mostly to address operations and safety issues, see for example (Martin, 2006; Martin & Levinson, 2012).

1.2 Problem Statement

Many studies indicate that the significant speed differentials between the adjacent general-purpose (GP) lanes and the reserved-lanes could lead to significant traffic safety problems. For example, there are concerns related to maneuvering of the authorized of vehicles between the adjacent lower-speed GP lanes and the higher-speed reserved-lanes, various studies (Cooner & Ranft, 2006; Duncan, Khattak, & Council, 1998; Garber, Miller, Yuan, & Sun, 2003) showed that this could the reason for higher collisions occurrence at these locations. Moreover, reserved-lanes on arterials are associated with more complex safety issues than those along uninterrupted highways, mainly due to the fact that there are more frequent access points (interruptions) along the arterials. These access points (i.e. driveways, parking lots, minor roads, etc.) are often times not signal controlled. This kind of design leads to more critical crossing/merging vehicular trajectory conflicts, including the HOV users.

How to reduce the vehicular trajectories conflicts to increase road safety while maintaining efficient traffic operations, should be cautiously considered and determined. According to Jang et al. (2012), traditional accident prediction model studies (El-Basyouny & Sayed, 2009; Lyon, Oh, Persaud, Washington, & Bared, 2003; Oh, Washington, & Choi, 2004; Park, Fitzpatrick, & Lord, 2010; Qin, Ivan, Ravishanker, & Liu, 2005; Usman, Fu, & Miranda-Moreno, 2011) are not suitable to distinguish between different collision types (i.e. rear-end collision, side collision and head-on collision). This is due to the fact that traffic accident data does not typical include the necessary information (i.e. details of vehicle positions at the time of the accident), but the police reports mostly focus on the property damage data. As an alternative to the accident history data, surrogate safety analysis is a method of conflict analysis that could overcome the disadvantage of traditional accident prediction models. A traffic conflict analysis tool - Surrogate Safety Assessment Model (SSAM) has been developed with support from FHWA (Federal Highway Administration). This tool is used to assess surrogate safety measures based on the output from traffic simulation models (Gettman & Head, 2003). The use of this tool could also overcome the difficulty of predicting accident frequency when new geometric alternatives or traffic operations strategies are proposed.

1.3 Research Objectives

This thesis focuses on the following objectives. First, it proposed a specific methodology that can be used in the existing SSAM tool in order to identify the type of vehicular conflicts more accurately. In addition, this thesis investigates specific roadway geometric design measures that can reduce the number of vehicle interactions along reserved-lanes in order to improve traffic safety at specific locations.

To achieve these objectives, atwo-step microscopic traffic simulation method has been used to evaluate traffic safety performance of different traffic geometric design scenarios using a real-world case study. First, a calibrated VISSIM simulation model has been configured using collected vehicle headways and speed distribution. In addition, different alternative scenarios, including variations of the existing geometric design and traffic demand have also been simulated. Second, the SSAM tool has been used with all the VISSIM scenarios. The simulation results from multiple scenarios were assessed through the number of vehicular conflicts. A binary-matrix methodology, implemented via MATLAB, has been proposed to categorize the simulated conflicts in order to reduce the SSAM output error. Statistical inference is used to evaluate the effectiveness of the proposed method.

1.4 Thesis Workflow

This thesis is structured in 7 chapters:

Chapter 1 presents the reserved-lane background, problem statement and objectives.

Chapter 2 summarizes the literature on reserved-lanes facilities and traffic safety issues and methodologies.

Chapter 3 provides some background on the geometric design of HOV lanes.

Chapter 4 proposes a simulation methodology used in this thesis to evaluate different scenarios of reserved-lane facilities.

Chapter 5 presents a reserved bus-lane case study along an arterial. The case study implemented the proposed two-step microscopic traffic safety evaluation model and provides the recommended operation and safety parameters.

Chapter 6 focuses on a bus-on-shoulder lane case study along a highway. It includes a similar assessment procedure of traffic safety as presented in chapter 5.

Chapter 7 concludes on the proposed assessment methodology of traffic operations and safety performance.

Chapter 2.

Literature Review

2.1 Bus Lane Facilities

New policies are now promoted to ease to traffic congestion effects on public transportation schedule and reliability. For example, such regulations would allow public transit vehicles to use arterial or highway sufficiently wide roadway shoulders. This concept is commonly referred to as Bus of Shoulder (BoS) implementations roadway shoulders typically represent the space adjacent to the right lane, usually dedicated to use of special vehicles (i.e. police, ambulance, etc.) or as temporary pull-over zone for disabled vehicles. For buses, to be able to use the shoulders as a bypass area the shoulder must be a hard surface shoulder, ideally designed for the full structural requirement for general traffic. In North America, BoS lanes were established as early as 1991, in Minneapolis-St. Paul, Minnesota. Presently, this first project contains more than 270 miles of BoS facilities, which is about ten times more than the total BoS length in the other US jurisdictions (Douma, 2007). And this number has continually increased to more than 290 miles in 2010 (Kuhn, 2010).

Currently, more and more cities implemented this type of mass transit operations into their roadway system. Table 1 shows a sample of major cities that started to use BoS and the year when their systems started to operate.

Table 1. Deployment of initial BoS facilities in various cities

Country	City	Year
Canada	Ottawa	1992
Canada	Toronto	2003
Ireland	Dublin	1998
New Zealand	Auckland	1991
U.S.	Atlanta	2007
U.S.	Miami	2007
U.S.	San Diego	2005
U.S.	Old Bridge	2006
U.S.	Columbus	2006

2.1.1 Safety performance

A completed design and implementing guide for BoS - *A Guide for Implementing Bus on Shoulder (BOS) Systems* has been published by TRB's Transit Cooperative Research Program (TCRP) (Martin & Levinson, 2012). In fact, six years before this guideline, the research program published a synthesis - *Bus use of shoulders* (Martin, 2006), which summarized the regulations and experience for BoS on freeways and arterial roads. The main argument for implementation BoS is that it allows to bypass traffic congestion, which leads to reduction in average passenger travel time when compared with conventional mixed-flow bus service. Therefore, it makes transit service more attractive. Kuhn (2010) focused on the shoulder safety issue for their usage as travel lane. The study provided a guidance for transportation agencies to improve highway capacity and efficiency by using shoulder lanes.

The author compared both Europe and North America experiences case by case, and summarized that bus on shoulder segments reflected significant operation reliability of transit trip time without additional right-of-way or invest of large amount of money, also the shoulders could relief the traffic congestion at several spot locations. The study provided before and after accident comparisons, with the implementation of shoulders, the crash frequencies and crash rates decreased in case study of Houston, the similar reductions have also been found in Netherlands, Germany and Great Britain case studies. However, several places, such as Virginia, Minnesota, and Massachusetts cases reflected no significant difference between before and after accident rates. This is mainly due to the short observation period, or the crash data were not available. The possible explanation for the decreasing of crashes is that under the use of shoulders, the capacity of the roadway has been increased. Kuhn (2010) also indicated that researchers have been found that for reserved-lanes facility, most of the accidents were rear-end accident during the peak hour, thus why Minnesota DOT personnel believed BoS facility could improve safety performance. This conclusion was based on the fact that Martin & Levinson (2012) found out that for the year 2003, 19 side swipe accidents out of 21 shoulder accidents were reported, and no injury or fatality were reported in the same Twin Cities BoS program. However, there are no before and after crash studies for this case study, yet.

2.1.2 Safety Problems

In a survey of transit operators, state and provincial departments of transportation, metropolitan planning organizations and other transportation authorities (i.e. motor-vehicle commissions and turnpike authorities), Martin (2006) identified eleven types of safety problems, as follows: *conflicts at on-ramps and off-ramps, sight distance adequacy* *(particularly at on-ramps), conflicts for motorists pulling onto the shoulder, loss of safe evasive movement shelter area, need for bus driver training, speed differential, impact on adjacent lane motorists, return merge distance adequacy, shoulder area debris hazards, reduced clearance for buses at bridge abutments*, and *highway drainage*. This study also suggests that the increase of accidents could be explained by the increase in the number of weaving of the motorists and bus trajectories along specific BoS locations.

Another study by Martin & Levinson (2012), proposed a possible solution that could reduce the number of BoS accidents. The authors suggested that authorized vehicles should continuously use their on-vehicle four-way flashers (i.e. hazard beacons or flashing light) when they traveling on the shoulder, while motorists should be advised not follow the bus under these circumstances. However, this researchers ignored the geometric configuration which could result various traffic behaviors and simply improve the operation policy about illuminating, such as on-vehicle flasher or illuminated sighs on buses, static signs on road, or roadside dynamic message sign (DMS) to indicate that the shoulders are used by transit vehicles.

There is limited knowledge about the safety performance after implementing shoulder lane as bus travel lane, but the existing literature indicates that BoS facilities may provide a good safety environment for buses. Kuhn (2010) evaluated the safety performance of several BoS facilities and found that only 20 accidents (consisting mainly of sideswipes or mirror hits with the bus) have been recorded in Minnesota shoulder bus lane after the implementation of BoS during the observation period from 1991 to 2001, and all of these are property damage only collisions. Goh, Currie, Sarvi, and Logan (2014) compared three bus lane scenarios to include mixed traffic condition, curbside lane relocated for bus use only condition, and new curbside lane implemented for bus use only condition using microscopic traffic simulation approach. The author compared three scenarios' performance using two safety performance indicators: Deceleration Rate to Avoid a Crash (DRAC) and Crash Potential Index (CPI). Their results showed that implementing reserved bus lanes could largely decrease the number of conflicts whether they were newly created bus lane or relocated bus lane.

2.2 Traffic Safety on Reserved-lane Facilities

The common safety issue of reserved-lane facilities was separated by the two categories of roadways: arterial and highway because of the following concerns.

First of all, there exist different road safety investigation methods (e.g. statistical, empirical, soft-computing, etc.) and their selection depends on the availability of data (e.g. before-and-after studies can only be made after the HOV lane is deployed), the type of HOV lane used (e.g. highway vs. arterial, line-separated vs. barrier-separated, bus-only vs. multiple users, etc.), and the scope of the study (e.g. analysis of accident occurrence vs. prevention of hazardous conditions occurrence). In addition, in most North-American jurisdictions, including Quebec, HOV facilities deployed along highway are typically under the jurisdiction of higher level transportation agencies (i.e. federal or provincial) while the HOV arterial facilities are typically under municipal jurisdiction. However, one has to acknowledge that for the most part of any analysis the two types of HOV lanes are more similar than not. Finally, it is interesting to note that no study has been found to investigate specifically the impact of extreme weather, such as winter conditions, on the road safety of HOV lanes. The summary presented below is intended to assist whenever suitable, as a concise basis for comparison of the analysis results which will be later obtained in this thesis with existing studies.

2.2.1 Road Safety of HOV Facilities on Highways

A summary of specific roadway safety aspects found in the evaluated literature is presented in this section. Some authors found that under certain conditions road safety was adversely affected by HOV lane deployments, as demonstrated by Benekohal (1997), Cooner & Ranft (2006), and Jang, Chung, Ragland, and Chan (2009). Other studies (Golob, Recker, & Levine, 1989; Lee, Dittberner, & Sripathi, 2007; Sullivan & Devadoss, 1993) concluded that HOV lane implementation has no significant impact on road safety. Yet, other authors suggested that HOV lanes on highways can lead to improvements in road safety (Jang et al., 2009; Wu, Du, Jang, Chan, & Boriboonsomsin, 2011).

While there is no strong opinion about the positive or negative aspect of a reserved-lane in general, the reviewed literature is more consistent in identifying several parameters as major safety predictors. For example, some authors found that in case of HOV lanes separated by solid white stripes, speed differential, gap acceptance and HOV lane width seem to be the most critical factors (Cooner & Ranft, 2006). Some authors found that the buffer size has significant impact on the accident occurrence (Benekohal, 1997; Jang et al., 2009). For HOV corridors with physical separation, the most affecting road safety factor was identified to be the spatio-temporal changes in the congestion pattern, typically affecting the GP lanes (Farnsworth & Ulberg, 1993; Golob et al., 1989). Yet other studies, determined that HOV lanes corroborated with truck lane restrictions may improve the road safety of the corridor (Kobelo, Patrangenaru, & Mussa, 2008), while other studies determined that this combination of highway operational restrictions may lead to worse road safety conditions (Lord, Middleton, & Whitacre, 2005). Moreover, Siuhi & Mussa (2007) suggested that when both HOV and truck lane restrictions are active, besides the road safety impacts, one has to evaluate the traffic operations effects. Other studies Vanderschuren (2008), used microscopic traffic simulation to demonstrate the positive effects on road safety of HOV lanes coupled with specific ITS deployments such as adaptive control speed and ramp metering systems.

2.2.2 Road Safety of HOV Facilities on Arterials

Very few studies focused specifically on the effects of the deployment of HOV lanes open to carpools on arterials. Among those which have been found on the subject, most of them were about the operational efficiency. For instance, some studies identified that HOV lanes generated travel time savings (McCormick Rankin Corporation, 2007; Polus & Reshetnik, 2001). Concerning safety, McCormick Rankin Corporation (2007) pointed out several important issues such as the interactions with cyclists and with turning vehicles of the general-purpose lanes. The very high violation rate of 3+HOV lanes was also highlighted by McCormick Rankin Corporation (2007) while the issue of enforcement was addressed by Turnbull & Capelle (1998) and by Stoddard (1996).

Concerning bus lanes, some studies have also been found about time savings such as a study done in Montreal (Robert, 1991). Concerning safety, some issues already identified for HOV lanes open to carpools have also been raised for bus lanes such as the interaction with cyclists (Laville, 2010). However, one point for which the study of bus lanes has turned out to be especially interesting is the comparison of different settings. Concerning this issue, Duduta, Adriazola, Wass, Hidalgo, and Lindau (2012) identified that counter-flow lanes were particularly dangerous, and confirming some previous observations (Société de transport de Montréal, 2005). Although to a lesser extent, Duduta et al. (2012) also found that curbside bus lanes tended to generate more accidents than center-lane systems.

2.3 Traffic Conflict Technique

TCT (Traffic conflict technique) is the most commonly used surrogate safety analysis technique because conflicts reflect the nature of a risk rather than the number of accidents. A conflict is defined as “an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of crash if their movements remain unchanged.” (Amundson & Hyden, 1977). When other traffic information (for example, different geometric alignments) is combined with this technique, one can use TCT to identify the optimal geometric configurations and suggest countermeasures to minimize vehicular conflicts.

A conflict is a scenario where two road users will likely collide without deploying an evasive action (i.e. abrupt or unintended change in vehicle trajectory). Statistical tests show that different severities of the potential conflicts can be distinguished. For example, using different thresholds of the conflict indicator TTC (Time-to-collision) (e.g. 1.5 seconds, 1.0 second, and 0.5 second, respectively) and PET (Post-Encroachment Time) different conflict levels can be determined. Time-to-collision (TTC) is a time-based traffic safety surrogate indicator defined as "The time required for two vehicles to collide if they continue at their present speed and on the same path" (Hydén, 1987). Post-Encroachment Time (PET) is another time-based traffic safety surrogate indicator which refers to the time lapse from the moment that the first vehicle departs a predefined conflict point to the moment that second vehicle approaches that point (Hydén, 1987). In order to separate different types of conflicts, Hydén (1987) presented classic pyramid-model: crashes, serious conflicts, minor conflicts, potential conflicts, and undisturbed passage.

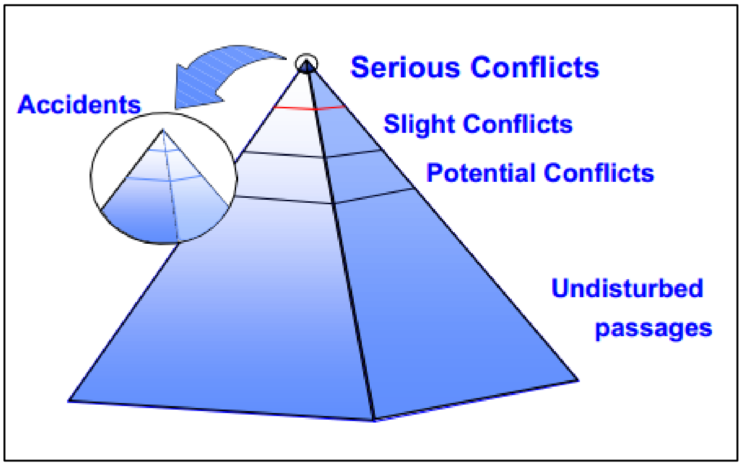


Figure 1. Pyramid represents accidents and conflicts

Figure 1 describes Hyden's model. The pyramid also presents the relationship between conflicts and accidents. Previous studies showed that a properly calibrated simulation model can be used to predict the distribution of these types of conflicts under different scenarios (e.g. changes in geometric alignment, daytime vs. night time, etc.). In addition, the safety performance could be measured not only by the observation of conflicts, but also it could be presented as accident prediction. However, this type of analysis required more accurate information about accidents history than currently available. For example, from the provided accident data information related to occurrence of accidents on specific lanes and the accurate information about specific vehicles types is not available.

2.4 Surrogate Safety Analysis

While road safety analysis through traditional crash prediction safety analysis is limited by the availability of accident data, the surrogate safety analysis has the advantage that it requires easily collectable driving behaviour information since it is based on conflict analysis. Additionally, the surrogate safety assessment has the benefit that it can be deployed for newly constructed roads, without the need to accumulate over extended periods of time safety related performance measures (i.e. accident records).

According to Tarko, Davis, Saunier, Sayed, and Washington (2009), traditional safety approaches based on crash history suffer from two main hindrances: a small quantity of data is available and its quality is often poor. Thus, other approaches have been considered such as surrogate safety analysis, which does not rely on accident history, but on other events. These events should occur more often, but be nevertheless statistically and logically linked to crashes. They can be for instance the changes of lanes on a highway or more complex events such as conflicts. A generally accepted definition of a conflict in road safety is an observable situation in which two or more road users approach each other in time and space for such an extent that there is risk of collision if their movements remain unchanged (Amundson & Hyden, 1977). Lane changes for instance can easily be observed by a trained observer, but conflicts are much more difficult to identify. In fact in the literature, conflicts are most often used in studies based on microscopic traffic simulation. In these studies, the vehicle interactions in the study area are modeled using a traffic simulator software package (such as VISSIM, CORSIM, etc.), and subsequently a relationship between the specific traffic performance measures and road safety is found. For example, lane changing is one of the outputs of most microscopic simulators, and its level of intensity can be converted into an indicator for road safety. This section presents several studies that employed microscopic traffic simulation and different surrogate measures for road safety in general, with some focusing on HOV lanes.

One category of studies focused on developing the best surrogate safety measures that could be obtained from microscopic traffic simulation. For example, Gettman & Head (2003) conducted an extensive study on surrogate measures for road safety. The authors focused their study on the safety of signalized and non-signalized intersections. The study compared the characteristics of the different existing microscopic traffic simulation software packages and the corresponding surrogate road safety measures that could be obtained were summarized. The authors suggested that none of the software packages considered did actually permit the derivation of surrogate measures of safety, and they developed a set of specifications integrated into a Surrogate Safety Assessment Model (SSAM). The developed road safety assessment tool is independent of the microscopic traffic simulation software and is capable of estimating surrogate safety measures based on a set of event description files generated by the microscopic traffic simulator (Gettman, Pu, Sayed, & Shelby, 2008). The authors claimed that the SSAM can be a tool for traffic engineers to obtain the best possible surrogate safety measures (for instance with distribution-based instead of average-based statistics).

In another study, Barceló, Dumont, Montero, Perarnau, and Torday (2003) developed a road safety indicator using vehicle trajectory generated via microscopic traffic simulation. The proposed indicator combines the impact of vehicles speeds, speed differentials and vehicles deceleration rates. The proposed safety indicator has been applied to a case study in Lausanne, Switzerland. The authors evaluated a ramp metering case study with AIMSUN (microscopic traffic simulator), for which they concluded that the presence of a ramp metering strategy would increase user safety.

In the same study, Barceló et al. (2003) developed a new method for estimating the incident occurrence probability. The method uses a hierarchical logit model based on various input parameters: traffic data (e.g. volume, speed, occupancy, etc.), weather data (e.g. clear skies, rainy, windy, etc.), road surface condition (i.e. dry/wet), and highway geometric alignment data (e.g. existence of ramps, vertical and horizontal curves, etc.). The proposed model has been calibrated in terms of threshold for discrimination of safe and unsafe conditions and in terms of parameters of the model using the available accident data. The model is called EIP-HLOGIT and is capable of being integrated to microscopic traffic simulation software packages for safety analysis. The authors have validated the model by applying it to a case study of an urban freeway in Barcelona. It is noteworthy that the proposed approach is capable of predicting the probability of linear collision and could not be applied for safety analysis of an intersection or junction.

Another category of studies identified possible safety indicators and attempted to use them to assess road safety under different scenarios. For example, Siuhi & Mussa (2007) used a simulation model to analyze the operational and safety effects of HOV lanes and truck lane restrictions used simultaneously on the same highway segment. In this study, the authors considered the number of lane changes and the speed difference between lanes as surrogate safety measures. The highway simulated in this study was a highly congested 83-mi corridor of I-95 in South Florida that presented three segments with different characteristics: one segment had only a HOV restriction on its leftmost lane, another had a HOV restriction on its leftmost lane and a truck restriction on the adjacent lane and the third segment had only a truck restriction on its leftmost lane. The truck lane restriction was permanently active and it targeted trucks with three or more axles, while the HOV lane allowed vehicles with at least two occupants only active during the morning and evening peak periods. The authors used historical data of geometrical and operational characteristics and collected travel time data using the floating-car GPS-based technique. The research team used ArcGIS and MATLAB to calibrate VISSIM using field observations. This study found that existing lane restrictions seemed to affect operational and safety performance mainly during peak hours. The authors noticed that during these congested periods, the density of vehicles was more important on the right lanes than on the left lanes and that approximately two times more lane changes occurred. Additionally, the study concluded that restricted lanes seemed to always have a significantly higher speed than GP lanes and that queue lengths at merging and diverging areas increased significantly with the percentage of trucks.

In another study, the impact of specific ITS strategies on road safety was investigated by Vanderschuren (2008). The authors studied a South African highway network using Paramics, a microscopic traffic simulator, due to its ability to capture the effect on road safety of drivers' aggressiveness and their different levels of awareness. The study evaluated three different strategies: one with scenarios that included a bus-lane and a HOV lane, one that considered a variable speed limit segment on the highway, and one with a ramp metering deployment. The safety performance of each scenario was evaluated based on time-to-collision (TTC), speed and headway parameters. The results showed that all three proposed scenarios lead to improvement of road safety. However, the author suggests that additional traffic operations parameters might affect adversely road safety. Therefore, the study recommends an integrated safety and traffic operations assessment of the network before an actual deployment.

More recently, Sobhani, Young, and Sarvi (2013) developed a road safety assessment framework for combining microscopic traffic simulation, Newtonian mechanics and statistical methods. The methodology was applied to a four-leg non-signalized intersection in Melbourne, Australia. Hypothetical vehicular conflicts of various severities were generated with VISSIM. The study evaluated the safety performance via three different statistical regressions that were combined to calculate a safety level indicator. First, the authors proposed to predict the presence or absence of driver reaction using the conflict characteristics simulated before. The second step of the methodology described is to predict the expected speed change for the subject vehicle using the conflict characteristics and the driver's reaction. Third, the research team suggested to derive the kinetic energy from this speed difference using Newtonian mechanics and to use it along with the type of impact and occupant characteristics (age, airbags, seat belt use) as inputs of a third model to determine the expected Injury Severity Score (ISS). Finally, the authors proposed to estimate the safety level using the number and severity of conflicts along with the potential injury severity. In order to obtain the three different statistical models discussed earlier, the authors used the Australian Crash In depth Study (ANCIS) database which contained information based on medical records, interviews of the patients at the hospital, inspection of the vehicles and of the site of the crash. After examining different types of regressions for the three dependent variables to be predicted, the authors adopted a Binary Probit Model for the driver reaction, a Log-Gamma model for the speed difference and a multiple linear regression for the ISS. To conclude, the authors suggested different improvements such as considering different conflict severity levels, adapting this framework to different kinds of locations (highways segments for instance) and evaluating the different parameters for different countries.

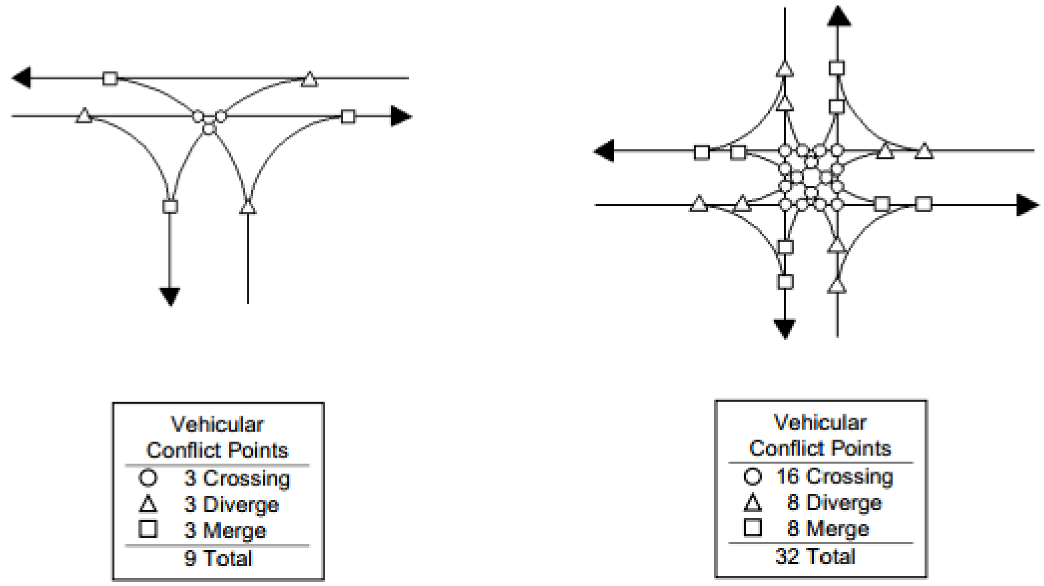
Finally, conflicts can also be used as a surrogate measure of safety without using microscopic traffic simulation, but using the same principle of investigating microscopic characteristics of traffic flow. Saunier & Sayed (2007) proposed a novel method for automatic conflict detection by processing vehicle trajectories captured from video data. The proposed approach is composed of two parts, one feature-based vehicle tracking algorithm developed for intersection and a traffic conflict detector which is based on clustering vehicle trajectories. A K-mean with hidden Markov algorithm and a heuristic were used to find the number of clusters. The authors applied the method to a real case study and found it feasible and applicable. The advantages of these type of road safety assessment methods are that they can be implemented in a pro-active fashion, they are less prone to error in data collection methods and post processing, and that they can be integrated into real-time incident prevention systems.

2.5 Geometric considerations - Access Management

Similarly to the bus-on-shoulder lanes operated on highways, the safety of reserved bus lanes along arterials can be analyzed using the same types of vehicular conflicts (e.g. rear-end conflicts, lane changing conflicts, etc.). These conflicts occur when vehicles on the reserved-lanes interact with vehicles on the adjacent general-purpose lanes. Highways facilities have a limited number of access points (entrance/exit from/to commercial areas). However, arterial facilities are designed to balance mobility and accessibility, hence there are multiple interruptions along a relatively short length, where traffic is controlled via traffic signals and signs. The increasing interactions between the buses typically travelling on shoulder lanes and the driveway vehicles should be carefully considered, since the volume of vehicles entering or exiting is increasing with the development of the adjacent commercial areas. There are a few studies investigating access management strategies to improve the operation and safety performance of reserved-lane facilities, and to the author's knowledge, there are no studies focused on the safety impact of access points for reserved bus lane facilities and bus on shoulder lane facilities.

Martin & Levinson (2012) suggested the designer employ access management to reduce the conflicts between bus lanes and driveways and improve the level of safety. Access management is defined as the systematic control of the location, spacing, design, and operation of driveways, median openings, interchanges, and street connections to a roadway (Committee on Access Management, 2003). A properly defined access management strategy could improve safety for all road users. The author also stated that this safety improvement is attributed by the decreasing of traffic conflicts.

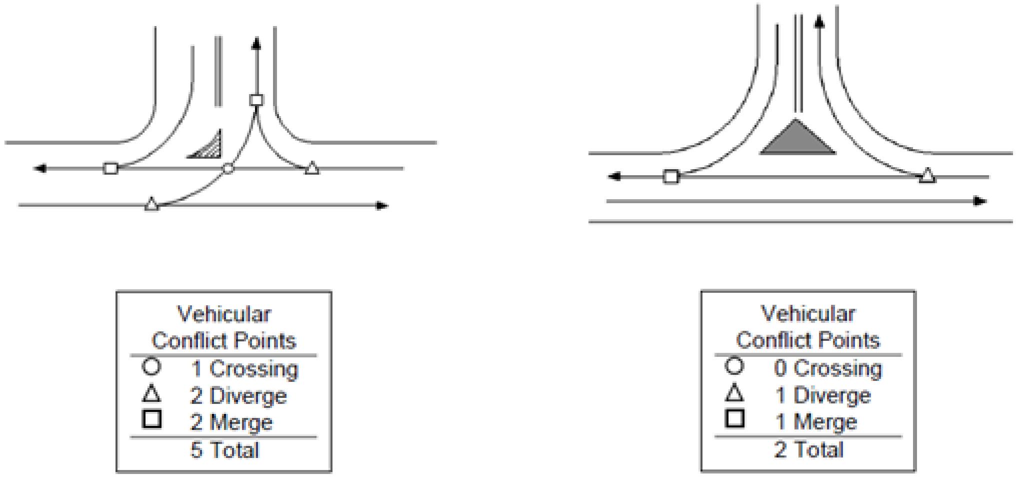
Generally, under the traffic movements at intersection, a three-way intersection have 9 conflicts points and a four-way intersection have the number of 32 conflicts (See Figure 2). To reduce the number of conflicts points, transportation regulatory agencies could implement different types of geometric alignments. For example, Figure 3 (a) shows the reducing conflicts when installing the non-traversable median into the traditional three-leg intersection, the number of conflicts is decreased from 9 to 5. In addition, another access type: right-in-right-out (RIRO) (see Figure 3 (b)), which even diminishes the number of conflicts into 2.



(a) Traffic conflicts at a three-leg intersection

(b) Traffic conflicts at a four-leg intersection

Figure 2. Different types of vehicular traffic conflicts at intersections

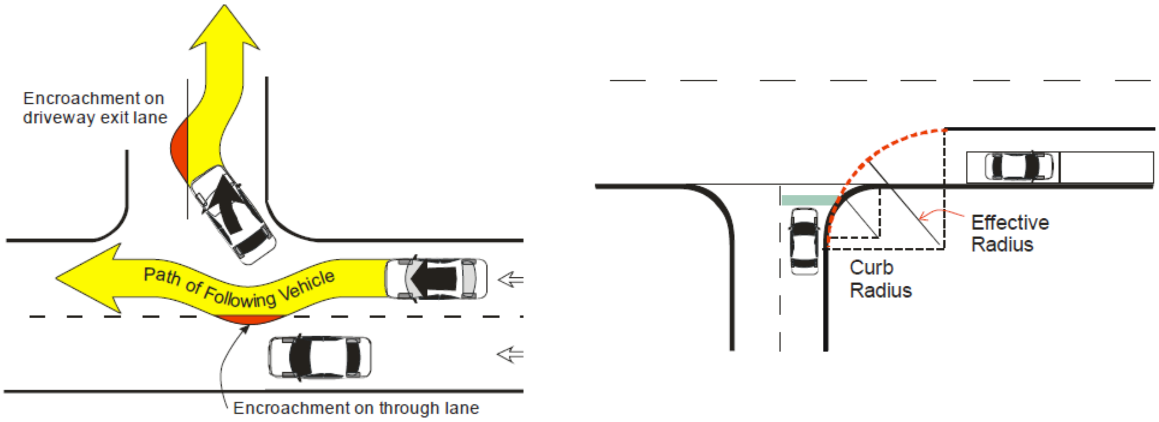


(a) Traffic conflicts at a three-leg intersection with a non-traversable median

(b) Traffic conflicts at a RIRO three-leg intersection

Figure 3. Traffic conflicts at a Three-leg intersection after proper access management (Alabama Department of Transportation, 2014)

A good driveway design is one of the access management technologies. Driveway is an access construction within the public right of way, connecting the public roadway with adjacent property (Bureau of Traffic Engineering and Operations, 1984). Sokolow, Stover, Broen, and Datz (2008) recommended designers several planning parameters include radius, driveway width, angle of driveway, driveway grade, channelization, driveway length, exclusive right turn lanes at un-signalized driveways (queue jump), etc. The author suggested that for a park lane or exclusive lane, the curb radius could be enlarged to the second lane. The dark and red line shows the before and after condition. Several studies investigated the encroachment effects of poorly designed alignments (Sokolow et al., 2008). The red areas in Figure 4 (a) demonstrate that the poor design may lead interactions between the merging vehicle and the vehicle in adjacent lane. This problem could be solved by changing the radius between driveway and shoulder lane. Figure 4 (b) shows an appropriate possible design for an exclusive lane (e.g. shoulder bus lane, or parking lane) with an optimized curb radius under access management.



(a) Effective radius for shoulder exclusive lane

(b) Effective radius for shoulder exclusive lane

Figure 4. Geometric design for access point (Sokolow et al., 2008)

It is important to note the geometric design of driveway should not simply rely on certain handbooks or guidelines, the designers should be concerned with their local traffic conditions (e.g. traffic volume, speed limitation, different types of travel lanes, etc.) case by case.

Farnsworth & Ulberg (1993) studied the safety and operational performance of one temporary HOV lane in Seattle. They employed a before-and-after accident rate comparison and determined that traffic congestion and traffic bottlenecks are the most important factors that affect the safety of the corridor. The authors suggested that some geometric design countermeasures could solve the safety issues of the study area. For example, extending the HOV lane to pass the access and egress point and to smooth the joint section of HOV and GP lane as it shown in Figure 5.

This study also included the responses to the survey that summarized the opinions and suggestions about the HOV lane. The results showed that the users perceived the HOV lane as being underutilized. In terms of efficiency, most of the users believed that the HOV lane should be extended in both directions. One of the limitations of the study was that the analyzed data might have yielded more relevant results if more comprehensive and detailed data would have been collected during whole periods of operation (e.g. gather the vehicle occupancy, collect information related to users' attitude towards mode shift, data collection should cover all seasons and all peak hours of operations, etc.).

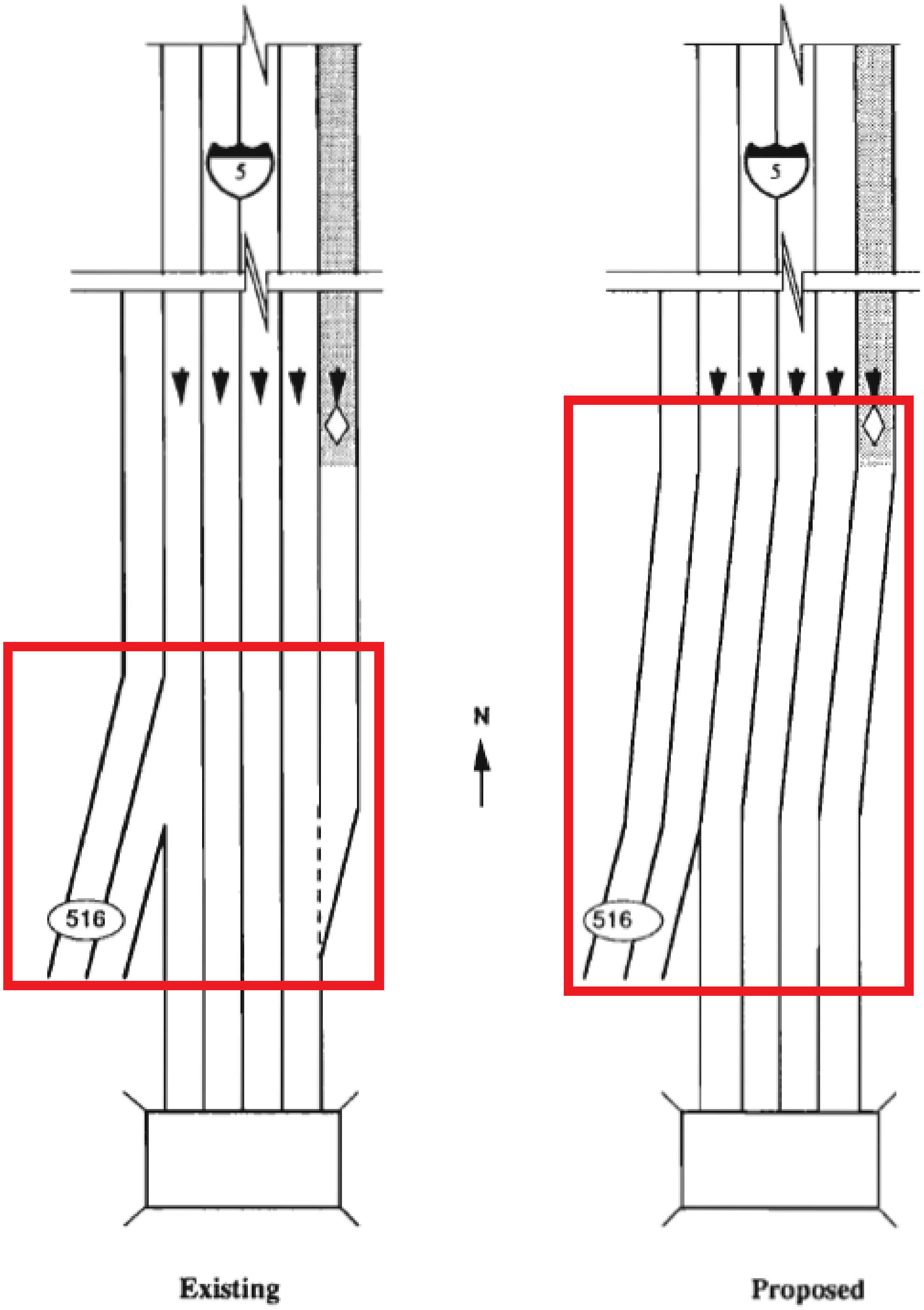


Figure 5. Proposed changes in geometric configuration of corridor to improve traffic safety (Farnsworth & Ulberg, 1993)

To conclude, literature showed reserved-lane facilities could provide reliable and effective traffic performance compared with traditional mixed lane facilities. However, with the increasing of capacity and speed of reserved-lane, interactions between reserved-lane vehicle and adjacent general purpose lane vehicle increased simultaneously. Traditional crash prediction method failed to take lane information into consideration, on the other hand, surrogate safety analysis may assist to evaluate the safety performance under a lane-to-lane condition. A good geometric countermeasure from access management strategy would also contribute to improve safety performance by minimizing the number of existing or potential conflicts for both reserved lane vehicles and adjacent general purpose lane vehicles.

Chapter 3.

Background of Geometric Design

The geometric design of reserved-lanes has to account for various traffic safety performance parameters. For example, it should consider design elements, such as cross-section (e.g. buffer-separated cross-section or barrier-separated cross-section), access points (e.g. ingress/egress), and detailed design for instance, buffer width and shoulder width, etc. Combining collision data, traffic volume and geometric features in their study, Jang et al. (2012) suggested a determination model for cross-section elements that could minimize the accidents occurrences. They evaluated their model by applying it to four different HOV corridors with different geometric thresholds.

Undoubtedly, the differences between various HOV lanes characteristics should be considered when traffic and operations are analyzed. For example, an HOV facility can be categorized by the following criteria:

Types of **access**: *limited, continuous*.

Type of **physical implementation**: *barrier, buffer,* and *contiguous*.

Types of **traffic operation**: *concurrent flow, contraflow, separated roadway,* or *reversible flow*.

The reviewed HOV guidelines and regulations from several different states and provincial agencies (AASHTO, 2004; Alberta Transportation, 2003; British Columbia Ministry of Transportation, 2000; Carter Burgess et al., 2006; Federal Highway Administrator, 2009; Fuhs, 1990; Kuhn et al., 2005; Markkula & Marketing Intelligence, 2004; McCormick Rankin Corporation, 2007; Ontario Ministry of Transportation, 2015), show that most of the geometric thresholds are very similar, however, different sources may define specific considerations for different implementations of reserved-lanes.

3.1 Geometric Standards

Despite various operation categories of HOV facility, such as limited/continuous HOV lanes, concurrent flow/contra flow/reversible flow/separated flow HOV lanes, buffer-separated/barrier-separated/contiguous HOV lanes, the geometric design standards requirements are similar. Table 2 summarizes the desired and minimum threshold values for several elements (e.g. lane width, buffer width, barrier width, and shoulder width.) design standards, as found in various sources.

Table 2. Geometric requirement (source: AASHTO, FHWA, and states DOT)

	Desired	**Minimum**
Lane width	12 feet (3.6 m)	NA
Buffer width	2 - 4 feet (0.6 m - 1.2 m)	2 feet (0.6 m)
Barrier width	10 feet (3 m)	6 feet (1.8 m)
Shoulder width	10 feet (3 m)	2 feet (0.6 m)

Kuhn et al. (2005) summarized the design criteria from four guidelines that include HOV facilities, shown in Table 3*: High-Occupancy Vehicle Facilities: A Planning, Design, and Operation Manual* (Fuhs, 1990)*, A Policy on Geometric Design of Highways and Streets* (AASHTO, 2001), *Manual for Planning, Designing, and Operating Transitway Facilities in Texas* (Mounce & Stokes, 1985), and *Guide for High-Occupancy Vehicle (HOV) Facilities* (Fuhs, 1990) .

Table 3. Summary of HOV lanes design criteria (Kuhn et al., 2005)

	U.S. Customary		**Metric**	
	Desirable	**Reduced**	**Desirable**	**Reduced**
Design Speed	**70 mph**	**50 mph**	**110 km/h**	**80 km/h**
Alignment				
Stopping Distance	730 ft	425 ft	220 m	130 m
Gradients				
Maximum (%)	4	5	4	5
Minimum (%)	0.5	0.5	0.3	0.3
Clearance				
Vertical	16.5 ft	14.5 ft	5 m	4.4 m
Lateral	4 ft	2 ft	1.2 m	0.6 m
Lane Width				
Travel Lanes	12 ft	11 ft	3.6 m	3.4 m

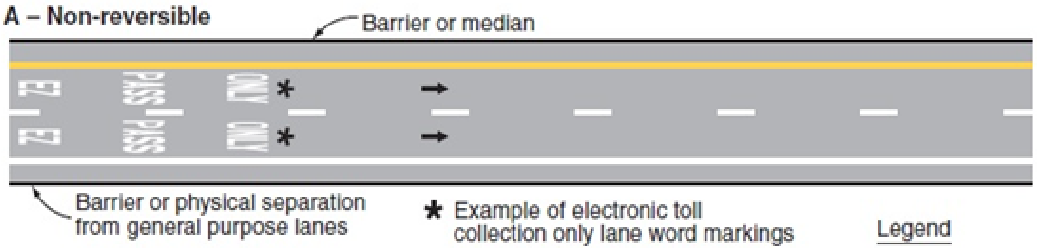
General design criteria in the table above provides standard threshold values for different speed limits. For example, stopping distance, also known as stopping sight distance (SSD) changes from 130 m to 220 m. All the guidelines suggest the use of standard lane width of 3.6 m (12 ft). However, when the speed limit is lower, narrower lane widths are allowed - 3.4 m (11 ft). The shoulder width, also known as lateral / horizontal clearance is recommended at 1.2 m, but no less than 0.6 m. Vertical clearance is recommended between 4.4 and 5 meters.

3.2 Pavement Markings

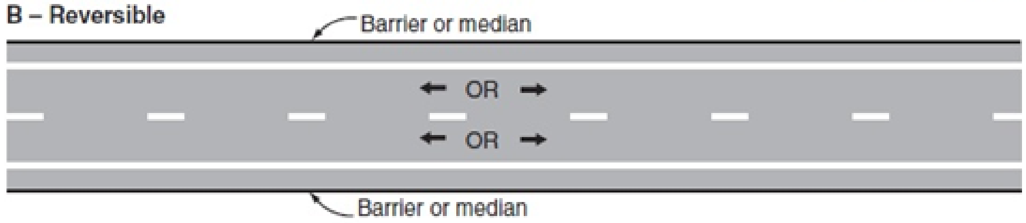
As previously stated, HOV facilities can be categorized by type of traffic operations as: separated roadway, concurrent flow, contraflow, reversible flow, etc. With respect to physical implementation, California. Division of Traffic Operations & California. Dept. of Transportation (1991) classifies HOV configurations as: barrier-separated, buffer-separated, and contiguous. Barrier-separated is a physical type of separation, which limits the access of non-authorized users into the reserved lane. Buffer separation is designated as a painted buffer, which may lead violators illegally cross the HOV lanes. Contiguous separation is different from the above two types because the former contain ingress and egress points, and the later one has no entrance and exit. The crossing behavior could be occurred anytime along the travel lane. In this section, pavement markings are presented in those three types above. Figures in this section are selected from an elaborated design regulations MUTCD (*Manual on Uniform Traffic Control Devices*), where the Federal Highway Administrator [FHWA] (2009) refers to HOV lanes as “preferential lanes”.

3.2.1 Barrier-separated Markings

Barrier-separated HOV facility is a distinct roadway or a lane built within the freeway right-of-way that is physically separated by barriers or pylons from the other GP freeway lanes, and that is designated for exclusive use of high-occupancy vehicles on a permanent basis or during specific time periods within the day. Several studies showed that barrier-separated HOV lanes have less number of accidents compared to the other types of HOV facilities, mainly because the physical separation limits the vehicle interaction associated with lane changing at high speed differentials. As defined by FHWA (2009), barrier-separated HOV are of two types: *non-reversible preferential lane* - a normal solid single yellow line at the left-hand edge of the travel lane(s), and a normal solid single white line at the right-hand edge of the travel lane(s), and *reversible preferential lane* - a barrier or median shall consist of a normal solid single white line at both edges of the travel lane(s). California. Division of Traffic Operations & California. Dept. of Transportation (1991) recommends the used of the non-reversible barrier-separated HOV type, if the space and budget allow. Several advantages pertain to the barrier-separated HOV facilities, such as: ease of enforcement (violations can be enforced at the ingress / egress locations, ease of incident management, unhindered HOV operation (without interference from the mixed-flow lanes, high level of driver comfort, etc. An example of pavement marking for barrier-separated HOV facilities in shown in Figure 6.



(a) Non-reversible barrier separation

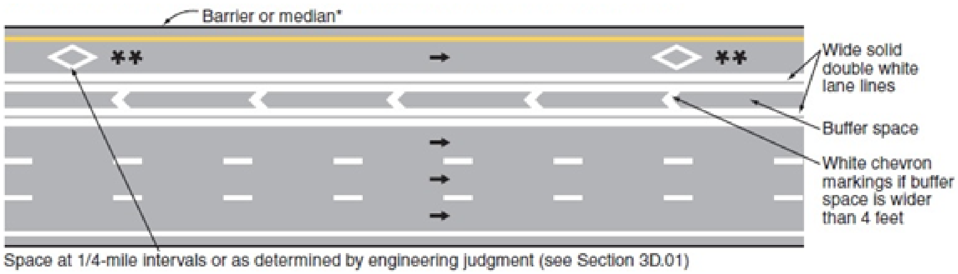


(b) Reversible barrier separation

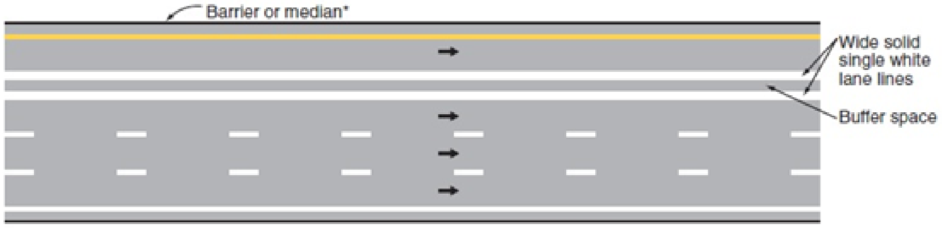
Figure 6. Marking for barrier-separated HOV lanes (FHWA, 2009)

3.2.2 Buffer-separated Markings

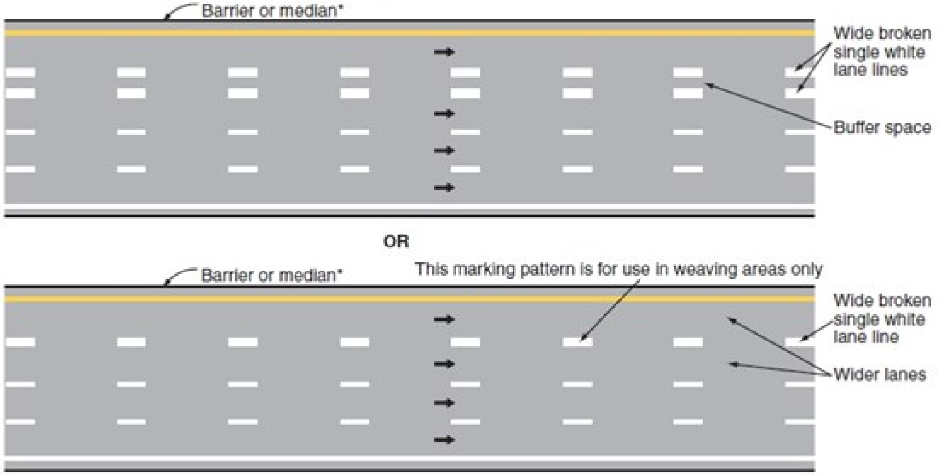
The buffer-separated HOV facility is defined as the lane or set of lanes apart or separated from the GP lanes by a buffer zone of variable width, generally 1.2 m or less. FHWA (2009) defined three types of buffer separation between the HOV lane and the adjacent GP lanes: *prohibited (limited) access* - the buffer contains double-solid white lines on both sides with chevron marking inside of it (if the width is more than 4 feet); *discouraged access* - two solid white lines with no minimum width required; and *open access* – marked with single or double wide broken lines (no buffer). Figure 7 shows the example of buffer separation markings. Several studies showed that buffer-separation HOV facilities provide a safer environment for motorists compared with contiguous (non-buffered) HOV lanes.



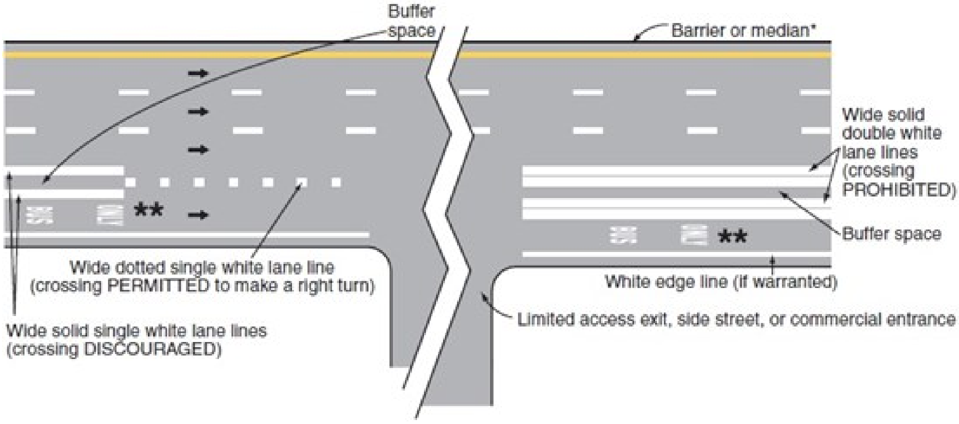
(a) Full-time buffer separation where enter/exit movements are PROHIBITED



(b) Buffer separation where enter/exit movements are DISCOURAGED



(c) Buffer separation where enter/exit movements are PERMITTED



(d) Buffer-separation with side street

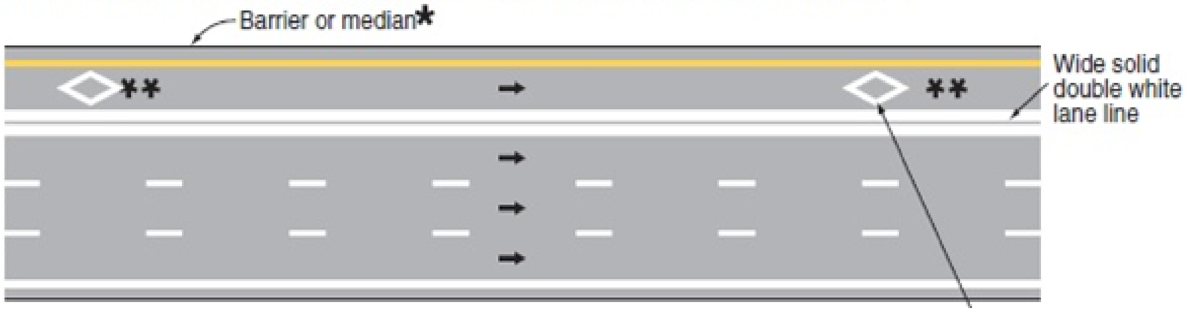
Figure 7. Marking for buffer-separated HOV lanes (FHWA, 2009)

3.2.3 Contiguous Markings

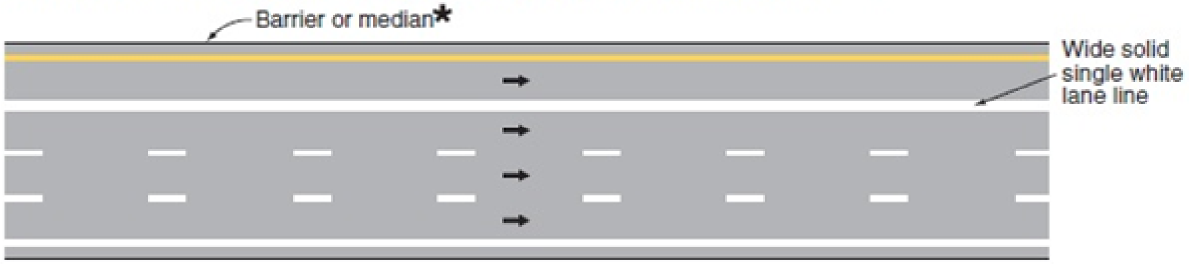
According to Caltrans contiguous HOV facilities are normally deployed in areas with short-duration, high-volume peak commute traffic periods.” (California. Division of Traffic Operations & California. Dept. of Transportation, 1991) The HOV drivers could enter or exit at any point along the HOV lane. Contiguous separation is defined in *The Manual on Uniform Traffic Control Devices* (MUTCD) (Federal Highway Administrator, 2009), and include three types as follows: *Prohibited access* – marked by a wide solid double white lane line where crossing; *Discouraged access* - a wide solid single white lane line where crossing is not recommended; and *Permitted access* – distinguished by a broken single solid white lane line where crossing (a wide dotted single white lane permitted all types of vehicle).

Figure 8 is an example of contiguous HOV lanes. Conversely with buffer-separated HOV facilities, which exist a ‘buffer’ space, contiguous HOV separation may lead more motorcycle accidents since the restriction are always be ignored by cyclists drivers. Also, the speed differential between HOV lane and GP lane could be reduced if the buffer space is existed.

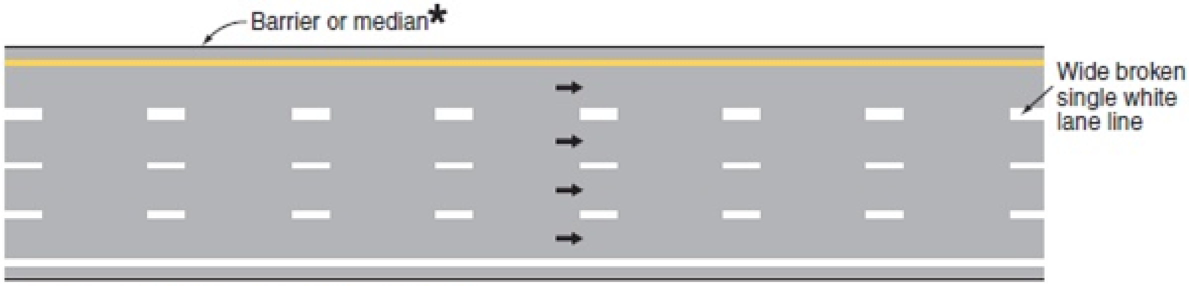
Compared to buffer-separated HOV facilities, contiguous separation HOV facility provide less level of service because the HOV traffic is free to enter and exit the lane along the facility at any location, increasing the interactions between vehicles.



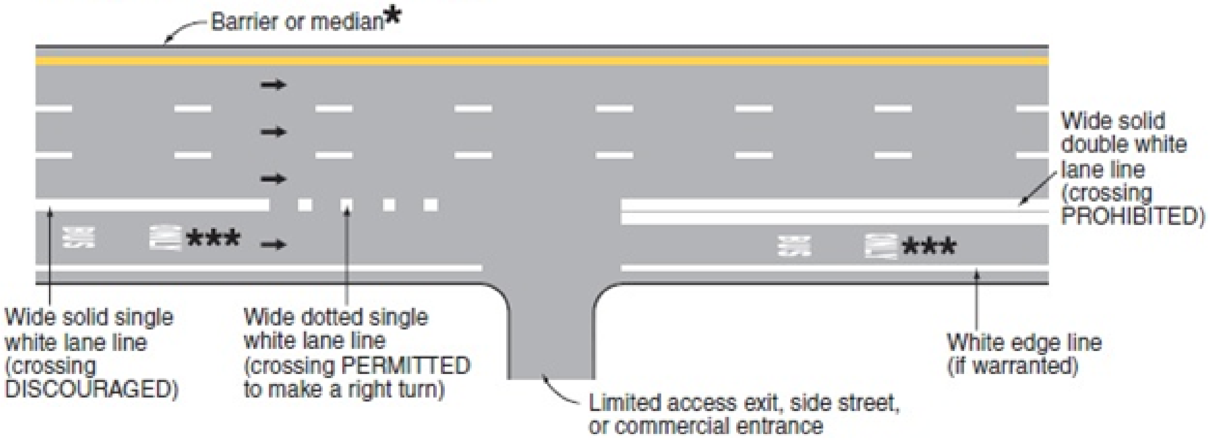
(a) Full-time contiguous separation where enter/exit movements are PROHIBITED



(b) Contiguous separation where enter/exit movements are DISCOURAGED



(c) Contiguous separation where enter/exit movements are PERMITTED



(d) Contiguous separation with side street

Figure 8. Marking for contiguous HOV lanes (FHWA, 2009)

3.3 Operation and Safety

In this section, three pairs of operation comparisons were discussed: limited vs. continuous HOV facility, buffer-separated vs. barrier-separated HOV facility, and concurrent flow vs. contra flow HOV facility.

3.3.1 Limited Access vs. Continuous Access

As in previous section, HOV lanes operational access can be provide as two types: limited access and continuous access. Contrast to continuous access which drivers could enter and exit of the HOV lane at any point, limited access HOV lane may only allow the drivers merge at ingress/egress areas. Both the barrier-separated and buffer-separated HOV facilities should be considered as limited-access operational facility. The initial purpose of limited access operation is to avoid the danger caused by the speed differential between the higher speed of HOV lane and the lower speed of GP lane. However, some research studies showed that there is no safety advantages of using limited access compared with continuous access.

California. Division of Traffic Operations & California. Dept. of Transportation (1991) indicated that contiguous HOV facilities (continuous access or non-separated HOV facilities) are commonly arranged in high volume and peak commute traffic periods. Unlike limited HOV facilities, vehicles were allowed to merge/diverge into HOV/GP lanes. In addition, as AASHTO (2004) specified in Guide for High-Occupancy Vehicle (HOV) Facilities, peak-period-only continuous access HOV approach could improve the traffic utilization during the hours of operation, and enlarge its utility for all types of vehicles during the off-peak periods. Therefore, many states authorities separate and restrict the full-time HOV facilities while not separate or restrict the part-time facilities.

Jang et al. (2009) compared the performances for limited-access HOV facility with continuous-access HOV facility. The comparison group included 279 mi part-time continuous access HOV facility and 545 mi full-time limited access HOV facility. Peak hour accident data were used to evaluate the effects of those two types of facility, other traffic characteristics include shoulder width, length of access, and proximity of the access to ramps. Two types of accidents: rear-end and sideswipe accidents were considered. More rear-end accidents have been found in limited access HOV facility than continuous access HOV facility, mainly because the restriction of access eliminated lane changing behavior, however, increased the interaction between the vehicles in the same travel lanes. Similarly, a large number of sideswipe accidents has been found in continuous-access HOV lanes. Statistical test was used to evaluate the difference of accident rate between continuous and limited access facility using the parameter of VMT (vehicle miles traveled). The results showed that the rates of PDO (property damage only) accidents and injury-related accidents for limited-access facility was much higher compared with continuous access facility. In addition, for continuous access HOV facility, the rate of PDO accidents was higher for HOV lanes than GP lanes. However, the injury-related accidents for this comparison is not statistically significant at the same level, the rate of this type of accident was lower in HOV lanes than GP lanes. Their result also showed that in a certain condition (shoulder + HOV lane + buffer), continuous access HOV facilities can reduce the rate of accidents compared with limited access.

3.3.2 Buffer Separation vs. Barrier Separation

Compared to barrier-separated reserved-lane facilities, buffer-separated and non-buffer separated reserved-lanes have been regarded as lower safety facilities. For example, Liu et al. (2011) analyzed the interaction between GP and managed lanes along four freeway HOV sites. The managed lanes included HOV and HOT lanes. The authors evaluated different operation strategies, including multiple separation types, and different numbers of managed lanes. The frictional effect between the managed lane and adjacent GP lane can be affected by different types of separation between lanes. For example, if there is no physical barrier – i.e. buffer or painted stripe between the GP and reserved-lanes, the drivers might break the rule, often times under congested conditions, and execute lane changing maneuvers at prohibited locations. As opposed to the concrete barrier case, where there is no lane changing friction effect. The author analyzed four different freeway segments: two-lane concrete barrier-separated HOT lane, two-lane soft barrier-separated HOT lane, single buffer-separated HOT lane, and two-lane buffer-separated HOV lane. The results showed that buffer-separated managed facilities have greater significant interaction between GP lanes and managed lanes compared with the barrier scenarios. The interaction condition from least to most is concrete barrier – soft barrier – buffer separation. The author suggested that measuring the safety performance for different managed lane facilities should consider each separation type isolate since there exists variations between the different types of separations and facility characteristics.

3.3.3 Concurrent Flow vs. Contra Flow

Traffic operation along HOV facilities can be implemented as concurrent flow or contraflow (AASHTO, 2001). Both types can be implemented for barrier separated, buffer separated or contiguous facilities.

The contraflow implementation utilizes during the peak-direction one or more lanes from the off-peak direction of travel for use HOV purpose. Basically, the purpose of the contraflow HOV facility is to redistribute the excess capacity in the off-peak direction to relieve congestion in the direction of peak flow. The traffic along the corridor can be separated by median crossovers into opposite direction. Removable pylons, movable barriers or additional lanes are the possible implementation.

AASHTO (2004) defined concurrent flow HOV lanes as freeway lanes in the same direction of travel, not physically separated from the general-purpose traffic lanes, and designated for exclusive use by HOVs for all or a portion of the day. Concurrent flow HOV implementation is the most common HOV application in North America, which always designated from retrofitting an existent freeway. Another commonly used implementation is to expand the right-of-way by adding a managed lane in original freeway. The median barrier or the left/right shoulders may also be used as HOV lanes.

Chapter 4.

A Two-step Microscopic Traffic Safety Evaluation Model

4.1 VISSIM

A microscopic traffic simulation software has been used as the modeling tool in this thesis. There are a variety of microscopic traffic simulation typically used in traffic impact studies. However, the reliability and accuracy of these models relies on how precisely the real-life traffic conditions are represented by the software parameters.

VISSIM is a microscopic traffic simulation software tool for the design of traffic actuated control systems (Fellendorf, 1994). There is a large selection of parameters available to calibrate the modelled network (e.g. speed distribution, headway distribution, lane changing parameters, car-following parameters, etc.). Speed distribution is the most commonly used parameter to calibrate the network because it is relatively easy to obtain accurate data on the cumulative of real traffic speed. However, gap acceptance is the essential parameter for safe driving in road crossing that requires accurate perception of the gap sizes in a dynamic stream of traffic (PTV, 2013).

To capture the effect of pavements marking and different geometric alignment configurations (e.g. solid or dashed line for HOV lanes, buffer/barrier separated HOV lanes, etc.) particular lane changing behaviors can be prescribed in the simulation model, which can be implemented for different types of vehicles. For example, partial compliance with crossing the painted buffers can be simulated by defining separate class of vehicles that are allowed to cross the separation buffers. Nevertheless, the reliability and accuracy of these models is directly related to the availability of representative data that reflects the real-world driving behavior.

4.2 SSAM

Given the infrequent and random nature of crashes, the process of building historical record of crashes is slow to reveal the need for remediation of either the roadway design or the flow-control strategy. This process is also not applicable to assess the safety of roadway designs that have yet to be built or flow-control strategies that have yet to be applied in the field. Therefore, alternative traffic safety assessment methods have been defined.

The surrogate safety assessment model (SSAM) developed by FHWA is one of the most commonly used microscopic traffic simulation and conflict analysis tool. Several research studies used VISSIM's vehicle trajectories output with SSAM, due to the microscopic traffic simulator's ability to provide a flexible driver behavior model, with user adjustable parameters. The stochastic vehicle trajectory output provide realistic information for analyzing vehicle to vehicle interaction.

Surrogate Safety Assessment Model (SSAM) is a technique that combines microscopic traffic simulation output and automated conflict analysis (Gettman et al., 2008). This methodology analyzes the frequency and the nature of narrowly averted vehicle-to-vehicle collisions under prevailing traffic conditions. This approach helps to assess the safety of the simulated facilities without waiting for crashes and injuries to actually occur at a rate that is statistically above a minimum arbitrarily selected threshold.

A conflict is a scenario where two road users will likely collide without deploying an evasive action (i.e. abrupt or unintended change in vehicle trajectory). To assess the traffic safety conditions of given roadway segment with SSAM, the expected vehicle interactions on the facility are first modeled using a traffic simulation environment capable to record individual vehicle trajectories under prescribed traffic conditions. Next, SSAM is used to analyze the vehicle-to-vehicle interactions from the simulation output, in order to identify and classify vehicular trajectory conflict events. Conflict classification is performed according to user specified criteria. For each such event, SSAM also calculates several surrogate safety measures, including the following:

- Minimum time-to-collision (TTC).
- Minimum post-encroachment (PET).
- Initial deceleration rate (DR).
- Maximum deceleration rate (MaxD).
- Maximum speed (MaxS).
- Maximum speed differential (DeltaS).
- Classification as lane-change, rear-end, or path-crossing event type.
- Vehicle velocity change had the event proceeded to a crash (DeltaV).

4.3 Microscopic Traffic Simulation

Using traffic simulation to evaluate road safety is a cost-effective modeling approach useful to evaluate different roadway designs when similar real-world study areas and data are not readily available (Chen, Yu, Zhu, Yu, & Guo, 2008; Deakin et al., 2006; Dijkstra, Drolenga, & van Maarseveen, 2007; Fitzpatrick et al., 2011; Li, Abbas, Pasupathy, & Head, 2010; Park et al., 2010). Microscopic traffic simulators contain different calibration parameters that can be used to assess the vehicle interactions via specific traffic control operations and driving behavior factors. These parameters default to a set of values that can also be adjusted by users. Considering the prevailing road conditions, traffic demand and driving behavior differences between different road users, one needs to calibrate and validate the simulation model's parameters to obtain realistic results. Over the past two decades traffic simulators have been improved to enhance the calibration methodology by adjusting the parameters of the behavioral models to the observed driving behavior, as they pertain to different countries in the world (Zhou, Li, Sun, & Han, 2010). El Esawey & Sayed (2011) proposed a set of requirements for the calibration of traffic simulation models. Park & Qi (2005) proposed a procedure for microscopic traffic simulation model calibration. Oketch & Carrick (2005) demonstrated that microscopic traffic simulation can be applied successfully to network analysis, but noted that detailed data is required to conduct the calibration and validation of the model successfully. Sun, Wu, and Yang (2005) presented the application of a simulated annealing algorithm as an optimization method for finding a suitable combination of VISSIM parameter values. Basically, many studies showed that microscopic traffic simulation could provide reliable simulation results after carefully calibration.

4.4 Surrogate Safety Analysis using Simulated Vehicular Conflicts

While road safety analysis through traditional crash prediction safety analysis is limited by the availability of past accident data, surrogate safety analysis has the advantage that it requires easily collectable driving behavior information necessary to assess vehicular conflict analysis. Additionally, the surrogate safety assessment has the benefit that it can be deployed for newly constructed roads, where traditional methods cannot be applied. Traffic conflict technique (TCT) is the most commonly used surrogate safety analysis method. This method is oftentimes used because conflicts reflect the nature of a risk rather than the frequency of the accidents. A conflict is defined as “an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of crash if their movements remain unchanged.” (Amundson & Hyden, 1977). When other traffic information (for example, different geometric alignments) is combined with this technique, one can use TCT to identify the optimal geometric configurations and suggest counter-measures to minimize vehicular conflicts.

VISSIM’s vehicle trajectory output provides realistic information for analyzing vehicle to vehicle interaction due to the stochastic nature of the simulator. Bachmann, Roorda, and Abdulhai (2011) and El-Tantawy, Djavadian, Roorda, and Abdulhai (2009) compared the vehicular conflicts by varying the proportion of trucks along an expressway in Toronto, Ontario. The authors improved their Time to Collision (TTC) detection algorithm and obtained more accurate classification of vehicular conflicts. Habtemichael & de Picado Santos (2014) combined VISSIM and SSAM to evaluate the safety performance of a highway. The authors used Post-Encroachment-Time (PET) as the performance measure for severity of conflicts. However, there are a few studies have attempted to calibrate the SSAM results. One study by Souleyrette & Hochstein (2012), evaluated the safety and operational performance for J-turn intersections using the same combination of VISSIM and SSAM. The authors considered several alternative geometric designs and proposed a methodology to calibrate and refine the conflicts by changing the thresholds of the conflict angle for each type. The authors validated their model with a historical accident dataset and found two threshold values for rear-end and lane changing conflicts, and for lane change and crossing conflicts, respectively. However, the applicability of this method is limited by the availability of detailed vehicle accident data (e.g. lane(s) where the accident occurred).

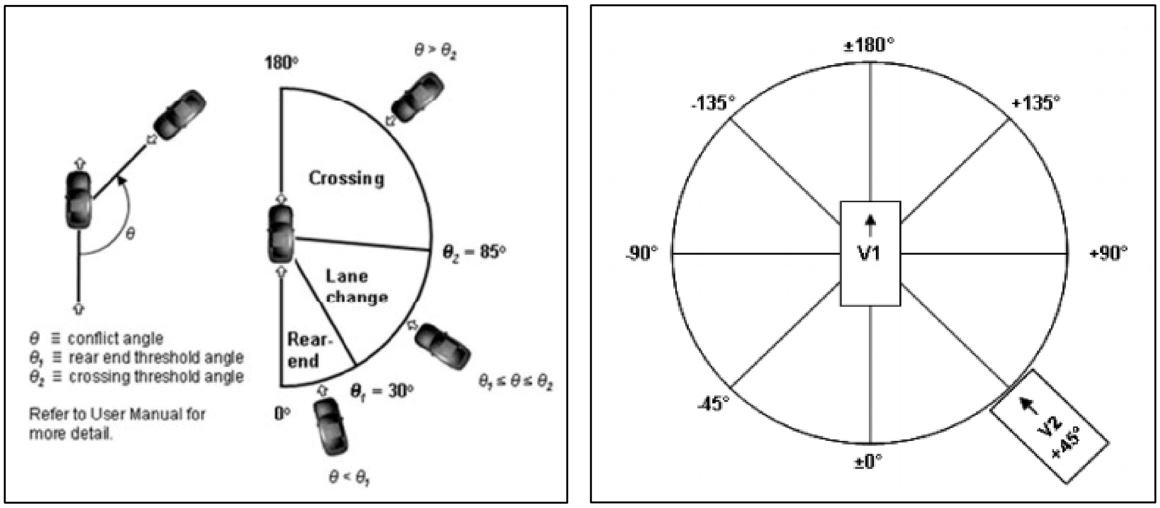
4.5 Enhancing Conflicts Classification in SSAM

The review of the existing literature shows that there are few studies related to the safety analysis of reserved bus lanes, and, to the authors knowledge no study investigated the impact of the length of merging/diverging section of reserved-lanes based on microscopic traffic simulation. Meanwhile, there is no study calibrated SSAM conflicts output by utilizing its details (such as link information, lane information, conflict angle, and etc.). A two-step simulation and calibration procedure is proposed and applied into two case studies: arterial and highway cases in chapter 5 and chapter 6, respectively. First, a VISSIM network should be calibrated using real-world speeds and headways. Second, vehicle trajectories generated from first step are fed to a SSAM analysis, which uses a newly developed conflicts calibration methodology.

Vehicular conflicts can be modeled with SSAM by using the output of any microscopic traffic simulator that is able to generate individual vehicle trajectories, such as VISSIM or AISUM. The types of potential vehicular conflicts are determined based on the estimated conflict angle, while the associated severity is categorized by TTC (time-to-collision) and the PET (post-encroachment time) threshold values. TTC is a surrogate indicator defined as the time required for two vehicles to collide if they were to continue on the same path without braking (Hayward, 1972). Post-Encroachment Time (PET) is another time-based surrogate indicator, which refers to the time lapse from the moment that the first vehicle departs a predefined conflict point to the moment that second vehicle approaches that point (Cooper, 1984). A limited number of studies attempted to evaluate the effect of different threshold classification values on the severity of conflicts. However, a consensus on a common set of values is not yet reached. Therefore, in this thesis the conflicts classification threshold values mostly used by previous studies were adopted.

The SSAM categorizes the detected conflicts into three types: rear-end, lane-change, and crossing conflicts, based on the conflict angle. The conflict angle is defined as an approximate angle of hypothetical collision between conflicting vehicles, and is derived on the estimated heading of the two vehicles, as shown in Figure 9.

To model conflicts from vehicle trajectories in SSAM, the angle thresholds should be set. According to the FHWA report (Gettman et al., 2008) rear-end conflicts are identified when the conflict angle is less than 30°, a crossing conflict occurs when the angle is greater than 85°, and a lane-change conflict is identified for all angles between 30° and 85° (Figure 9 (a)). In this thesis, the recommended measurements from Gettman et al. (2008) were used: the rear-end conflicts has been defined as less than 2º , the lane-changing conflicts has been classified from 2º to 45º, and crossing conflicts has been called when the angle is larger than 45º. (See Figure 9 (b))



(a) SSAM default conflict angle (b) User defined conflict angle

Figure 9. Conflict angles diagram

Tao, Foomani, and Alecsandru (2015) proposed a new method to process additional information about the conflicting vehicles. Mainly, by utilizing detailed vehicles' link and lane information the reliability of SSAM output can be enhanced. For example, if both vehicles are located on the same link and the same lane, the conflict is classified as rear-end. If both vehicles are located on different lanes of the same link, it is classified as lane-change conflict. Also, if both vehicles are traveling on two distinct links, the conflict is identified as a crossing type. The output of SSAM presents the details of individual conflicts in the form of the link and lane numbers, and the TTC and PET values associated with the two vehicles estimated to produce a potential conflict. Using this information it is possible to identify whether the conflict between the two vehicle might occur on the same link or not, and whether the two vehicles travel on the same lane or not.

To better classify the types of vehicular conflicts, a two-dimensional binary matrix is built to present the conflict information for each conflict event. For example, when we compare the vehicles link numbers the binary output is set to one if the vehicles travel on the same link, otherwise the number is set to zero. Similarly, if the vehicles travel on the same lane, the output is set to one, vice versa. The link and lane information can be used to build the binary matrix, and conflict event is associated with link and lane information. The flowchart of the proposed method to classify conflicts is shown in Figure 10.

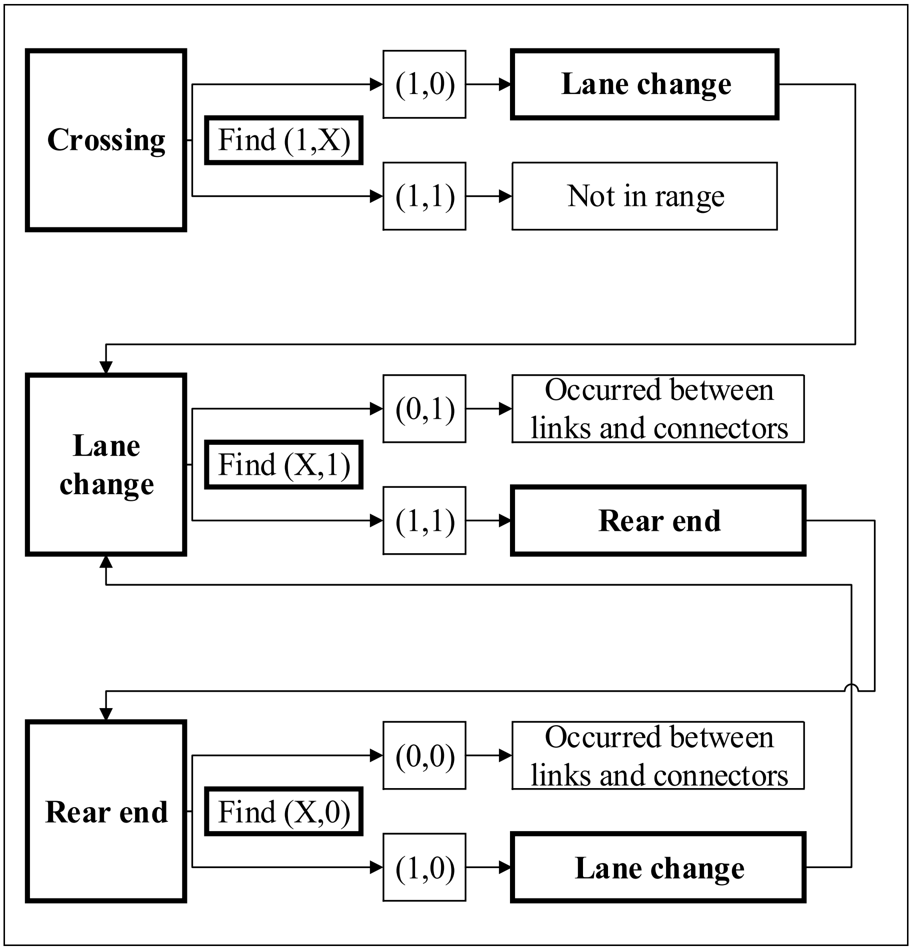


Figure 10. Flowchart of binary matrix calibration procedure (Tao et al., 2015)

In this flowchart a (0, 0) conflict type occurs when the two vehicles a located on distinct links and different lane, a (0, 1) conflict represents vehicles on different links and but on the same lane, a (1, 0) conflict is for vehicles locates on the same link and on different lanes, and a (1, 1) conflict identifies vehicles that are on the same link and the same lane. This flowchart describes all possible conflict types, considering that a VISSIM network is coded using links and connectors, as individual network entities. Consequently, the conflict sresults could be better classified using a user-defined angle situation. For example, if the results are crossing conflicts, conflicting vehicles should be occurred in the different link. Those results of (1,0) have to be removed and considered as lane change conflicts, since 1 refers to same link and 0 means vehicles are located in different lanes. Calibration details will be presented in chapter 5 and chapter 6 under arterial and highway traffic conditions.

Chapter 5.

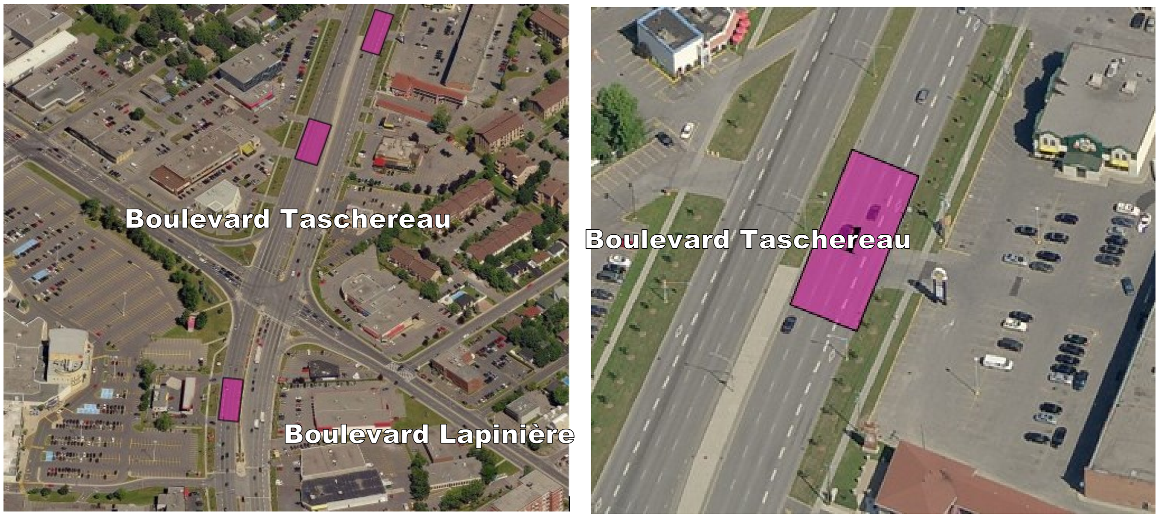
Arterial Case Study

5.1 Data Description

Boulevard Taschereau is one of the main arterials located on the south shore of St. Lawrence River in Greater Montreal Area (GMA) (see Figure 11(a)). East of the A-10 highway, between Ave. Panama and Ave. Auguste a two-km long exclusive bus/taxi lane has been implemented. This reserved lane runs along the right-side shoulder, in both directions, along an alignment with a raised median. The raised median permits the left turns movement of the vehicles only at intersections. The boulevard has an additional three lanes on each direction that can be used by the general traffic. The reserved bus/taxi lane is in effect 24/7 with the purpose to accommodate a more reliable schedule of the public transit system. The objective of the lane is to curb the vehicular traffic crossing the limited number of bridges between the South Shore of Montreal and the downtown core by increasing transit passengers. Because the major bus terminal on the South Shore (Panama terminal) is located at the southern end of the reserved lane, the main purpose of the exclusive bus lane is as a feeder lane for all of the transit buses travelling between the terminal and other locations along the South Shore of Montreal.

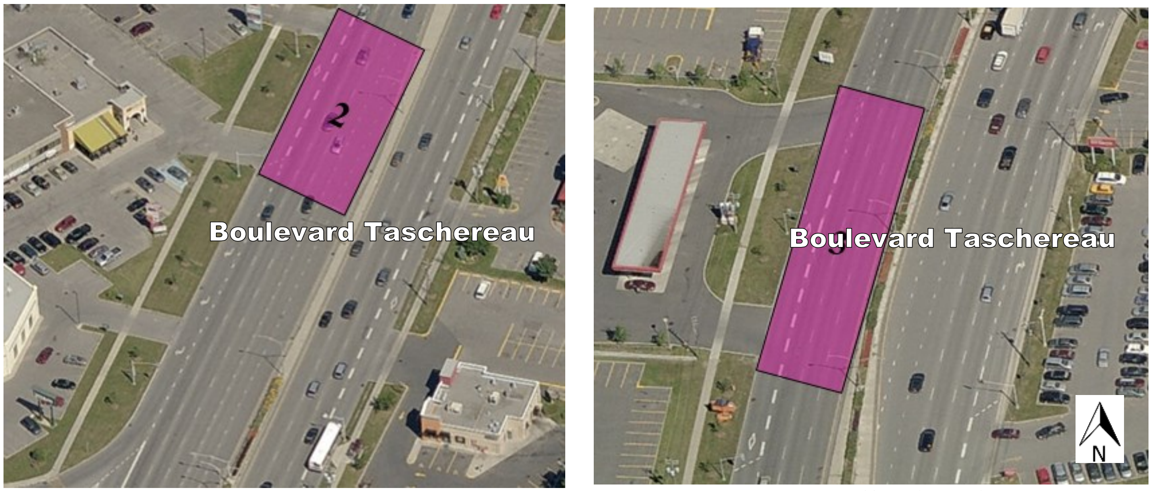
Signal timing along this corridor was provided by the local transportation authorities. Vehicle interaction video-data has recorded for three weekdays during the afternoon peak-hours (4:00 to 6:00 pm) in April 2013 (i.e. Tuesday, Wednesday, and Thursday) at three locations (Figure 11 (b) (c) (d) (e)). This data was used to calibrate vehicle speeds and headways at four access points along arterial. These points include different driving behavior types – access/egress to parking lots in a commercial zone with restaurants, gas stations, and other shopping establishments. The 800 meters long study segment consists of three signal-controlled intersections, two stop-sign intersections and three commercial areas. The segment contains three travel lanes in addition to the reserved bus lane. All the lanes were considered to be 12 feet wide, and there is no buffer was modeled for the reserved bus lane. The access points in the study segment have been categorized into two types: access/egress (site 1) and egress only (site 2 and 3) (see Figure 12).

(a) Geometric layout



(b) Data collection sites

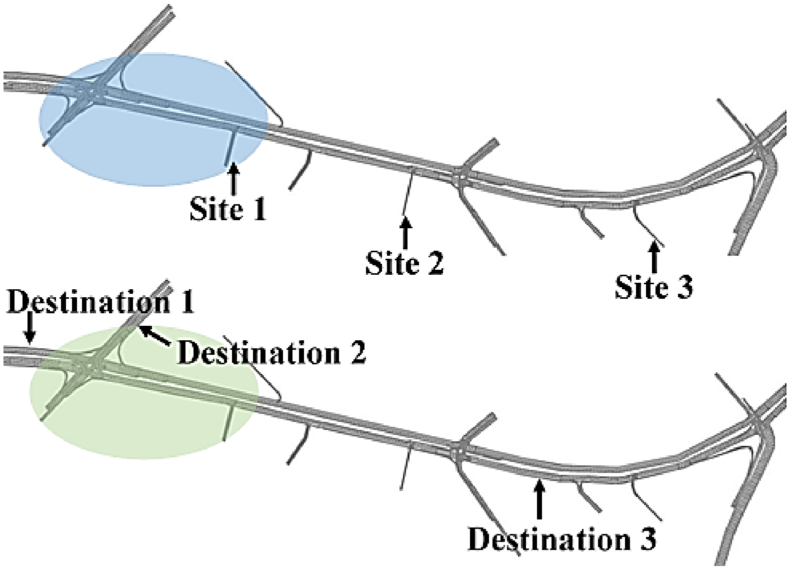
(c) Data collection site 1



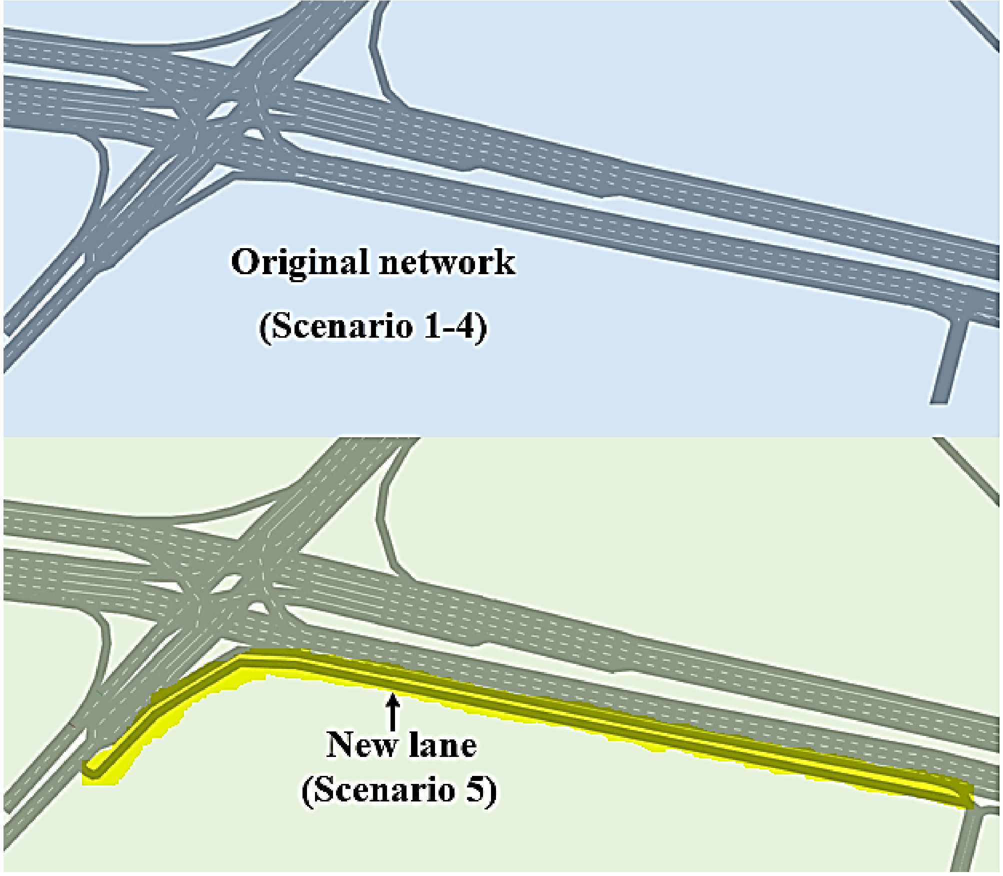
(d) Data collection site 2

(e) Data collection site 3

Figure 11. Layout of the Taschereau Blvd. tested segment



(a) Network layout



(b) Before and after networks for scenarios 1-4 (top) and scenario 5 (bottom)

Figure 12. Taschereau blvd reserved lane segment testing locations in VISSIM network

5.2 Traffic Simulation and Conflict Analysis Model for an Arterial Reserved Lane Facility

In this study, VISSIM 6.0 has been used to estimate the travel time along the arterial in order to assess the impact of different geometric alignment scenarios on the traffic operations and road safety. The network was simulated for the current conditions and for several alternative models, which include different geometric design configurations at the access points identified in Figure 12 (a). Ten simulation runs have been generated using different random seeds for each scenario, to account for the stochastic properties of the microscopic traffic model.

In order to evaluate the effect of traffic volume on vehicular conflicts along the reserved-lanes, four traffic demand scenarios have been evaluated. The first scenario is the base-case, representing the traffic demand as provided the local transportation authorities in 2013 (the prevailing vehicle demand as of 2013, around 1978 to 2060 vehicles along the major segment, which were measured from the platoons after three four-leg intersections during PM peak hour.). Three additional traffic demand scenarios considered an increase in vehicle demand on the major arterial by 10%, 20%, and 30%, respectively. The VISSIM model has been calibrated based on real-world speed distributions, which were generated from analyzing the recorded video data with an open source vehicle trajectories processing software, Traffic Intelligence (Jackson, Miranda-Moreno, St-Aubin, & Saunier, 2013). The observed vehicle headways at the three locations along the study segment (Figure 11 (b-e)) have been used to adjust the parameters controlling vehicle interactions at the conflict areas defined in VISSIM (PTV, 2013). The minimum gap time used was three seconds, and minimum headway of five seconds, respectively, with normal distributions. A total of 200 simulation runs (five scenarios × four traffic demand cases × ten random seen runs) were performed and analyzed. Each case was evaluated for one hour under afternoon peak hour traffic volume, using a ten-minute warm-up period. In order to determine if alternative geometric alignments can improve vehicle interactions, and, consequently traffic safety, five additional alternative cases have been tested in addition to simulating the existing geometric configuration.

- For scenarios 1 to 4, using the existing geometric alignment, a 20, 30, 40 and 50 m long weaving section was simulated at each access/egress location along the segment, respectively (see Figure 12 and Figure 13).
- For scenario 5, vehicles are only allowed to access the commercial destinations from the arterial via the current existing access points. However, the reinsertion of vehicles back into the arterial is only allowed via a hypothetical new service lane that provides direct access to nearby signalized intersections (as shown in Figure 12).

In order to eliminate the impact of different platoon formation and to maintain consistency in all simulation cases, for all scenarios it was assumed that the status-quo signal phasing of the base-case during the peak period is maintained. The purpose of the proposed alternative scenarios is to identify the impact of the weaving section on vehicle interactions along the bus-lane. For example, if the weaving section is too short, there may not have enough time for vehicles to accelerate/decelerate in order to safely execute merging/diverging maneuvers. On the other hand, when the length of weaving section is long enough, the speed differential related safety issue could be alleviated. However, it is expected that unauthorized drivers might be attracted to use the reserved lane to bypass the congested adjacent lanes, leading to an increase in weaving maneuvers.

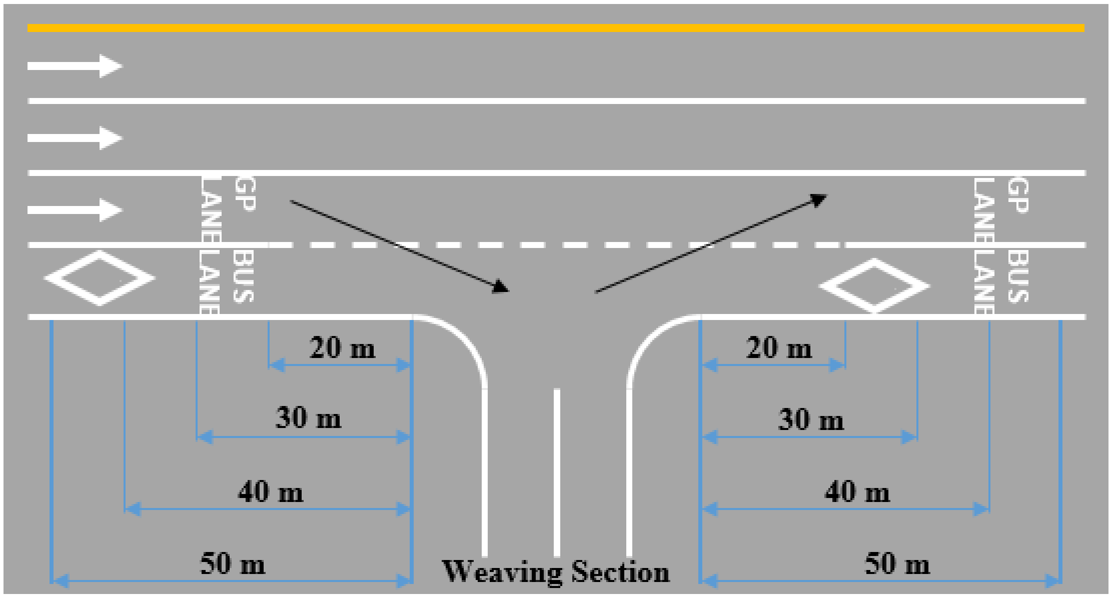


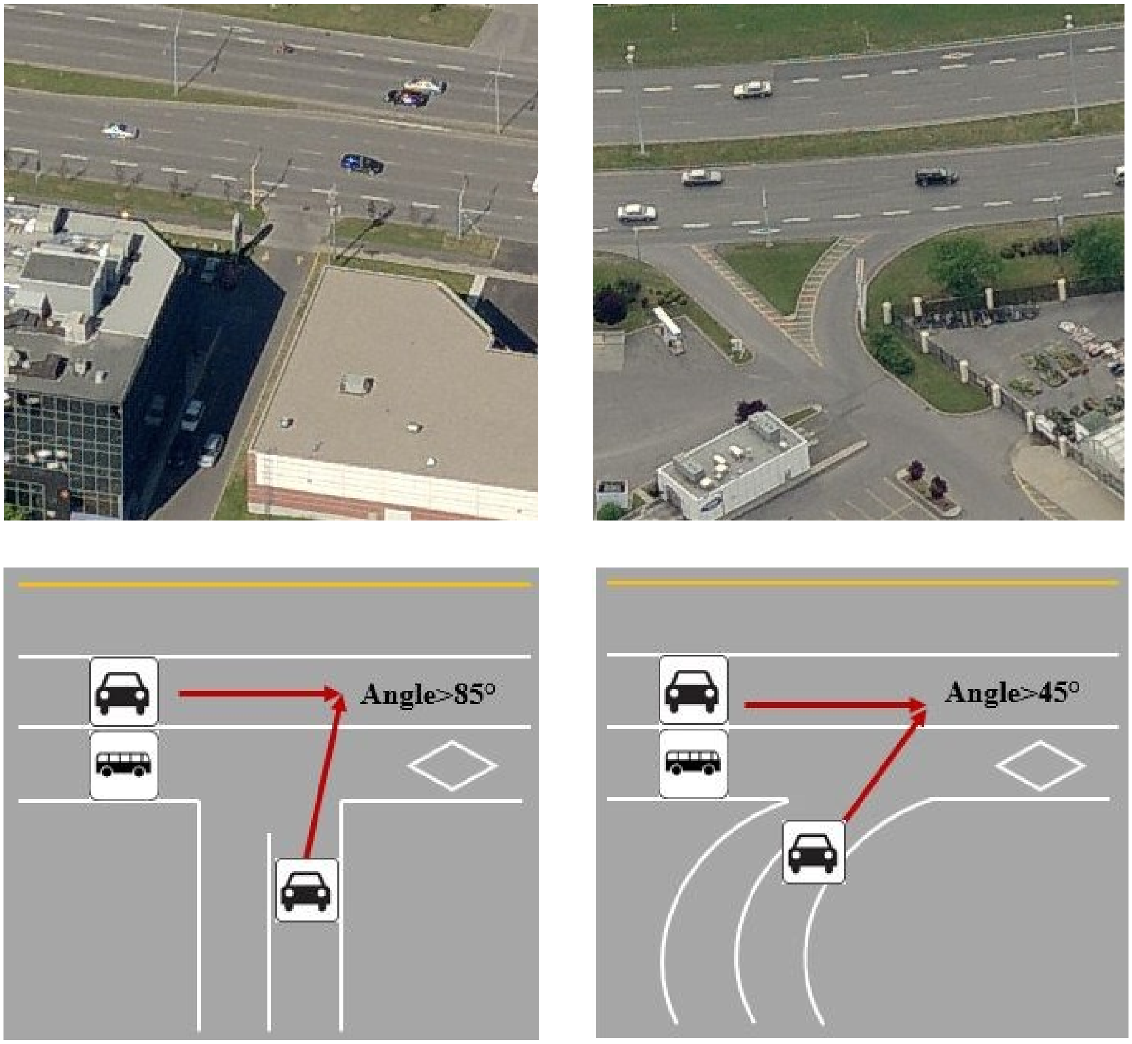
Figure 13. Weaving section for scenario 1 - 4

The four lengths of weaving sections scenarios were simulated at three locations, namely sites 1, 2, and 3. Under the current conditions, site 1 allows access and egress into/out of the commercial destinations, while at site 2 and site 3 vehicles are only allowed to egress into the Taschereau Boulevard. The simulated 100 veh/h flow rates (i.e. entry/exit volumes) at these locations were approximated from the collected traffic dataset. The fifth geometric alignment scenario allows only egress maneuvers from the arterial, across the bus lane, and redirects all vehicles merging from the commercial destinations into the arterial, via the neighboring signalized intersections, based on the shortest path to their desired destinations (See Figure 12 (b)). Three hypothetical destinations (as shown in Figure 12 (a) have been arbitrarily selected to evaluate the impact on travel of various geometric alignment and traffic flow combinations.

SSAM allows users to define conflict from vehicle interactions using conflict identification thresholds, TTC and PET. Once those thresholds values are determined, the

SSAM can generate conflict results automatically from the simulated trajectory files into a conflict database, which includes conflict details, such as location, time, link, lane information. The most commonly used TTC and PET thresholds values, 1.5 seconds and 5 seconds, respectively, were used to assess all the vehicular conflicts in SSAM using the VISSIM output. Additionally, to distinguish between different types of conflicts, the angle threshold values were used. As it suggested by the FHWA report (Gettman et al., 2008), the assumed rear-end conflict is defined by a conflict angle smaller than or equal to 2º, and the crossing conflicts was assumed to be at least 45º, while any conflict angle between these two thresholds is classified as a lane-change conflicts.

However, the use of SSAM for different real-world scenarios, is often times very specific to the particular traffic operations conditions and geometric alignments. For example, in this arterial case study, for traditional three-leg intersection (e.g. site 1 and site 2), the angle between driveway and the major road is about 90 º (Figure 14 (a)). But, this angle in a three-leg intersection with right-in/right-out (RIRO) median (e.g. site 3) is much smaller, and the crossing movement might occur at very small angles (Figure 14 (b)). The 45º threshold for crossing conflicts is not applicable at site 3, where the angle between merging vehicle and major stream vehicle is less than 45º. Hence, the proposed conflict calibration method were implemented in order to enhance the accuracy of conflicts classification. A MATLAB script was written and used to calibrate the initial classification results. For each conflict, a binary matrix was generated and stored into the database. After following the flowchart as it has been presented in Figure 10, the conflicts removed from the initial type if the binary matrix fits to change into another conflict type.



(a) Typical three-leg intersection without median (e.g. site 1 and 2);

(b)) Three-leg intersection with right-in/right-out (RIRO) median (e.g. site 3)

Figure 14. Different conflict angle in different geometric alignments

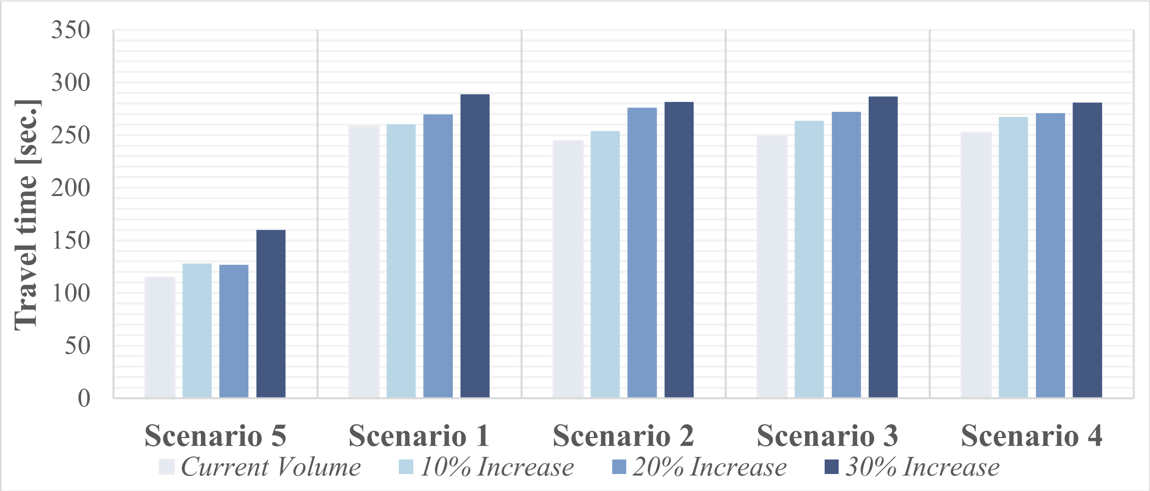
5.3 Simulation Results and Analysis

5.3.1 Effect of Geometric Alignment on Travel Time

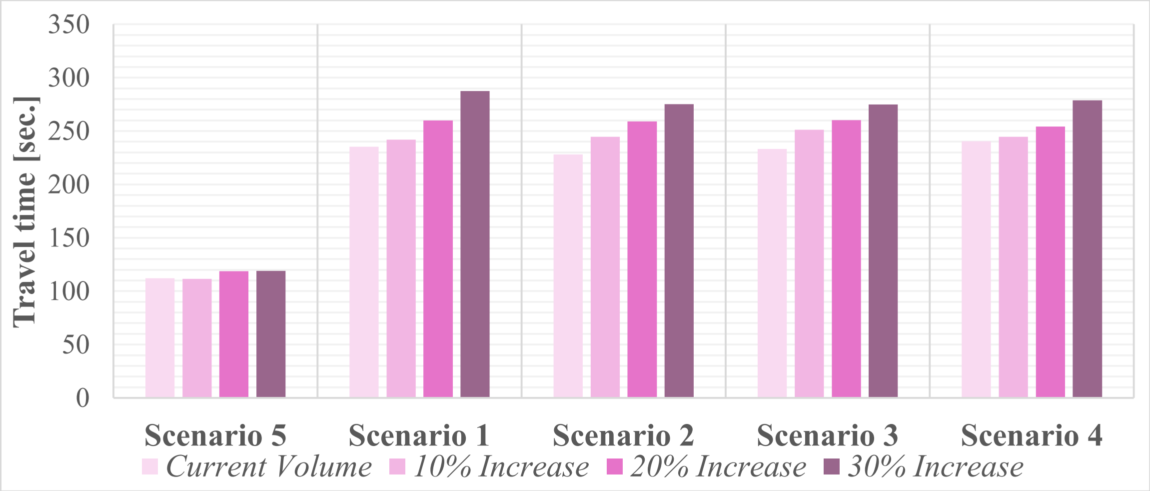
The impact on traffic operations was estimated by measuring the average vehicle travel time between the individual sites 1, 2 and each of the arbitrarily selected destinations 1, 2 and 3. A MATLAB script was written to process individual vehicles passing over the virtual detectors at each origin and destination pairs. Figure 15 and Figure 16 present 1 average travel time results of vehicular routines from 2 sites to 3 destinations under 4 traffic demands in 5 scenarios. For each of the three sites, it was found that the 30-m long weaving section leads to the lowest average travel time between site 1 and destination 1 for most travel input scenarios (i.e. current demand, 10% increase, 20% increase, and 30 % increase of volume, respectively). The corresponding travel times ranged between 244 seconds and 281 seconds (see Figure 15). Similarly, the smallest average travel time between Site 1 and Destination 3 corresponds to the 30-m long weaving section for all travel demand scenarios and it ranged between 110 seconds and 134 seconds. Finally, the minimum average travel time for vehicles between Site 1 and Destination 2 was not obtained consistently for the same length of the weaving section. It was found that the lowest average travel time occurred when the weaving section is 30 meters in current volume condition, and the minimum travel time in 10%, 20%, 30% volume increase scenarios are in 20 m, 30m, and 40m, respectively. However, those minimum values are just less than 2.5 seconds for all those three scenarios, which is not considered statistically significantly different. The travel time of vehicles from site 2 were the lowest for the same 30-m long weaving section for all the traffic demand scenarios and for each of the three destinations (See Figure 16). The average travel times ranged from 240 to 499 seconds, from 217 to 470 seconds, and from 92 to 391 seconds, corresponding to destinations 1, 2 and 3, respectively.

The simulation results also show that the restriction of vehicles (to install new lane – scenario 5) to egress into the arterial only via the neighboring intersection is beneficial mostly all routines (Site 1, 2 to Destination 1, 2 and 3) while the average travel time for the vehicles from site 1 and 2 to Destination 3 is not statistically significantly smaller, and in some of the results, the minimum travel time have been found at 30 meters weaving section scenario (i.e.

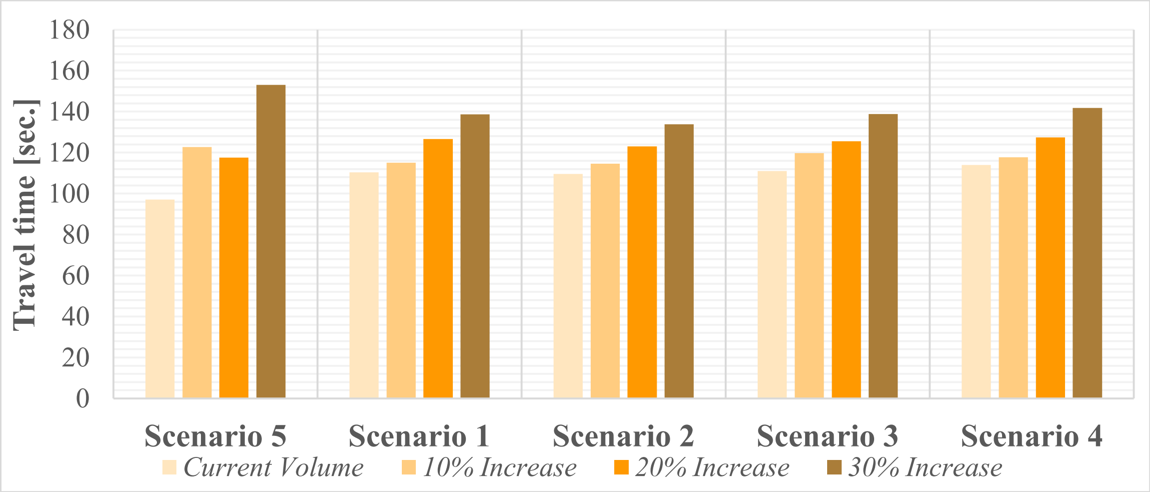
the minimum average travel time from Site 1 to Destination 3 in 10% volume increase scenario - 115 seconds has been found in scenario 3 (30 m weaving section), while the average travel time is 123 seconds in scenario 5 (new lane scenario). Similarly as the results to site 2 to destination 3, where the minimum results occurred at 134 seconds in 30 m weaving scenario). This difference can be explained by the fact that when employ a new paralleled lane, vehicles should follow the new lane to enter the nearest signalized intersection since the restriction for those vehicles. For such scenarios, the travel time results might be involved with the signal timing of its nearest intersections. It is important to notice that simply compare the results of scenario (new lane) to the other different lengths of weaving section scenarios may not reflect a proper comparison results. When new lane employed, the traffic demand had been changed because the weaving vehicles are traveling along the main arterial and increased more traffic interactions. In this section, the author only discuss the different effects of scenario 2, 3, 4 and 5 is mainly because the reason above. The new lane scenario will be discussed more in the conflict analysis section.



(a) Site 1 to destination 1

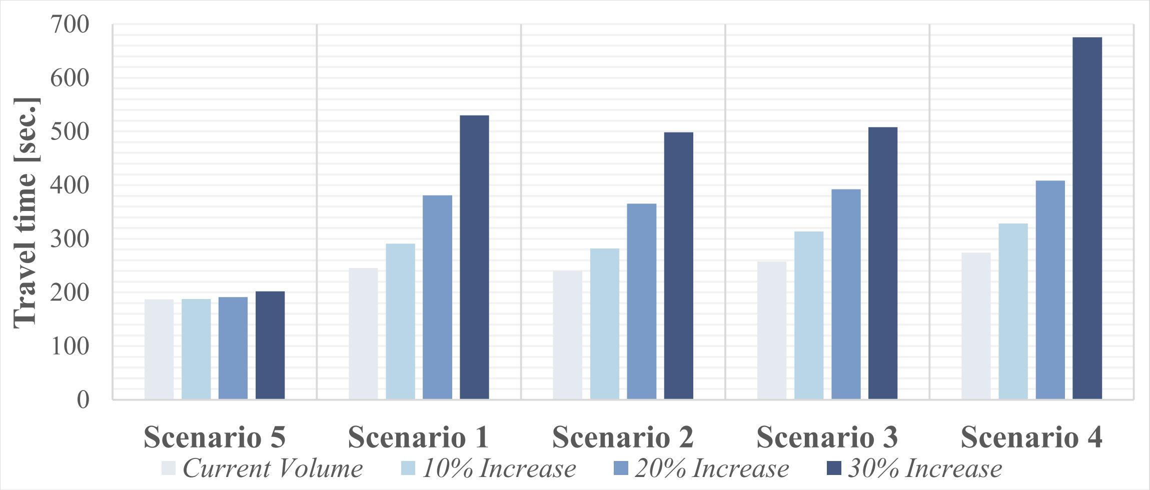


(b) Site 1 to destination 2

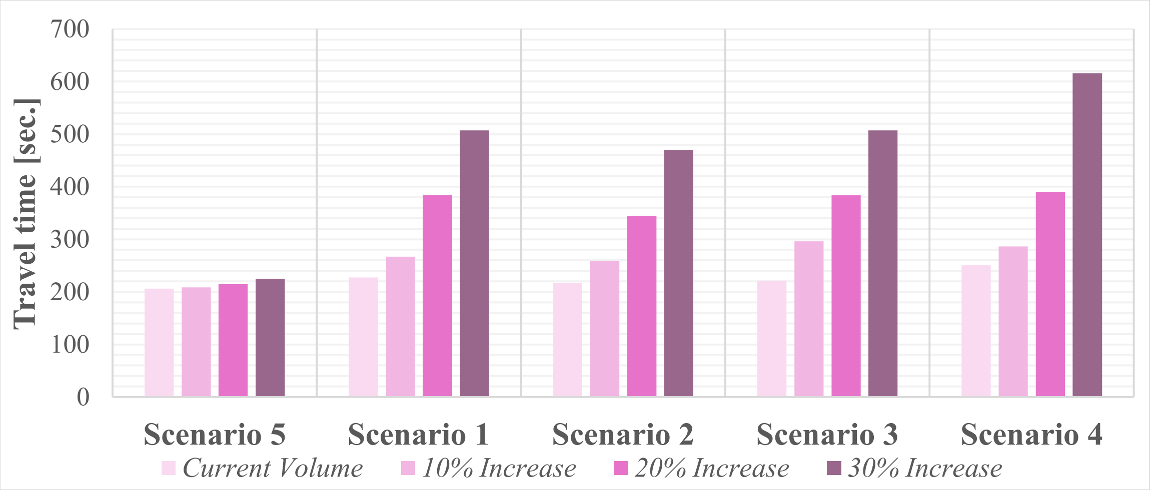


(c) Site 1 to destination 3

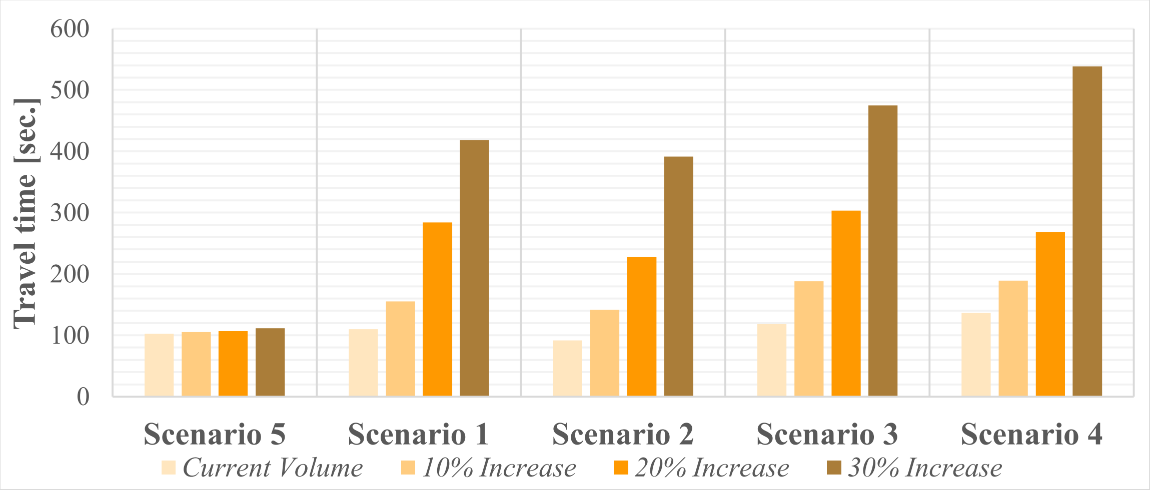
Figure 15. Effects of geometric alignments on travel time (Taschereau Blvd. Site 1)



(a) Site 2 to destination 1



(b) Site 2 to destination 2



(c) Site 2 to destination 3

Figure 16. Effects of geometric alignments on travel time (Taschereau Blvd. site 2)

5.3.2 SSAM-based Classification of Vehicular Conflicts

The SSAM detailed output of potential conflicts was processed using the proposed binary matrix method. The method is expected to enhance the reliability of angle-based classification of the conflicts.

From each SSAM results, ten simulation runs were used for each scenario. In total 20 comparison cases and for each case 200 distinct trajectories have been utilized. For the binary matrix (X, Y), the X and Y values identify if the conflicting vehicles, travel or not on the same link and lane, respectively. The proposed method uses “1” to indicate that the two conflicting vehicles travel on a common link, or on the same lane, while “0” indicates otherwise. For example, if two conflicting vehicles were on the same link, the proposed method generate a (1, X) output, while a (X, 1) output indicates that the conflict occurs on the same lane. This method allows to identify the crossing conflicts by the pair (0, X), because a crossing conflict occurs necessary for the vehicles travelling on different links.

Hence, this method allows to identify conflicts more reliable because, while SSAM classifies the conflicts only based on the conflict angle, without the proposed method, the conflicts of the type (1, X) at an angle greater than 45° would be wrongly classified as crossing type, instead of lane changing type (both vehicles are on the same physical link). Moreover, in some cases, where multiple geometric types of intersections along one single network, one should consider different crossing angles (for example Site 1, 2 and Site 3 in this study). Similarly, lane-changing conflicts should occur between vehicles traveling on different lanes, and consequently a lane-changing conflict characterized by the matrix (X, 1) would be erroneously reported. Finally, rear-end conflicts could be the wrongly attributed in their category if their matrix is of the form (X, 0), because in the vast majority of incidents rear-ending accidents occur between vehicles traveling on the same lane.

The processing of the SSAM results showed that most exceptions were found among the (0, 1) and (0, 0) categories, for lane change and rear-end conflicts, respectively. This limitation of the default SSAM behavior may be due to the fact that conflicting vehicles travel on interconnecting links and connectors. A MATLAB script was written to process the SSAM based on the proposed methodology. As it is shown in Table 4, Table 5, and Table 6, after calibrating, the number of crossing conflicts decreased in all scenarios, meanwhile, more rear-end conflicts have been classified by using the proposed binary matrix method. Most cases show that the different between the number of conflicts for each type, between the SSAM direct and processed output is statically significant with 90% confidence, except where noted.

Table 4. Crossing conflicts for before and after calibration of Taschereau Blvd. bus-lane

Crossing conflicts				
	Traffic Volume	**SSAM Mean**	**Calibrated Mean**	**P-Value**
Scenario 1	Current	59.4	32.3	0.001
	10%	68.5	36.8	0.000
	20%	78.2	38.8	0.000
	30%	103.4	42.3	0.000
Scenario 2	Current	61.6	26.1	0.000
	10%	57.1	25.8	0.002
	20%	63.4	24.7	0.000
	30%	70.5	26.0	0.007
Scenario 3	Current	56.0	38.2	0.061
	10%	78.2	54.5	0.077
	20%	73.7	48.8	0.063
	30%	83.5	55.3	0.135*
Scenario 4	Current	81.1	33.3	0.003
	10%	94.9	38.4	0.003
	20%	83.3	31.5	0.016
	30%	102.1	37.4	0.001
Scenario 5	Current	37.0	28.9	0.043
	10%	38.0	29.8	0.082
	20%	38.1	27.6	0.016
	30%	46.6	33.2	0.004

The results with * indicates few exceptions for which the difference is not statistically significant

Table 5. Lane change conflicts for before and after calibration of Taschereau Blvd. bus lane

Lane change conflicts				
	Traffic Volume	**SSAM Mean**	**Calibrated Mean**	**P-Value**
Scenario 1	Current	602.8	534.5	0.012
	10%	655.0	583.1	0.009
	20%	734.2	657.9	0.083
	30%	790.5	725.6	0.091
Scenario 2	Current	580.3	524.2	0.016
	10%	632.6	563.1	0.013
	20%	704.9	631.8	0.051
	30%	745.8	672.5	0.014
Scenario 3	Current	566.1	506.2	0.039
	10%	674.4	601.9	0.056
	20%	666.6	594.1	0.055
	30%	751.8	675.2	0.007
Scenario 4	Current	580.3	543.5	0.153*
	10%	599.1	564.3	0.098
	20%	663.2	621.6	0.277*
	30%	760.8	721.2	0.402*
Scenario 5	Current	688.0	621.3	0.026
	10%	780.1	705.3	0.011
	20%	797.7	721.0	0.000
	30%	867.7	784.8	0.006

The results with * indicates few exceptions for which the difference is not statistically significant

Table 6. Rear end conflicts for before and after calibration of Taschereau Blvd. bus lane

Rear end conflicts				
	Traffic Volume	**SSAM Mean**	**Calibrated Mean**	**P-Value**
Scenario 1	Current	404.0	499.7	0.000
	10%	436.5	540.2	0.000
	20%	440.9	556.8	0.000
	30%	479.3	608.8	0.000
Scenario 2	Current	405.0	496.5	0.000
	10%	417.2	518.3	0.000
	20%	442.2	556.5	0.000
	30%	466.8	584.9	0.000
Scenario 3	Current	387.4	465.3	0.000
	10%	422.6	519.0	0.000
	20%	421.3	519.3	0.000
	30%	462.5	569.7	0.000
Scenario 4	Current	387.7	472.6	0.000
	10%	414.8	506.1	0.000
	20%	422.5	516.5	0.000
	30%	459.1	564.5	0.000
Scenario 5	Current	483.1	557.9	0.001
	10%	524.6	607.6	0.000
	20%	546.6	634.3	0.000
	30%	565.6	662.2	0.000

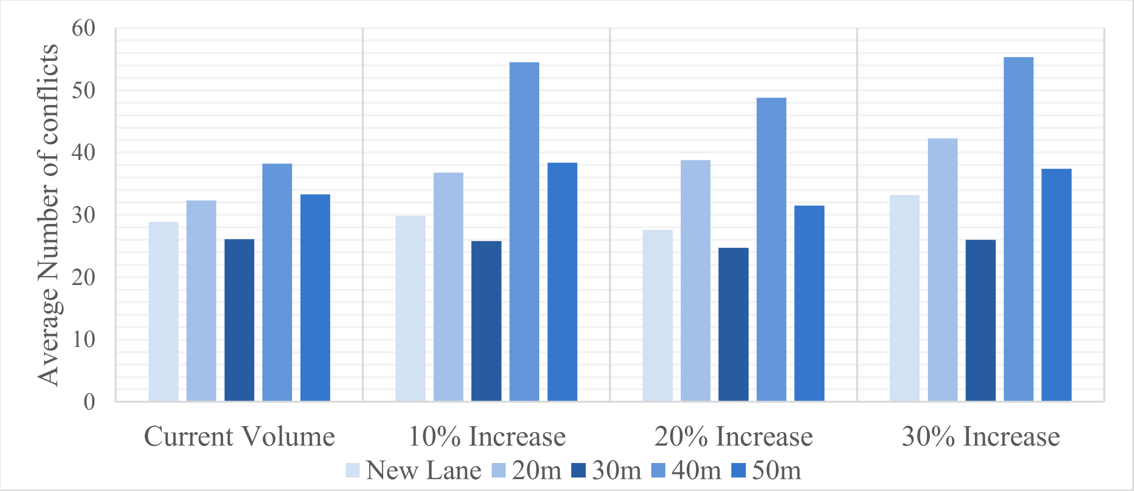
The results with * indicates few exceptions for which the difference is not statistically significant

Table 4, Table 5, and Table 6 compare the average number of conflicts in each category, between the direct SSAM output and the processed output based on the binary matrix method. For each scenario, 10 simulation runs have been used. Thus, for each scenario, a total of 20 samples in two data group are compared using a two-tailed T-test, with 18 degrees of freedom. For rear-end conflicts type (i.e. 20 m, 30 m, 40 m and 50 m weaving section and new lane scenario, respectively) all the results present statistical significant difference with 90% confidence. Several non-significant comparison results in crossing and lane change conflicts were founded in Scenarios 3, and 4 (i.e. 40, 50 meters weaving section, respectively). This can be explained by the fact that as the weaving sections length increases, the number of potential conflicts also increases, with the similar proportion for all types of conflicts. The results strongly suggests that using solely the conflict angle to classify the conflicts as it is defined in the SSAM software it is not always reliable.

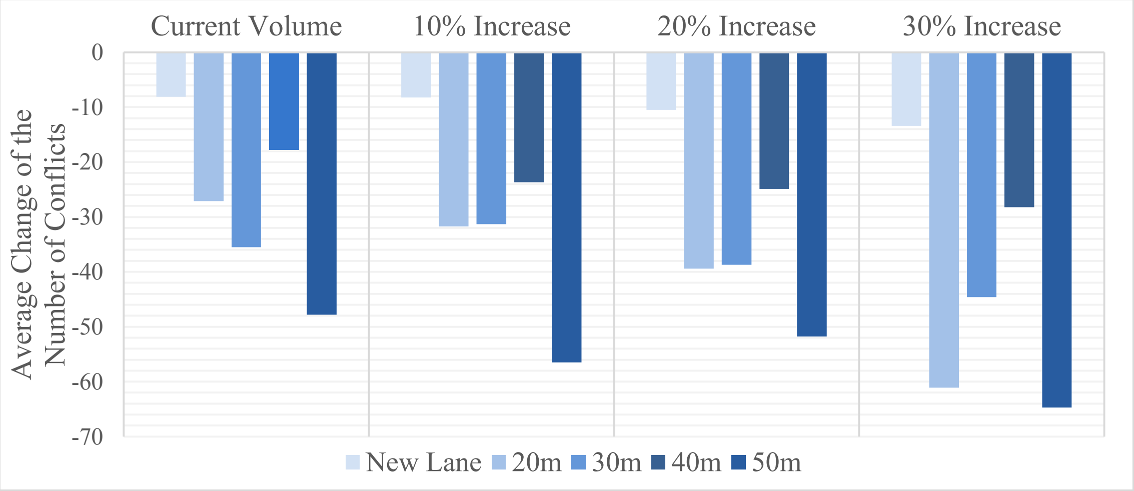
Finally, the frequency of conflicts is compared across different scenarios. With respect to individual types of conflicts, it was found all 30 meter weaving sections under all the four traffic volume conditions (current, 10%, 20%, 30% increase) present the lowest number of crossing conflicts (Table 7). The average crossing conflicts after calibration were very similar, which ranged from 25 to 26 for all four traffic demand conditions. However, the changes of the calibration results for crossing conflicts varied about -57.6%, -54.8%, -61.0%, and 63.2%, respectively. Both of 30 and 40 meters weaving section contribute to the minimum number of lane change conflicts (Figure 18). The calibration results changed from -9.7%,-11.0%, -10.4%, and -9.8%, respectively. However, for rear-end conflicts, a 50 meter weaving could largely reduce the number of this type of conflicts (Figure 19). This could be explained that when the weaving section becomes longer, there is more time and space for vehicles decelerate in advance of a collision. Also, the total number of conflicts were showed in Table 7. The minimum total number of conflicts were found in 30 meter weaving section (scenario 2) under traffic 10% and 30% increase condition, and in 40 meter weaving section (scenario 3) under the other current and 20% traffic volume increase conditions.

Table 7. Total number of conflicts of Taschereau Blvd. bus lane

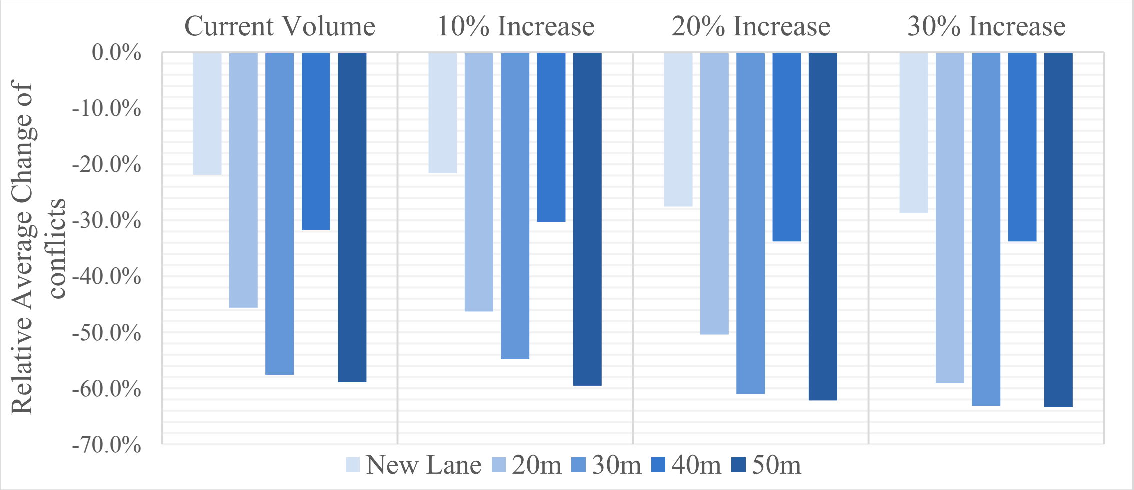
	Traffic demand	**Total conflicts**
Scenario 1	Current	1067
	10% increase	1160
	20% increase	1254
	30% increase	1377
Scenario 2	Current	1047
	10% increase	1107
	20% increase	1213
	30% increase	1283
Scenario 3	Current	1010
	10% increase	1175
	20% increase	1162
	30% increase	1300
Scenario 4	Current	1049
	10% increase	1109
	20% increase	1170
	30% increase	1323
Scenario 5	Current	1208
	10% increase	1343
	20% increase	1383
	30% increase	1480



(a) Number of conflicts after calibration

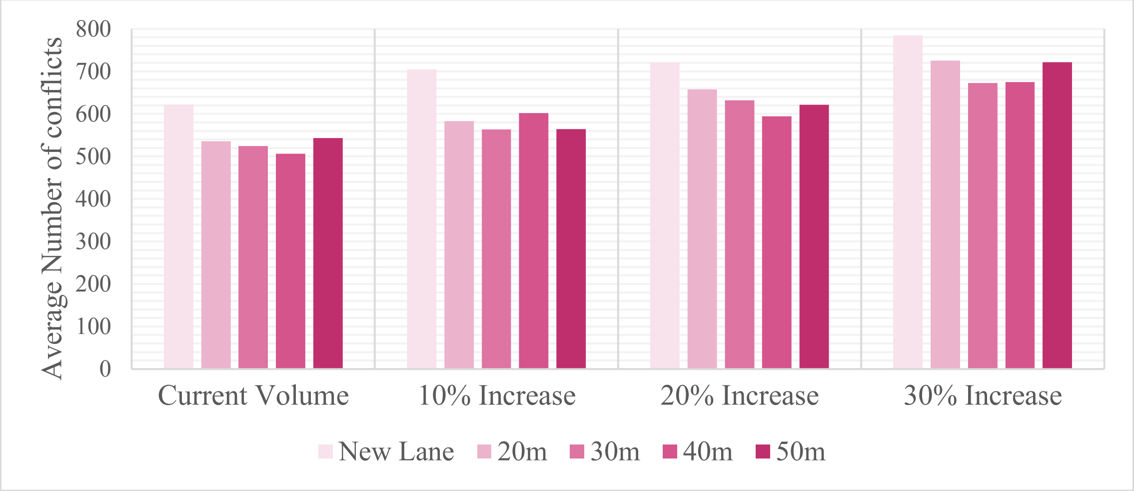


(b) Difference of expected conflicts

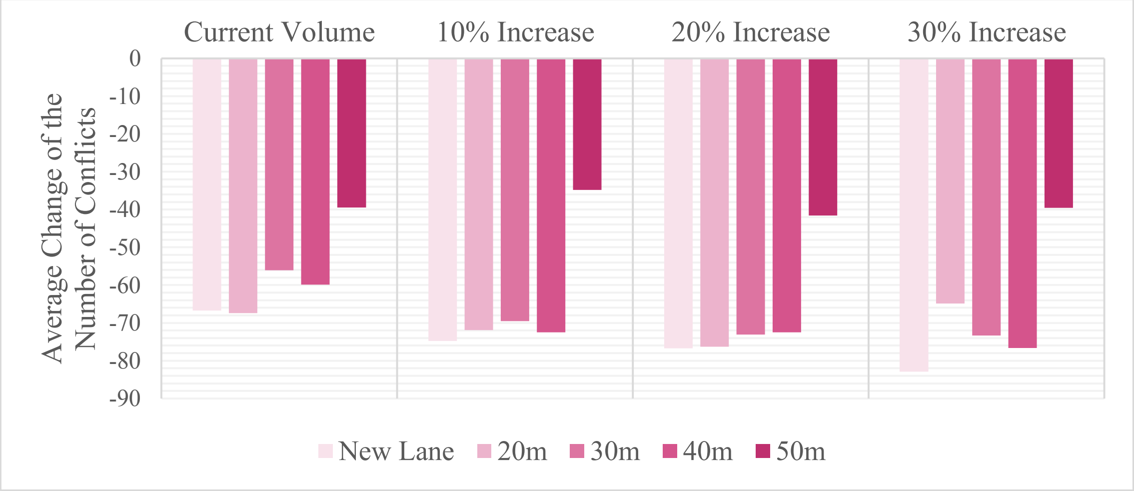


(c) Relative conflicts change

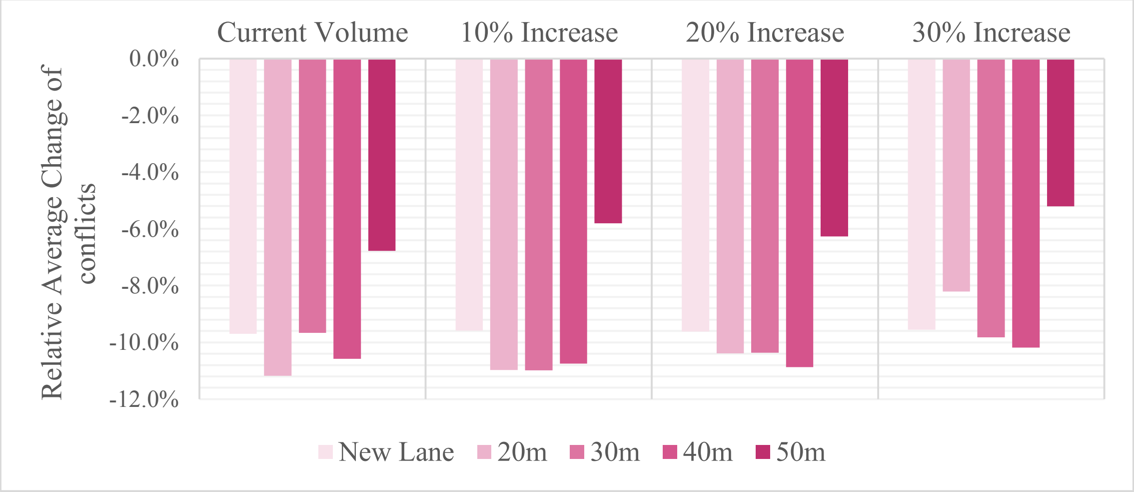
Figure 17. Effects of calibration for crossing conflicts in Taschereau Blvd. bus lane



(a) Number of conflicts after calibration

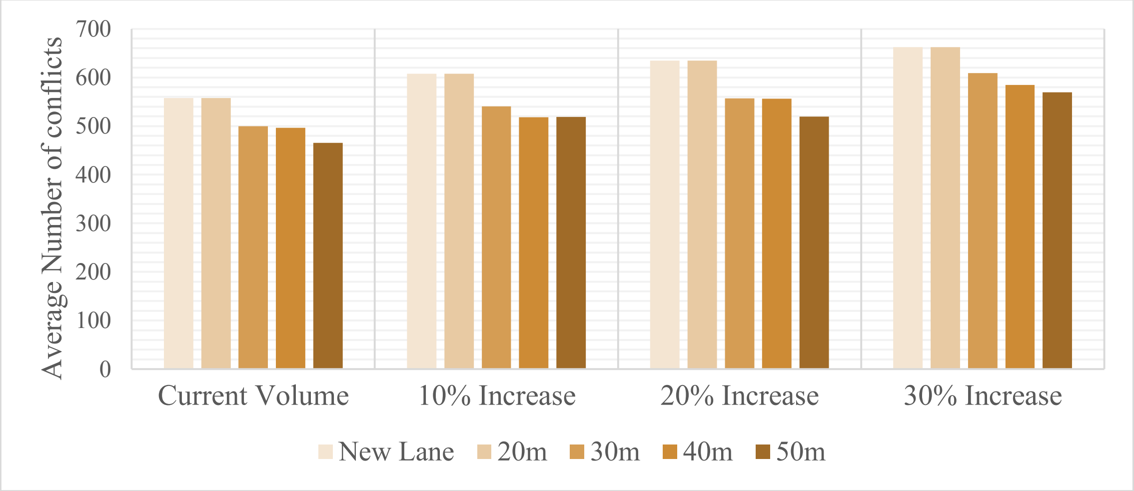


(b) Difference of expected conflicts

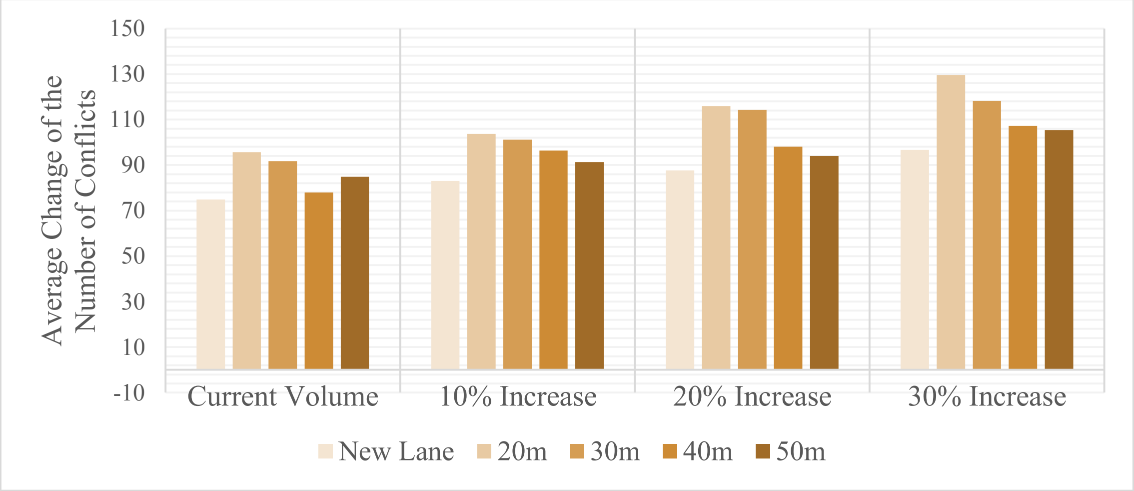


(c) Relative conflicts change

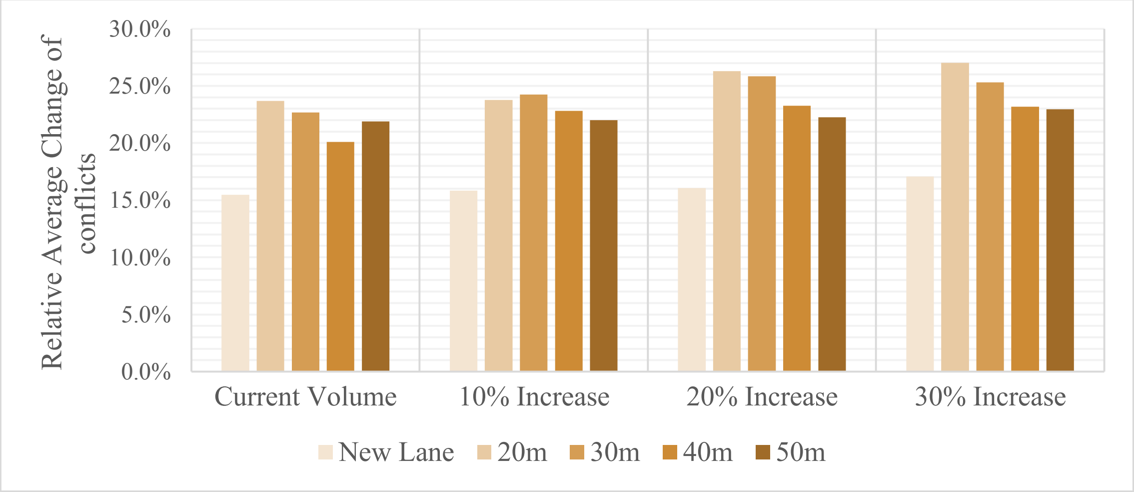
Figure 18. Effects of calibration for lane change conflicts in Taschereau Blvd. bus lane



(a) Number of conflicts after calibration



(b) Difference of expected conflicts



(c) Relative conflicts change

Figure 19. Effects of calibration for rear end conflicts in Taschereau Blvd. bus lane

For safety analysis purposes, in addition to conflict management, based on the geometric characteristics, access management should also be considered, since different types of separation affect the safety and traffic operations conditions. Many studies show that different geometric designs reflect various safety performances. Determining a suitable threshold is essential and general guidelines are not available, but rather specific, local constrains would lead to the appropriate values. The investigated sites in this chapter did not exhibit various values of the geometric elements (i.e. buffer, barrier, etc.), and therefore a real-world comparative safety assessment study could not be conducted. However, a calibrated microscopic traffic simulation model of Boulevard Taschereau has been used to determine the optimal weaving section of the vehicles crossing the HOV lane. It was found that a 30-meter weaving section is the best alternative for that specific arterial.

The case study presented in this chapter is one typical example of arterial reserved lane. However, it is expected that the bus lanes on divided highways present different traffic behavior since there are no crossing conflicts, rather the conflict analysis should more focus on rear-end and lane changing conflicts. Nevertheless, the methodology proposed in this thesis is capable to undertake this task.

Chapter 6.

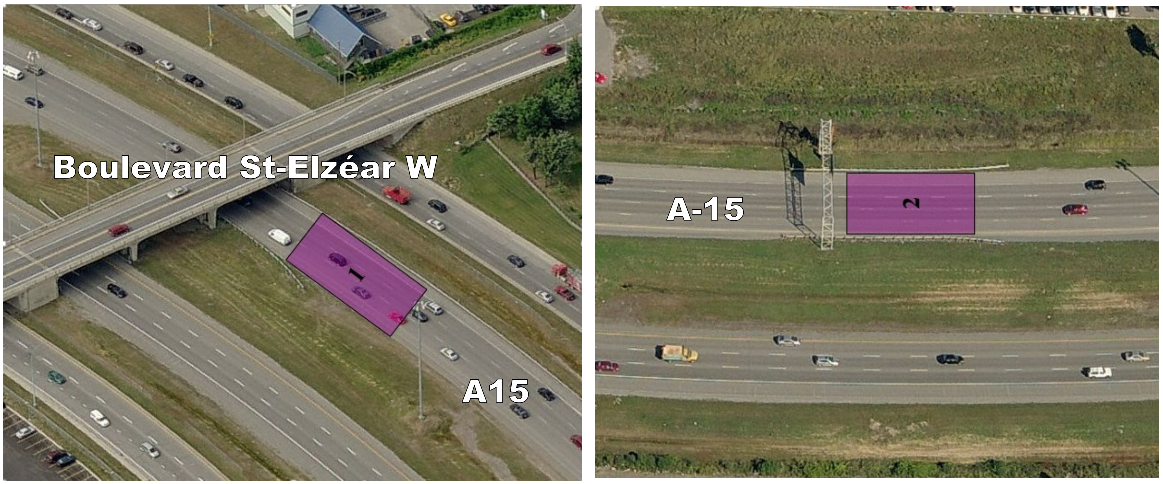
Highway Case Study

6.1 Data Collection and Processing

Autoroute 15 has two types of reserved-lanes. One is an HOV 2+ lane, about 9 km long, that runs between Rue Sauve overpass and the interchange with Autoroute 440. This lane allows taxis and passenger vehicles with 2 or more occupants in the northbound direction only, during the weekday afternoon peak periods (15:30 PM to 18:30 PM). Outside this time interval, the lane is open for all vehicles. In addition, A-15 has several the bus-on-shoulder (BoS) segments that run both ways, southbound and northbound, and that are used only by CITL buses. The BoS facility on A-15 in Laval, which is open permanently, but it mostly utilized during the morning and afternoon peak periods, to allow the sub-urban commuter buses to maintain a reliable schedule. Figure 20 shows the layout from one of the BoS segment.

Figure 20. Layout of the A-15 BoS segment

The open source vehicle trajectory processing software Traffic Intelligence (Saunier and Sayed, 2007), has been used to determine the speed and flow at the locations identified on Figure 20 by the processing of video recordings collected on site. Videos were collected via a GoPro® camera, at a rate of 30 frames per second and 720 HD resolution from four weekdays, during the afternoon peak period (13:30 to 17:30 pm) in June 2014 (Tuesday, Wednesday, Thursday, and Friday). The two data collection sites are located upstream and downstream of an onramp ramp, where the reserved BoS lane is interrupted to accommodate the merging traffic (See Figure 21 (a) (b)). Figure 22 shows the camera location and the orientation. Site 1 (Figure 22 (a)) is situated on the St-Elzéar overpass, where the camera is adjusted directly above the traffic lanes on A-15. Site 2 (Figure 22(b)) is mounted in the proximity of the BoS shoulder. The recordings are automatically saved to the external memory of the camera in 26 minute long files, which were selected to eliminate some camera shaking periods and lighting interruptions due to sunset/storming conditions. Because, at times, severe traffic congestion makes vehicles almost stop on their lanes, due to the limitation of the Traffic Intelligence software to estimate the speed of very slow moving objects, those severely congested periods were not used in this study. In total, all the videos have been cut into 120 (2.5 hour × 4 days ×12 segments/hour) files with 5-minute length for each, in order to present the results in a high resolution.



(a) site 1 (b) site 2

Figure 21. Layout of the A-15 BoS segment data collection sites

(a) site 1 (b) site 2

Figure 22 Camera location and orientation

A total of 12 hours video data has been collected on Autoroute 15 in Laval, Quebec. A-15 is a typical urban highway which service for a large number of flows. Contrary to arterial, highways facilities are always separately located on each side of the road. The conflicts occurred only involved the vehicles traveling in the same direction. In A-15, the bus on shoulder lane starts and ends at several locations to escape the upstream ramp flow, where buses interrupt the continuous movement of general vehicles (See Figure 23).

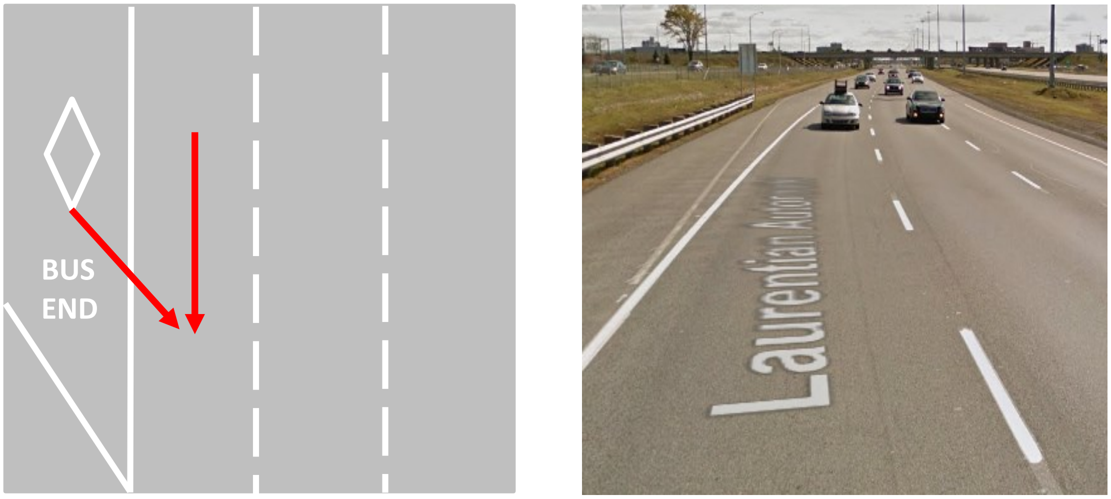


Figure 23. A-15 BoS segment merging section

6.1.1 Flow and Speed Results

The Traffic Intelligence software was developed using Python and C++ to include a feature-based moving object tracking algorithm based on OpenCV and KLTlibraries (Jackson et al., 2013). The data processing is done under a Linux environment (Ubuntu 12.04) through a VirtualBox on a Macintosh machine.

The first step to process video data is to calibrate the image from camera. A homography file in the form of a 3×3 matrix has been generated based for each location using a superposition of a camera snapshot and the real world coordinates – generated via Bing Maps®.

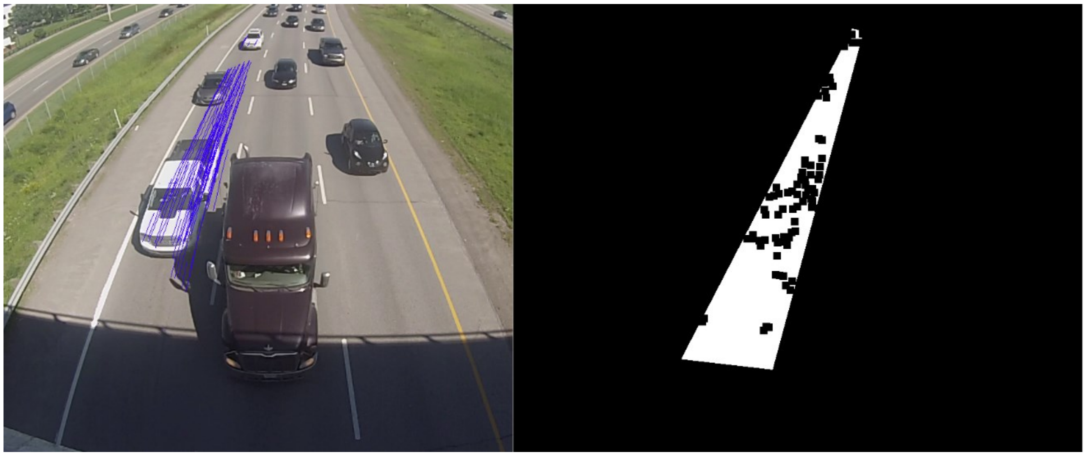
The second step consists in tracking individual vehicle features, which is done by identifying individual vehicle's trajectories via their multiple features, using the homography matrix. The identified vehicle trajectories are stored in a database file at the same time.

In the third step the features of individual vehicles are grouped.

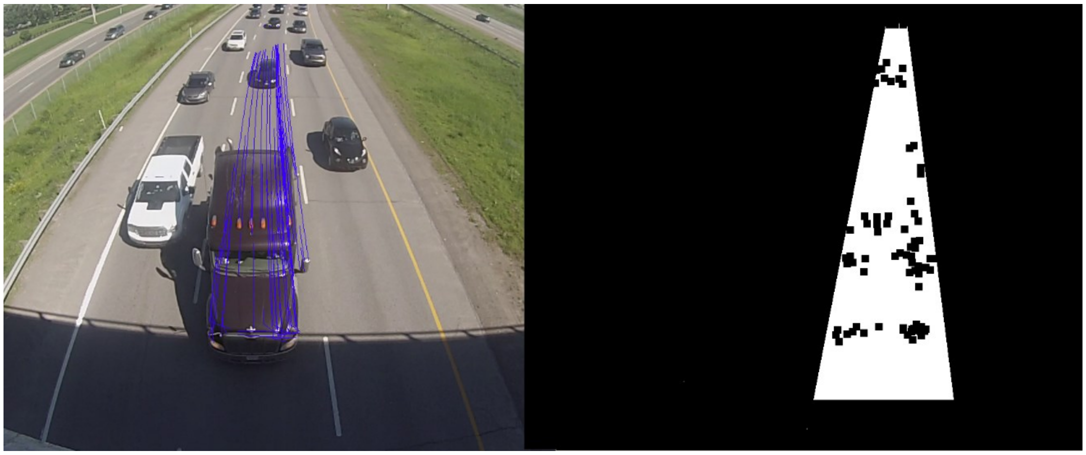
Speed can be estimated via the homography file and SQL database information. The homography file generated from the first step could help to estimate the travelled length from the camera images. All recordings were made at a rate of 30 frames per second, which means that, for example, one meter movement between two consecutive frames is associated with a travel speed of 30 m/s (108 km/h).

It is important to note that to process video data, a mask file is necessary to be defined among the analysis area or certain lane, otherwise, the system will process all the moving objects along the whole area covered by the camera field of view. The video processing of the recordings displays the trajectories on both the original video image and also on the defined mask image. Figure 24 presents three-lane segment along A-15 during processing procedure. It can be seen that the figures on the left side show the features/trajectories over the video image and the figures on the right side present how the mask file defines the processing area. A total of 120 video files were used to separate the processing work (120×3 masks= 360 times) in order to compare the different results in different lanes.

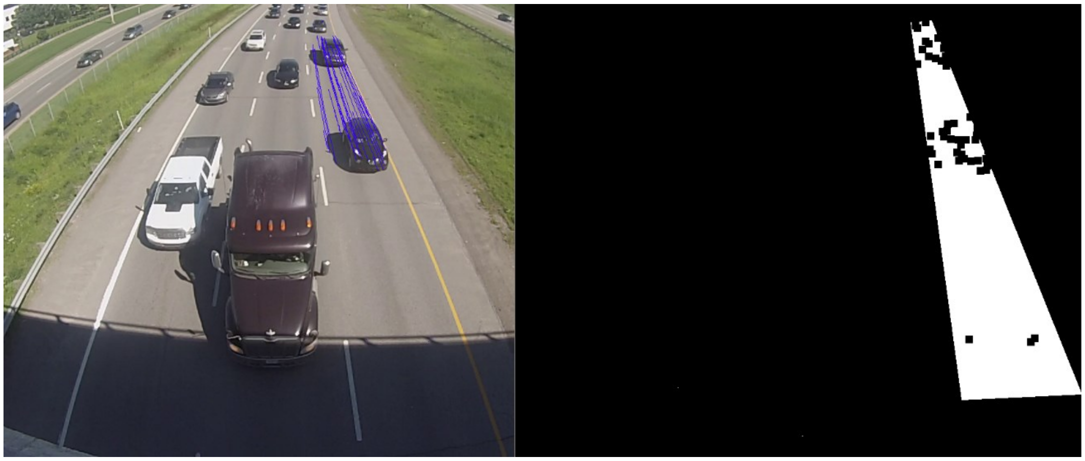
The speed detection results were validated in several videos with a probe vehicle that travelled through the network with a known constant speed. The error has been manually verified by adjusting the parameter in Traffic Intelligence. Also, the determined traffic volumes were validated by manually counting the number of vehicles in several selected videos, and adjusting by calculating the ratio of processed and observed data. Then, results were compared with the results of speed, since each moving object has its own speed result, when the author deleted the vehicle with bad speed results (i.e. some interruption of birds, motorcycles, etc.), the related flow changed simultaneously. Therefore, videos are well selected manually to avoid such bias.



(a) Lane 1



(b) Lane 2



(c) Lane 3

Figure 24. Vehicle trajectories based on tracking features features

Figure 25 presents the average speed distribution of individual lanes from all four days during the afternoon peak. As expected, the speed of lane 1 is larger than the other two lanes at most of the observation periods. Mainly because there is a ramp in front of site 1, and more vehicles are entering into lane 1 from the ramp. Many vehicles traveling along A-15, upstream of the ramp, shift their trajectories onto lanes 2 and 3 in order to avoid the interactions with merging flows from the ramps. Lane 2 presents the second high speed results among the three lanes.

The 5-minute average speed and flow values during the afternoon peak are presented in Figure 26, Figure 27, and Figure 28. It can be seen that even though the traffic conditions are not stable, overall, as the number of vehicles increases, the speed decreases in each of the three lanes. The possible explanation for this kind of fluctuation is not only the natural random arrival of vehicles, but also the effects of the on-ramp flow which brings in traffic from major neighboring interchange with A-440.

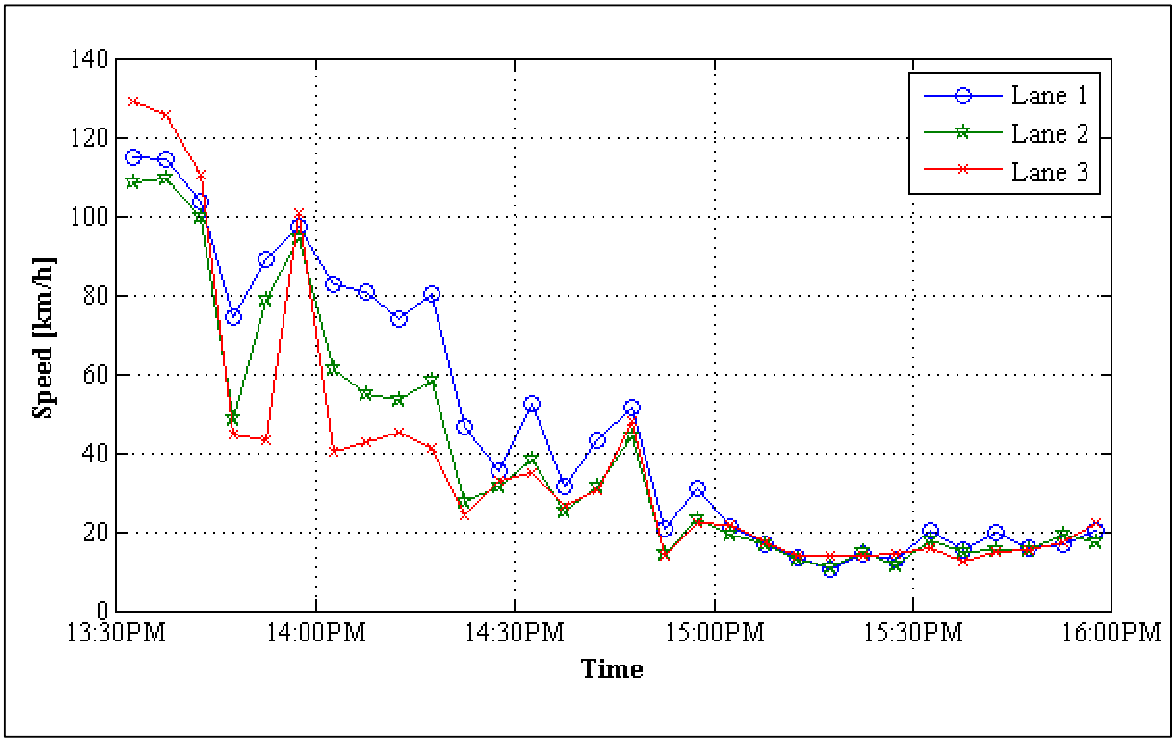


Figure 25. Speed results on A-15 Laval segment

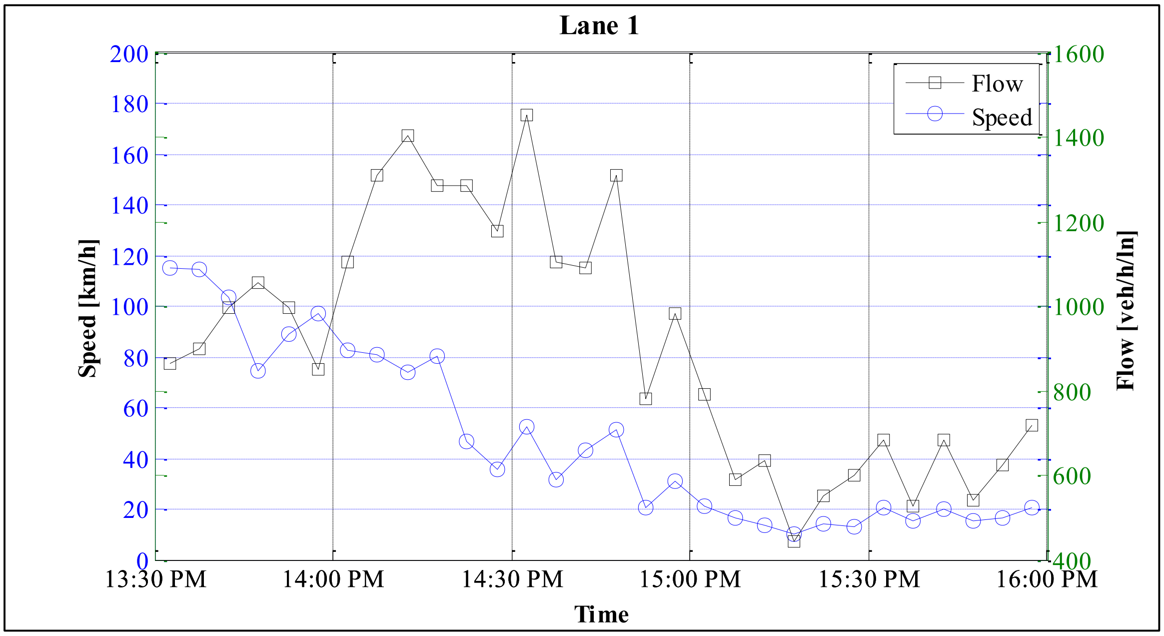


Figure 26. Speed and flow results of lane 1

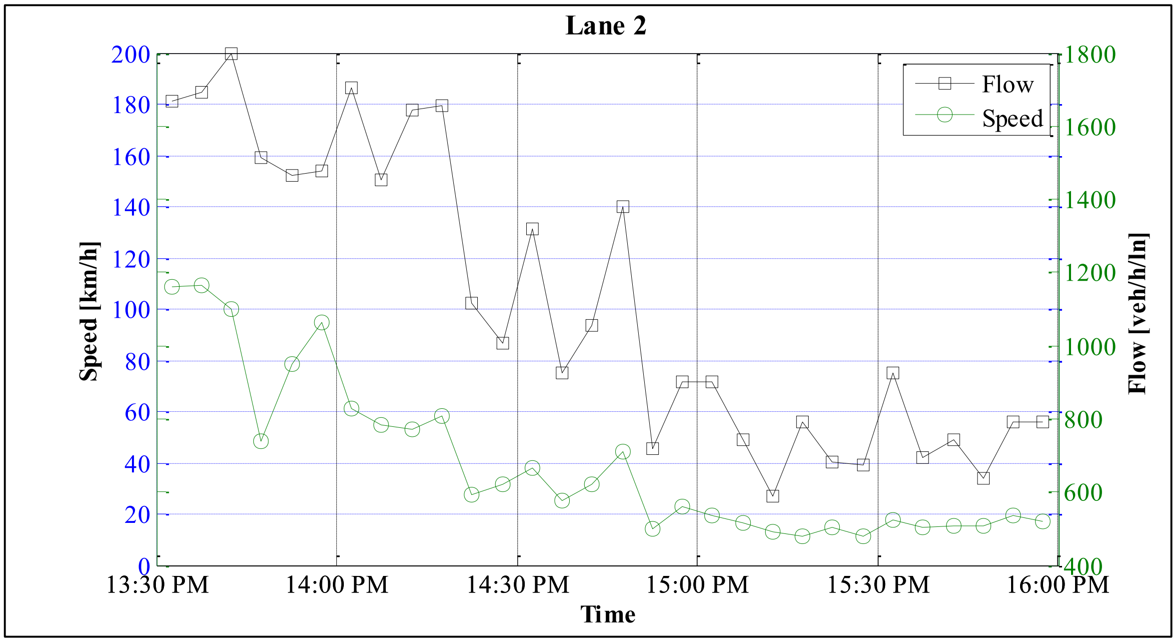


Figure 27. Speed and flow results of lane 2

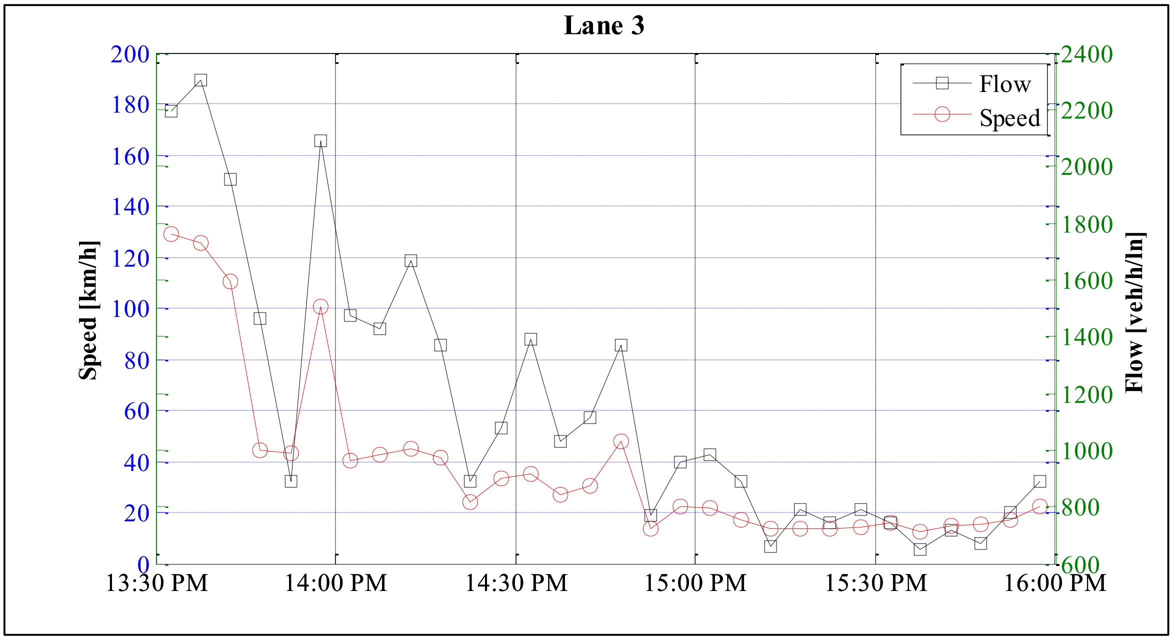


Figure 28. Speed and flow results of lane 3

6.1.2 Gap Time between Bus and Vehicles

A total of four weekdays' of video data (12 hours during the afternoon peak) were processed. This data includes 89 buses using the BoS facility between 1:30 PM to 4:30 PM in each day. For every bus, the gap acceptance headway has been evaluated (time differential between consecutive vehicles in the adjacent lane when the bus has to execute a lane changing maneuver, typically at the end of BoS segment). This value of the gap acceptance headway is particularly relevant when traffic conditions are transitory and speed of flows in the adjacent lanes are relatively high. Therefore, highly congested traffic conditions –data between 4:30 and 5:30 PM were excluded from the analysis, because merging speed were very low and the safety of BoS facility was not affected, but rather the operations of the buses.

The results in Table 8 reflect the average value of gap acceptance headway for the buses using the observed facility during the transitory traffic condition is 4.6 seconds. These results are significantly larger than the values observed in the previous arterial case study (3 seconds). This can be explained mainly due to different type of flow separation and also due to the higher speeds along the uninterrupted highway vs. the signal controlled arterial.

Table 8. Gap time for buses merging from the BoS lane at site Laval

Number of Buses	**Minimum gap**	**Maximum gap**	**Average gap**
89	3 sec	8 sec	4.6 sec

6.2 Traffic Simulation and Conflict Analysis Model for a Highway BoS Facility

There are several locations, typically in the proximity of an overpass, where due to limited lateral clearance, the BoS lane is interrupted and buses have to merge into the adjacent general purpose lane, where they travel without priority, like any regular vehicle. Figure 29 shows the current condition geometric configuration at these locations.

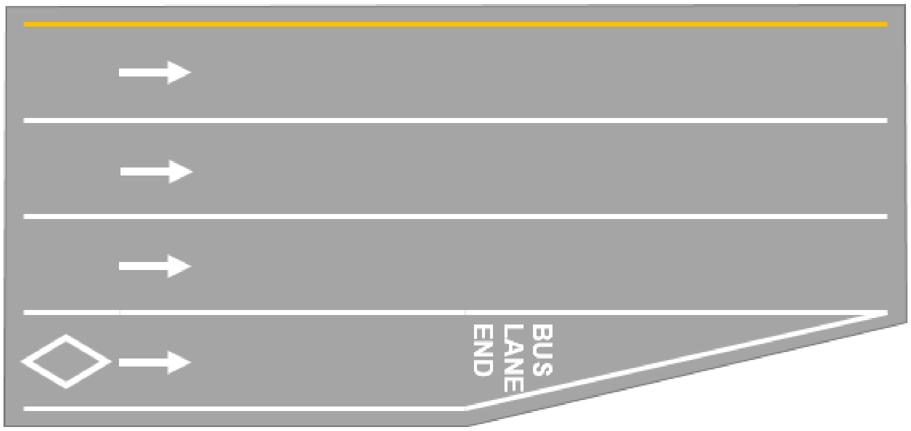


Figure 29. Current merging area of Laval A-15 BoS segment

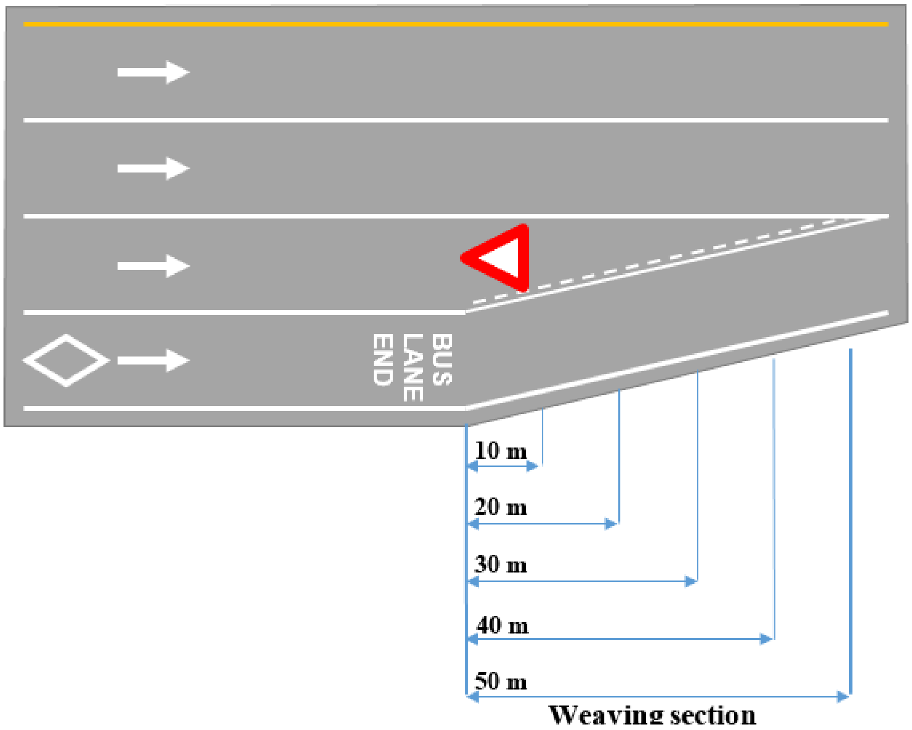


Figure 30. Proposed right-of-way-merging scenario

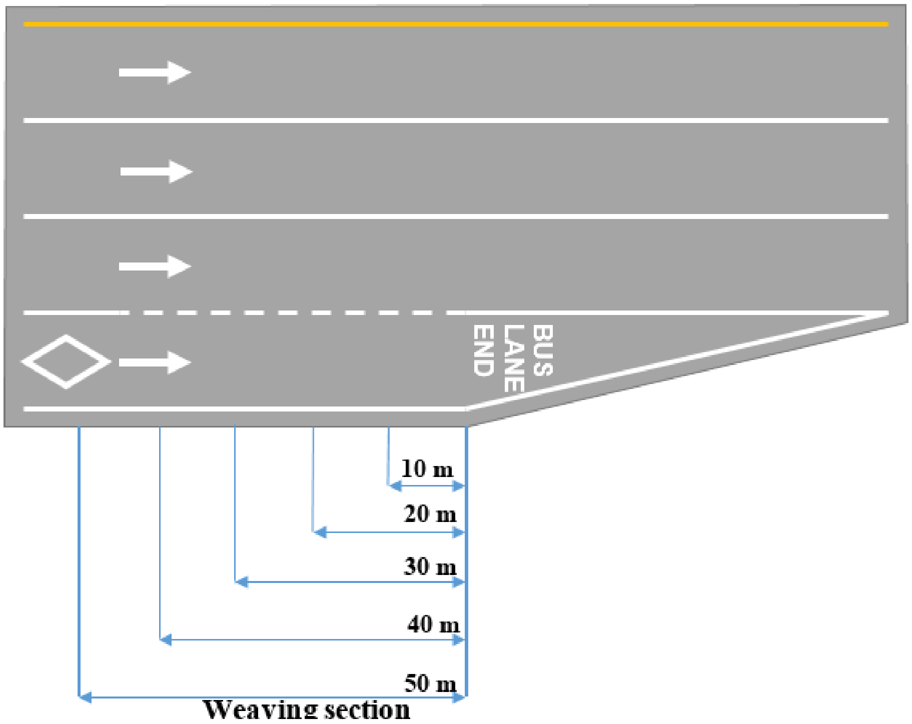


Figure 31. Proposed yield-merging scenario

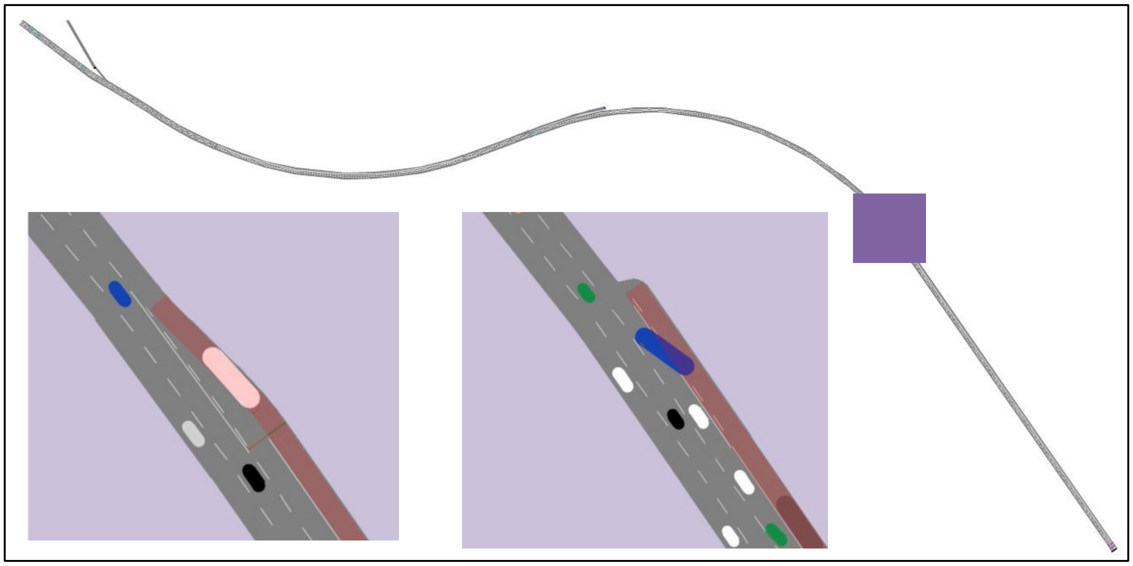
The traffic operations of these locations are not controlled by any traffic sign, and the observed behavior reveals that most buses rather stop just few meters before the end of the lane in order to merge safely under congested conditions. At relatively low speeds, this maneuver has little safety issues, but as the speed increases the impact on traffic safety and operations may be more substantial. Therefore, this thesis investigates the effects of specific lengths of BoS merging section with respect to vehicle interactions between BoS users and the users traveling on the adjacent lane. In this highway case study, two types of merging behavior have been investigated. First, a special right-of-way merging geometric alignment has been tested. Second, a regular yield type of merging geometric alignment has been simulated using different merging length zones in both cases. In total, 10 different scenarios have been simulated and compared to evaluate the impact on traffic safety and operations.

- Scenarios 1 to 5 (shown in Figure 30) include the special ***right-of-way-merging*** geometric alignment scenario. In these scenarios, buses are given the right-of-way to merge into the adjacent regular travel lane, while vehicles in this lane have to obey the yield sign installed on the adjacent general purpose lane. In addition, the impact of different length of merging section has been evaluated in each scenario, by using a merging zone of 10m, 20m, 30m, 40m, and 50m, respectively.
- Scenarios 6 to 10 (shown in Figure 31) represent the typical ***yield-merging*** geometric alignment scenario. This is the most common type of merging similar to the merging from the on-ramp lanes, in which buses should yield to the traffic in the adjacent general purpose lane, to safely change lanes. Each of these five

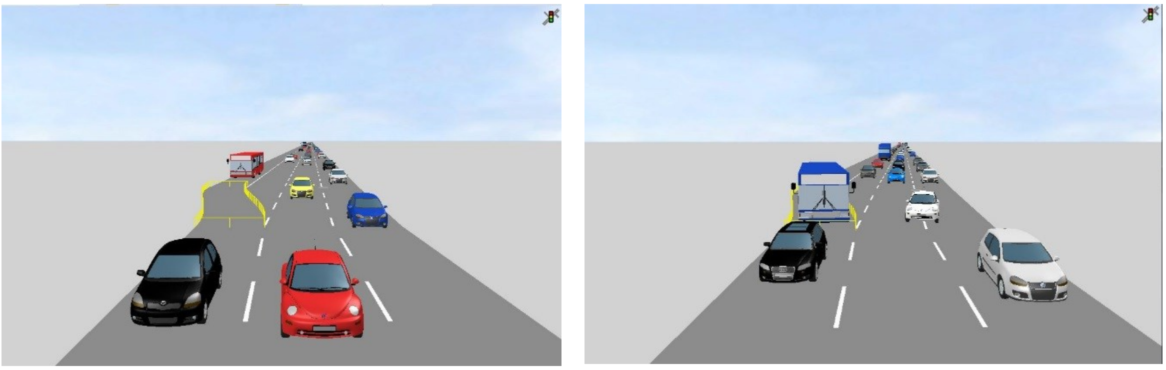
scenarios use different lengths of the merging zone (i.e. 10 m, 20 m, 30 m, 40 m, and 50 m, respectively).

A total of 100 simulation runs (10 scenarios × 10 random seen runs) were performed and analyzed. Each case was evaluated for one hour under afternoon peak hour traffic volume, using a ten-minute warm-up period. The traffic volume and speed distribution were set based on the results from the processed video data, in order to represent realistically the observed traffic conditions.

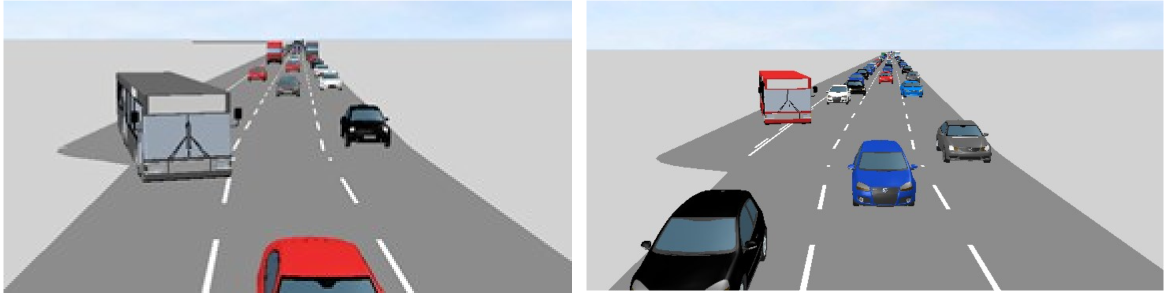
Figure 32 (a) shows the VISSIM network of Laval A-15 BoS merging section. The left side of the figure shows proposed special right-of-way-merging scenario, while the right-side of the figure depicts the typical yield merging scenario. Snapshots of the corresponding simulated conditions are shown in Figure 32 (b) for the right-of-way-merging scenario and the Figure 32 (c) for the yield-merging scenario.



(a) Network layout



(b) Right-of-way-merging in VISSIM 3D model



(c) Yield-merging scenario in VISSIM 3D model

Figure 32. Laval BoS segment testing locations in VISSIM network

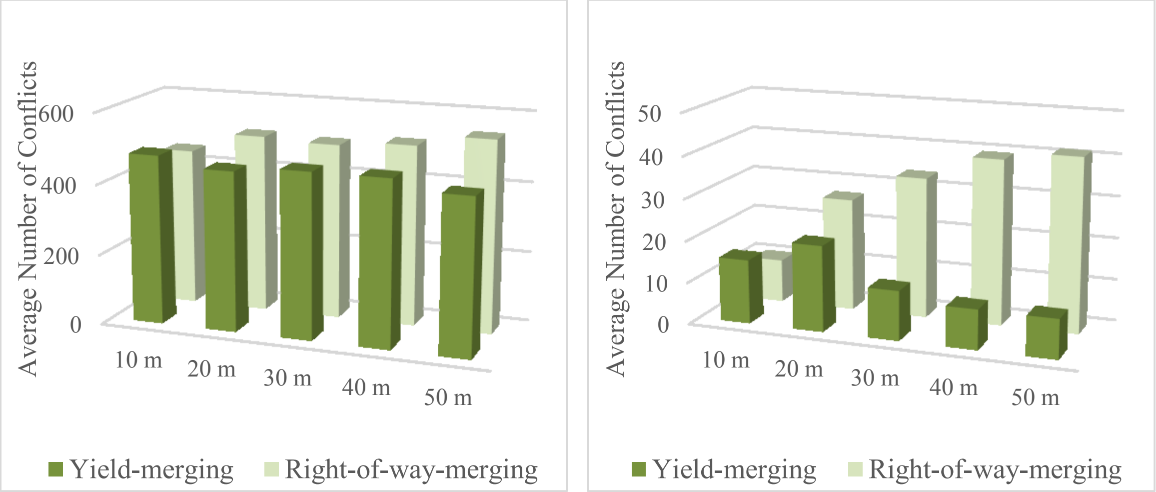
The analysis of conflicts simulated in the previous case study has been done at the network level, due to vehicle intersection along the exiting of proposed reserved-lane geometric alignment which in turn affects the operation at the adjacent intersections. However, the case study presented in this chapter includes a single BoS highway section, and the conflict analysis was separated into three different levels, in order to isolate the benefits of the proposed analysis method. The conflict analysis has been performed for the entire network, and separately for the merging area, and for the non-merging area. The conflict analysis was done via a MATLAB script that implemented the proposed calibration algorithm. The SSAM default values for the TTC and PET parameters were used, i.e.1.5 seconds and 5 seconds, respectively.

6.3 Simulation Results and Sensitivity Analysis

As previously described, the BoS segment has been simulated using 10 scenarios. Each scenario was simulated 10 times with distinct random seeds. Hence, 100 trajectory files were generated from all the VISSIM simulations and were analyzed through SSAM in order classify the vehicular conflicts.

The analysis distinguished between the two types of merging maneuvers for the users of BoS, the proposed right-of-way-merging and the typical yield-merging, respectively. Each type has been used with different merging zones of 10m, 20m, 30m, 40m, and 50m length, respectively. The results show that assuming all other traffic parameters constant (e.g. traffic demand volume, geometric alignment, etc.) by utilizing the proposed right-of-way merging (to protect buses at the end of the merging section) the frequency of conflicts increases. Therefore, without considering the length of the merging section, it can be concluded that the typical yield-merging alignment presents the best safety performance. In

Figure 33 below, it can be sent that the overall network frequency of conflicts are comparable, However, within the merging area, the average frequency of conflicts for right-of-way merging is more than double the average frequency of conflicts for yield-merging configuration.



(a) Number of total conflicts for overall network

(b) Number of total conflicts for merging area

Figure 33. Number of total conflicts of A-15 BoS segment

These results suggests that, among the tested lengths, when considering the overall tested network, the 50-meter yield-merging section provides the lowest number of conflicts, as shown in Figure 33 and Table 9. For the merging area only, the 40 m and 50 m scenarios yield the lowest number of conflicts (i.e. 9.4 and 9.3 mean values, respectively) that lead to better traffic safety performance. In Figure 33 it can be seen that the number of conflicts tend to increase with the length of the merging section, for the right-of-way merging type, therefore higher lengths were not tested. The main objective of this case study was to compare the two types of merging geometric alignments and future work will include more scenarios (e.g. 60 m, 70 m, etc.) only for yield-merging category in order to evaluate the number of conflicts in detail.

Table 9. Total number of conflicts of Laval BoS segment

	Merging type	**Mean of conflicts**
10 m	Yield-merging	479.7
	Right-of-way-merging	447.3
20 m	Yield-merging	452.6
	Right-of-way-merging	505.2
30 m	Yield-merging	469
	Right-of-way-merging	497.3
40 m	Yield-merging	469
	Right-of-way-merging	511.6
50 m	Yield-merging	440.2
	Right-of-way-merging	544

A two-tailed t-test compared the before and after average number of conflicts results in Table 10. Each scenario, a total of 20 samples in two data groups are tested under 18 degrees of freedom. The results presents strong statistical significance for all crossing and rear-end conflicts at 95% confidence interval.

Especially, as discussed before, highway facility is a traffic system without intersections, crossing conflicts cannot be occurred in this situation. From Table 10 and Figure 34, the mean of crossing conflicts decrease from [30.3, 36.8] interval into [0.1, 0.8] interval in the total network scale of yield-merging scenario. And the mean of crossing conflicts decrease from [30.4, 36.7] interval into [0.1, 1.5] interval in the total network scale of right-of-way-merging scenario. Similarly, it can be seen from Figure 37 and Figure 40 that the average number of crossing conflicts decline from a sizable number to less than 2, for the merging area as well as for the non-merging area. These findings demonstrate that the calibration method helps avoiding the conflict classification error. It also shows that the proposed binary matrix calibration method is suitable for both arterial and highway conditions.

Table 10. Crossing conflicts for before and after calibration of Laval BoS segment

	Merging Type	**SSAM Mean**	**Calibrated Mean**	**P-Value**
		Crossing conflicts		
10 m	Yield-merging	33	0.5	0.000
	Right-of-way-merging	30.4	1.5	0.000
20 m	Yield-merging	30.3	0.8	0.000
	Right-of-way-merging	35.5	0.5	0.000
30 m	Yield-merging	31.1	0.1	0.000
	Right-of-way-merging	36.1	0.1	0.000
40 m	Yield-merging	36.8	0.1	0.000
	Right-of-way-merging	32.3	0.1	0.000
50 m	Yield-merging	35.3	0.1	0.000
	Right-of-way-merging	36.7	0.1	0.000

The results with * shows which is not statistically significant at 95% confidence interval.

Table 11. Lane change conflicts for before and after calibration of Laval BoS segment

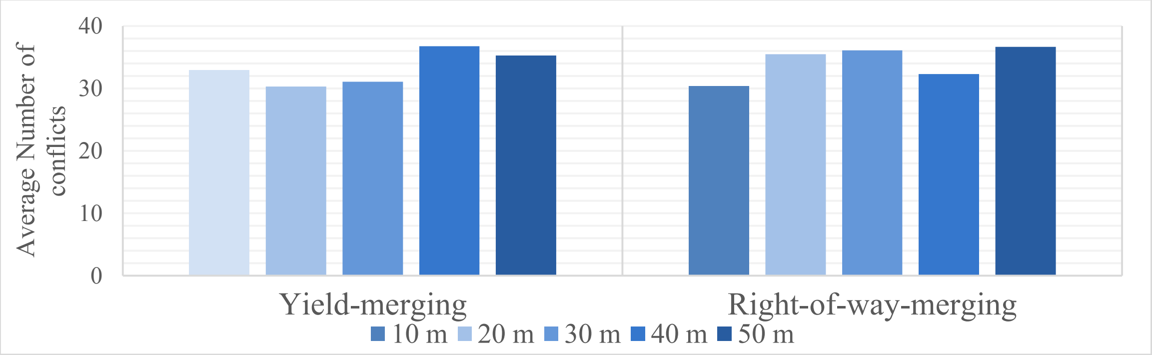
	Merging Type	SSAM Mean	Calibrated Mean	P-Value
Lane change conflicts				
10 m	Yield-merging	392.2	374.3	0.228*
	Right-of-way-merging	357.5	341.5	0.042
20 m	Yield-merging	367.5	350.8	0.198*
	Right-of-way-merging	409.7	394.7	0.282*
30 m	Yield-merging	381.8	360.2	0.104*
	Right-of-way-merging	401.1	390.9	0.441*
40 m	Yield-merging	379.7	366.9	0.360*
	Right-of-way-merging	414.5	401.2	0.334*
50 m	Yield-merging	351.3	338.7	0.205*
	Right-of-way-merging	438.9	426.5	0.308*

The results with * shows which is not statistically significant at 95% confidence interval.

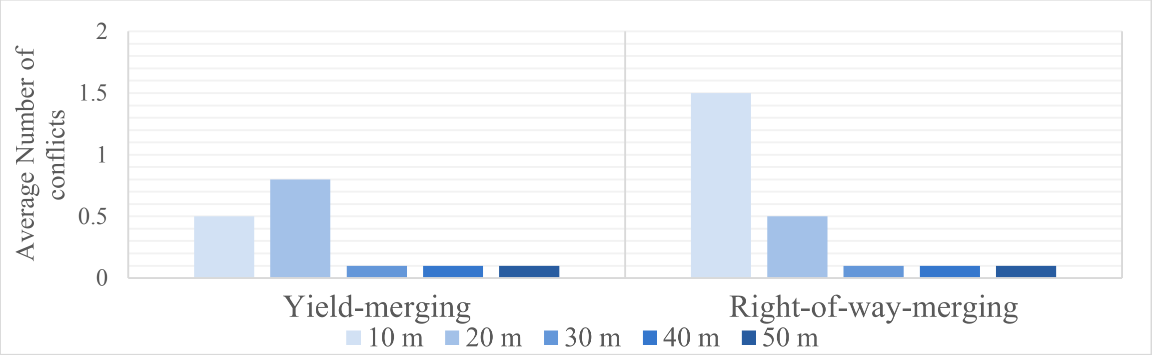
Table 12. Rear end conflicts for before and after calibration of Laval BoS segment

	Merging Type	SSAM Mean	Calibrated Mean	P-Value
Rear end conflicts				
10 m	Yield-merging	54.5	104.9	0.000
	Right-of-way-merging	59.4	104.3	0.000
20 m	Yield-merging	54.8	101	0.000
	Right-of-way-merging	60	110	0.000
30 m	Yield-merging	56.1	108.7	0.000
	Right-of-way-merging	60.1	106.3	0.000
40 m	Yield-merging	52.5	102	0.000
	Right-of-way-merging	64.8	110.3	0.000
50 m	Yield-merging	53.6	101.4	0.000
	Right-of-way-merging	68.4	117.4	0.000

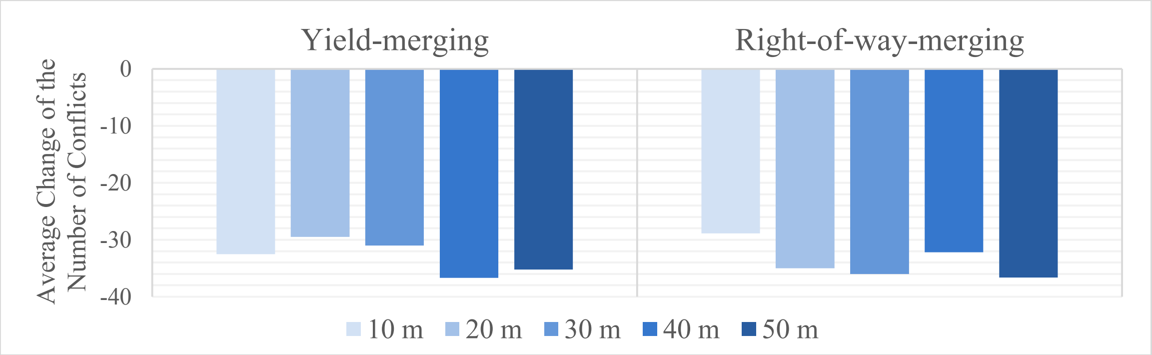
The results with * shows which is not statistically significant at 95% confidence interval.



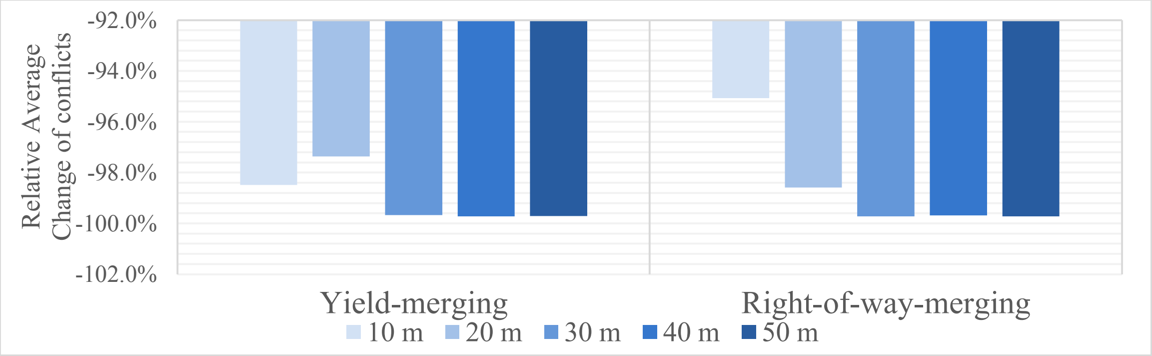
(a) Before calibration



(b) After calibration

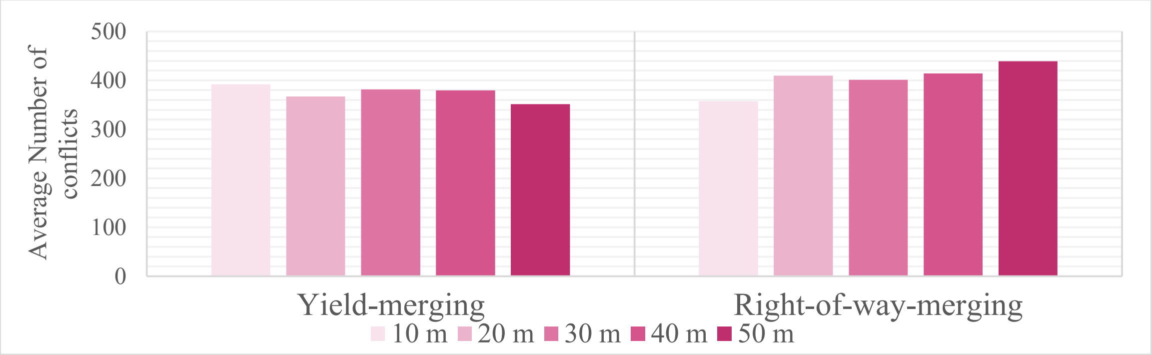


(c) Difference of expected conflicts

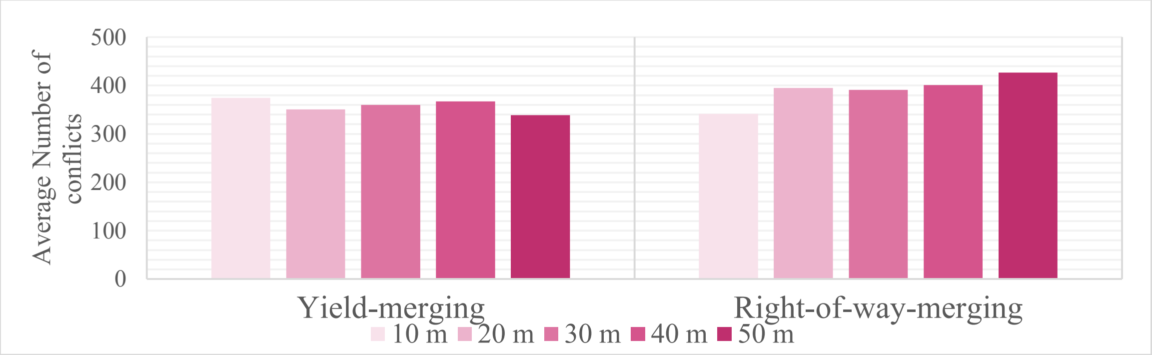


(d) Relative change

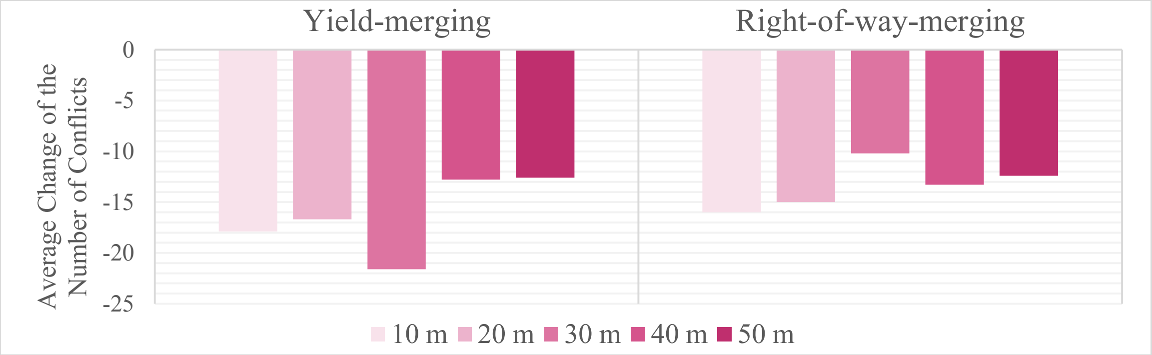
Figure 34. Effects of calibration for crossing conflicts within the whole network



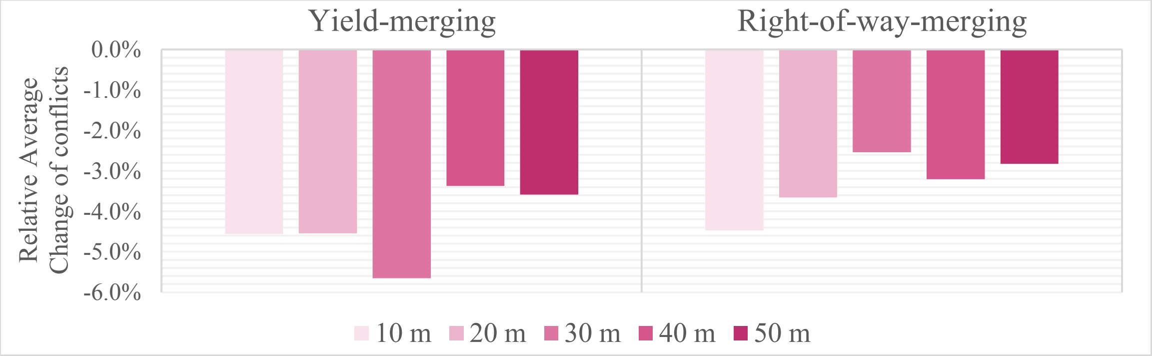
(a) Before calibration



(b) After calibration

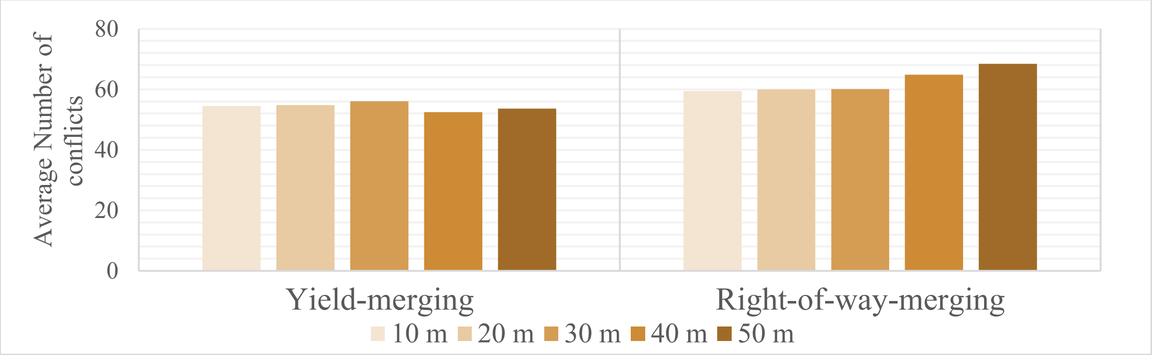


(c) Difference of expected conflicts

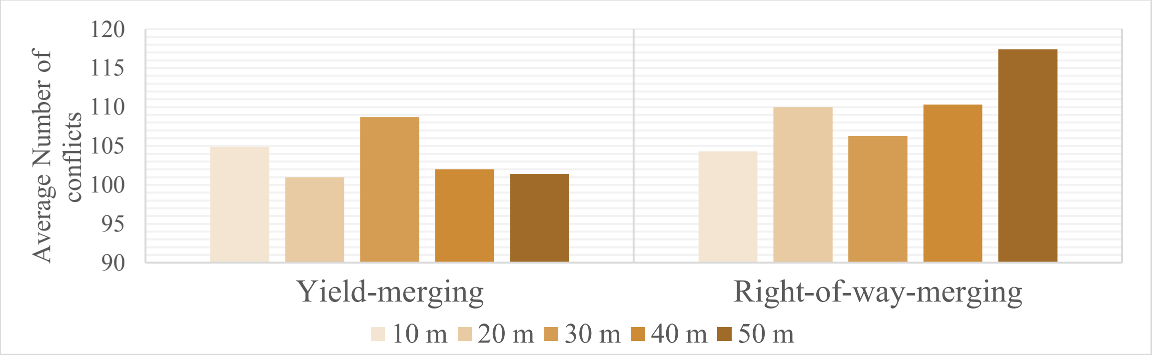


(d) Relative change

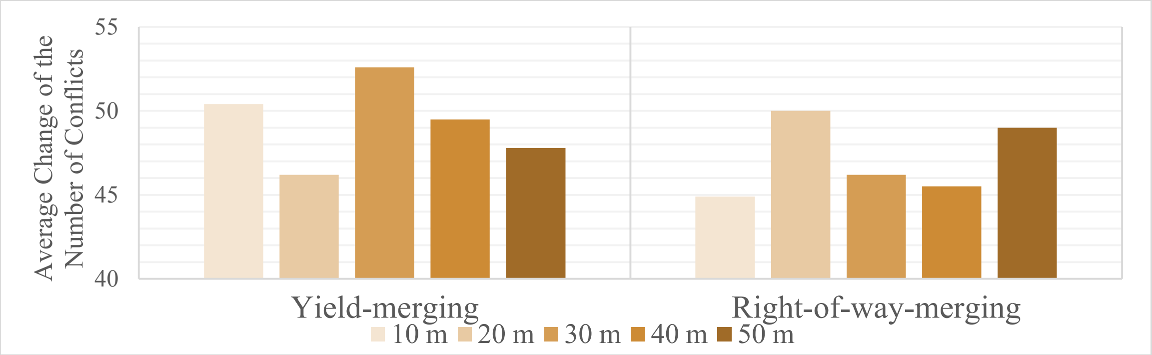
Figure 35. Effects of calibration for lane change conflicts within the whole network



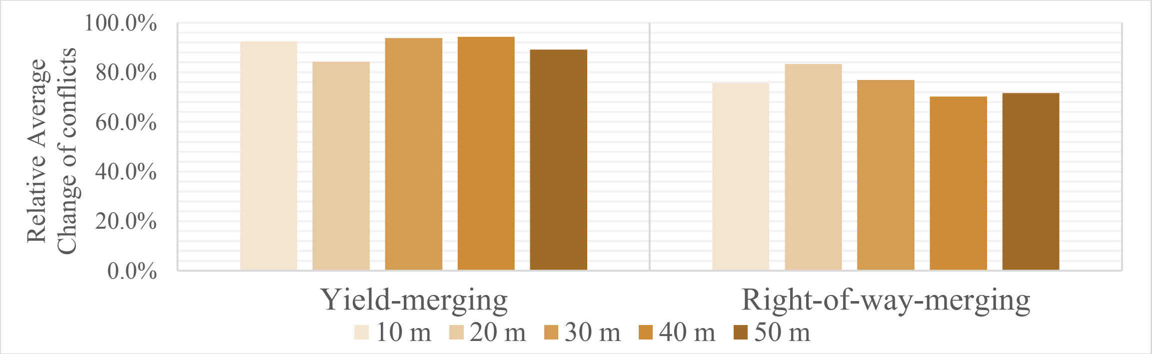
(a) Before calibration



(b) After calibration

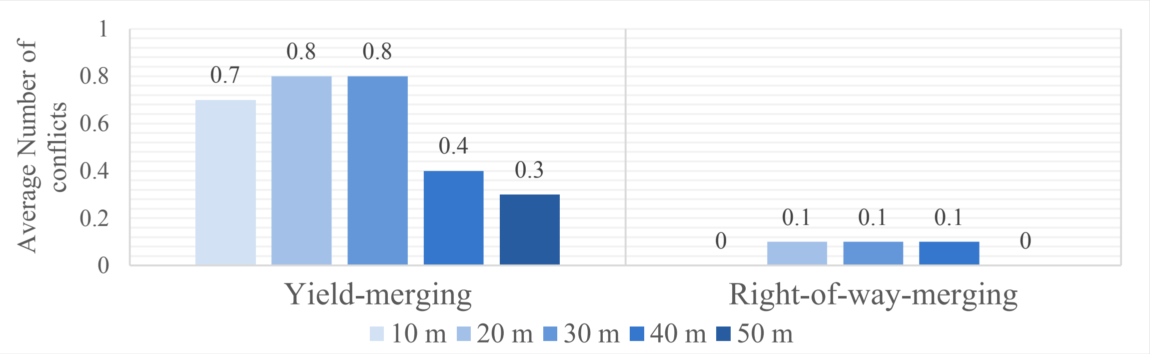


(c) Difference of expected conflicts

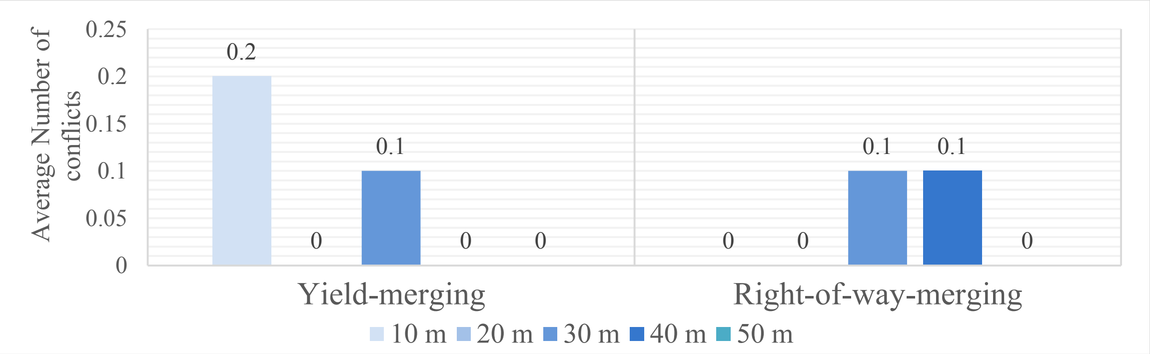


(d) Relative change

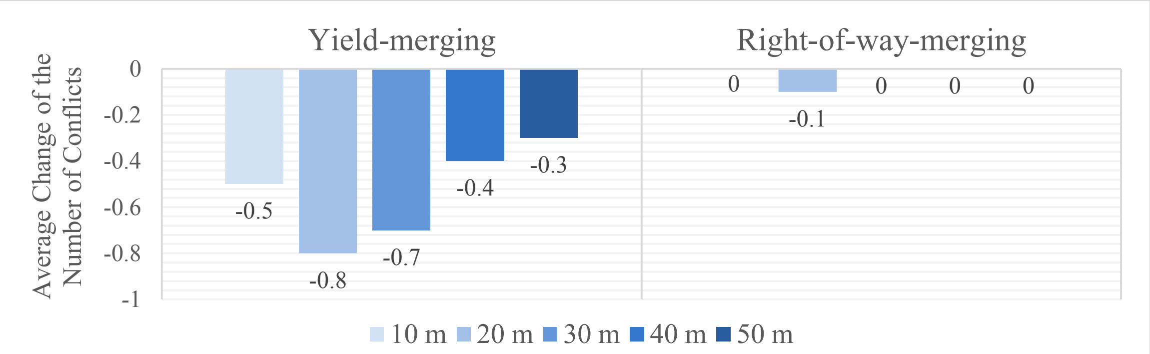
Figure 36. Effects of calibration for lane change conflicts within the whole network



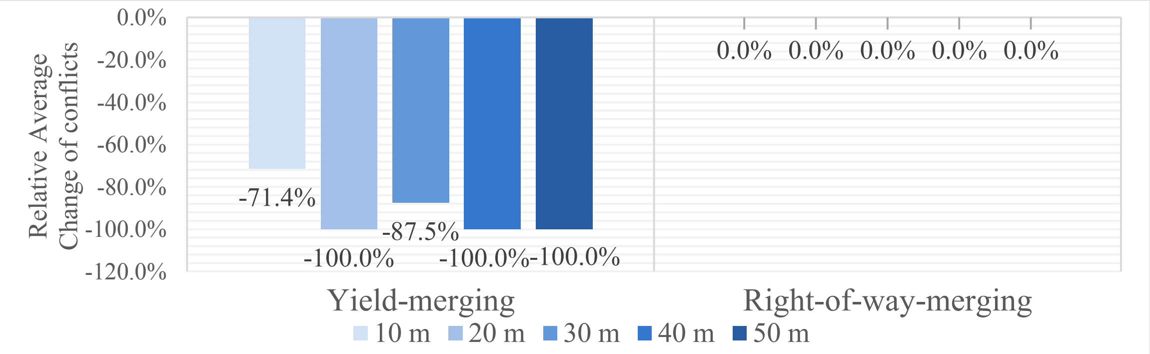
(a) Before calibration



(b) After calibration

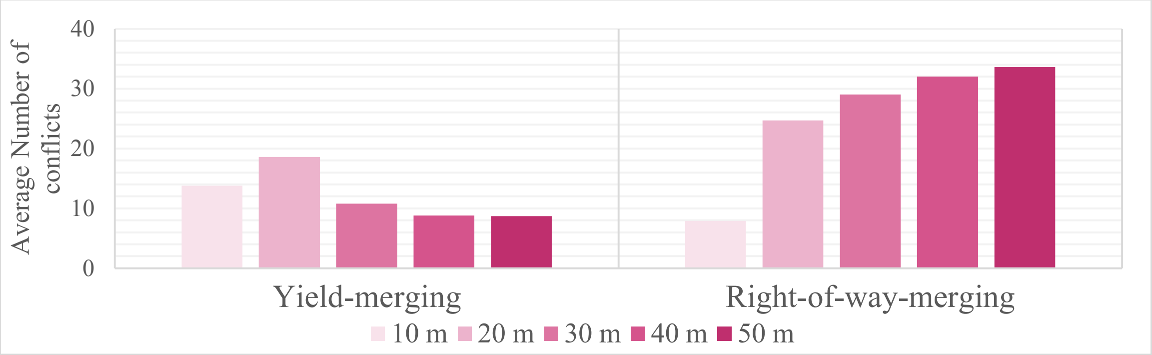


(c) Difference of expected conflicts

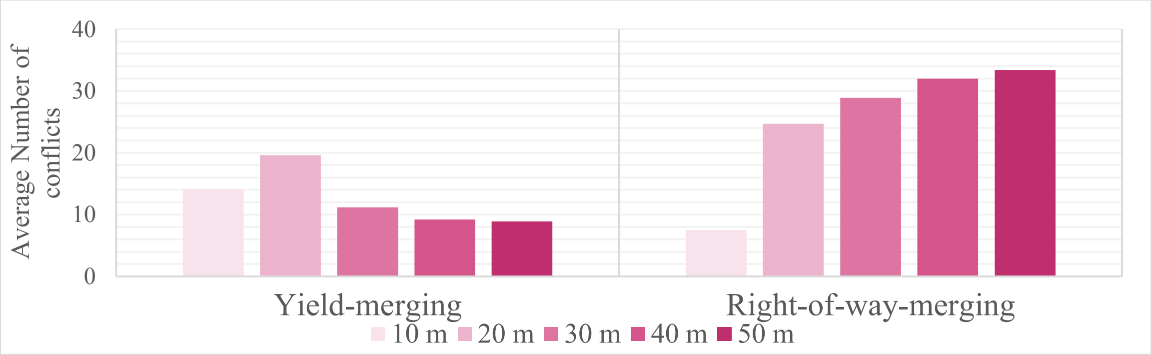


(d) Relative change

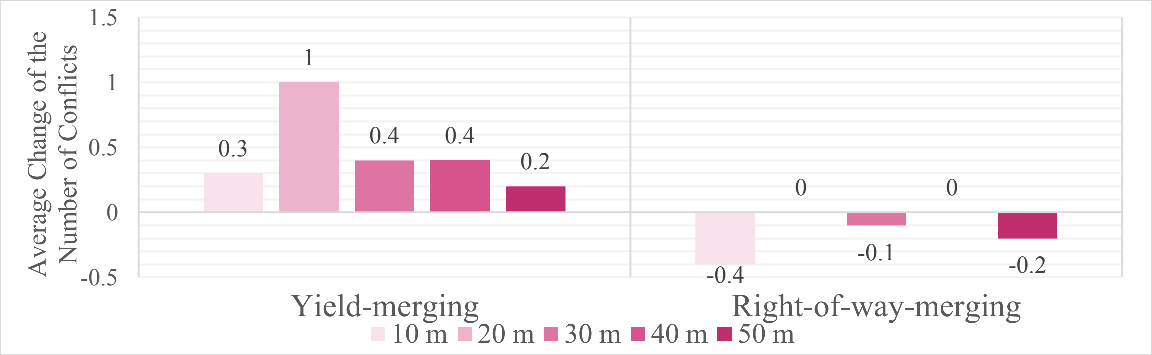
Figure 37. Effects of calibration for crossing conflicts within merging area



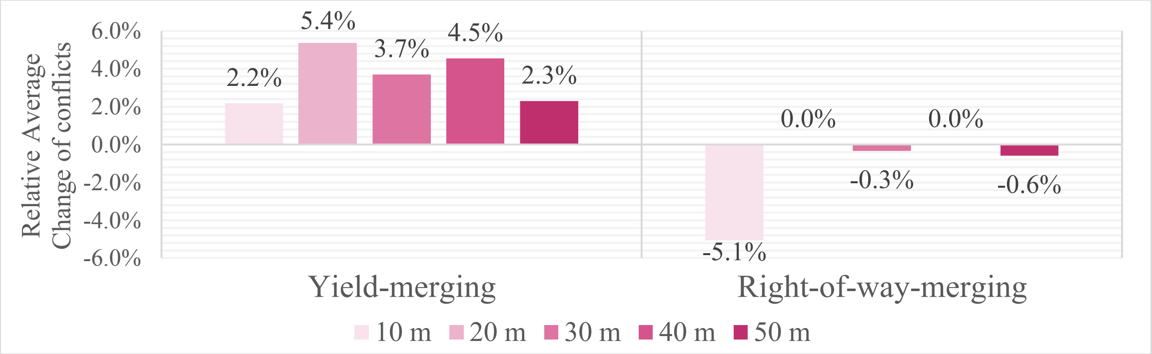
(a) Before calibration



(b) After calibration

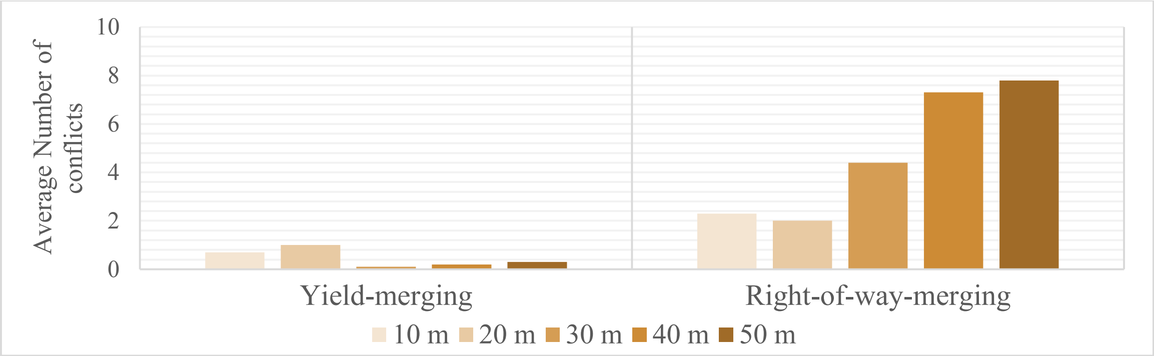


(c) Difference of expected conflicts

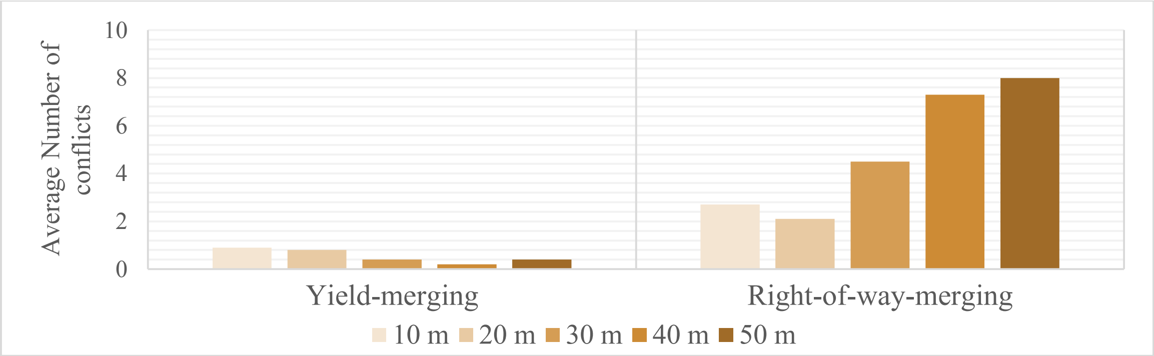


(d) Relative change

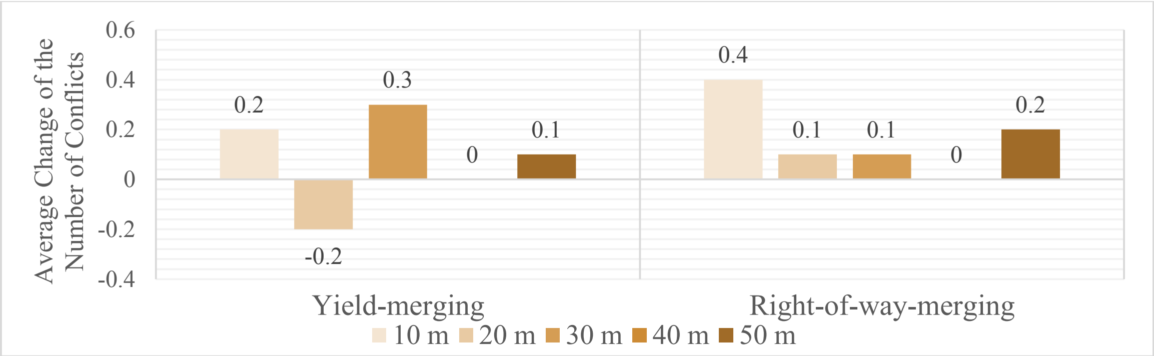
Figure 38. Effects of calibration for lane change conflicts within merging area



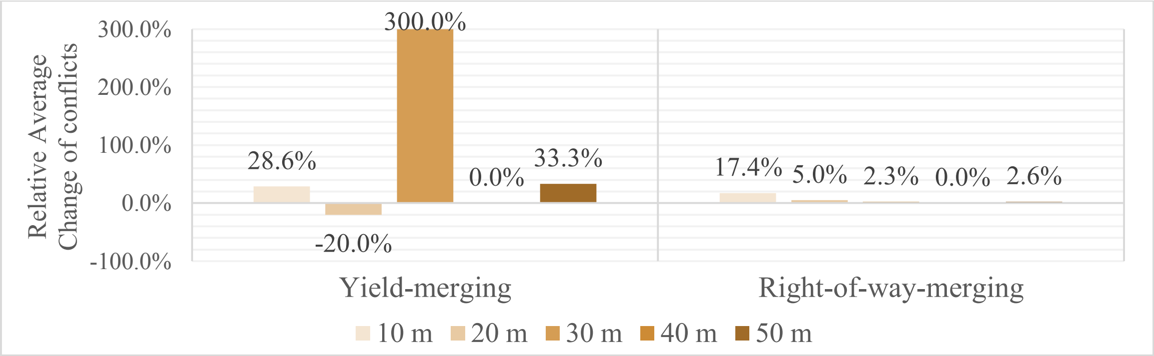
(a) Before calibration



(b) After calibration

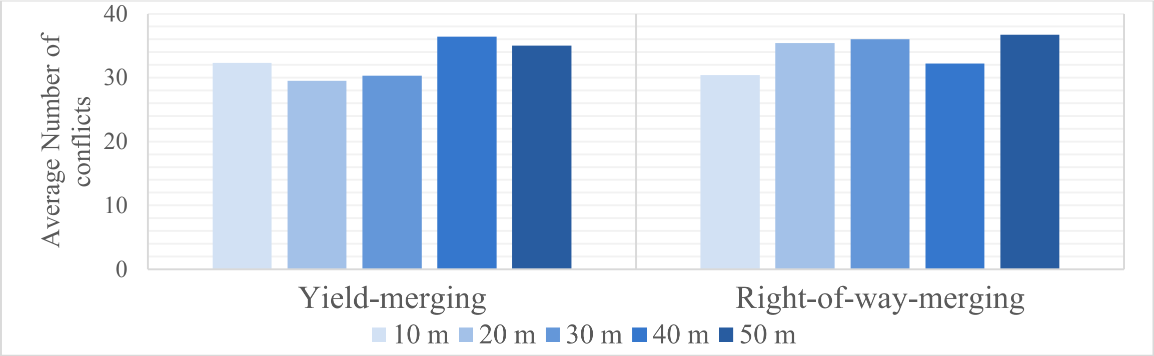


(c) Difference of expected conflicts

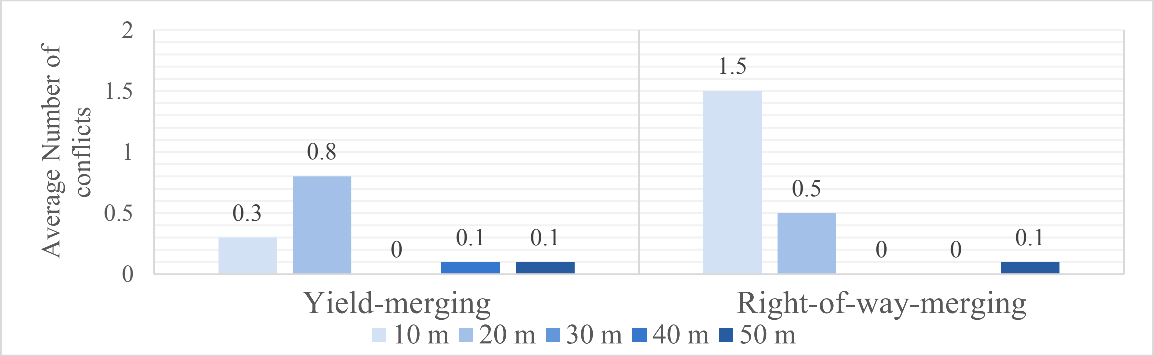


(d) Relative change

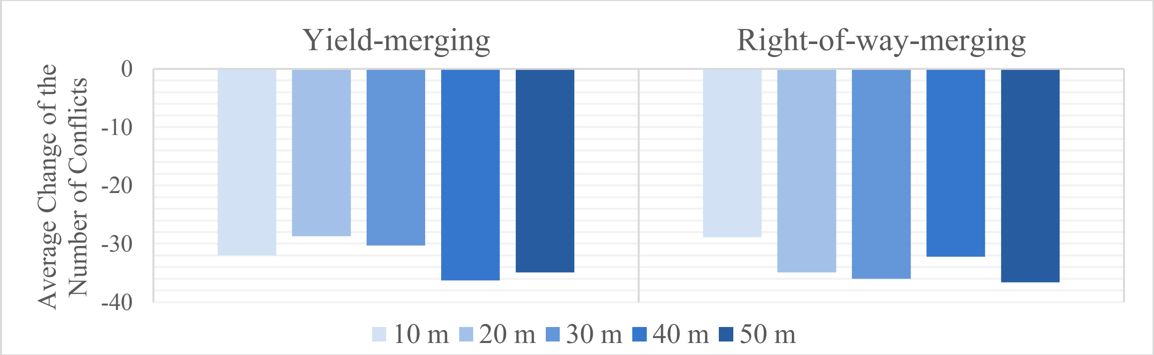
Figure 39. Effects of calibration for rear end conflicts within merging area



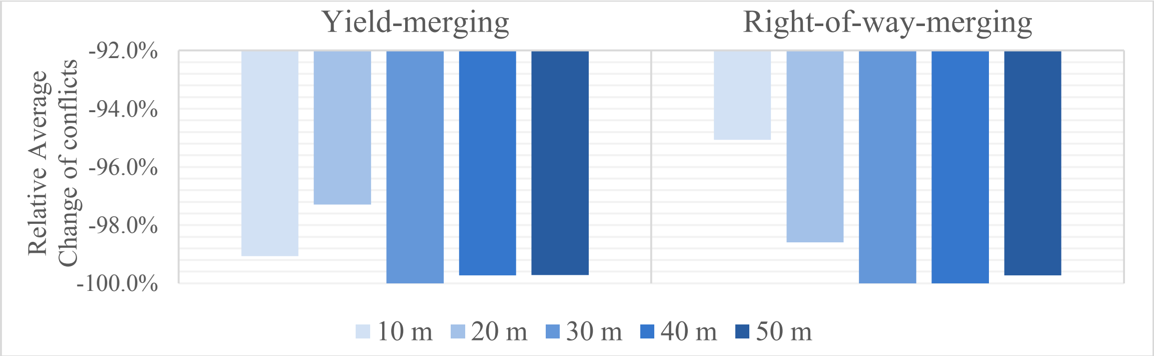
(a) Before calibration



(b) After calibration

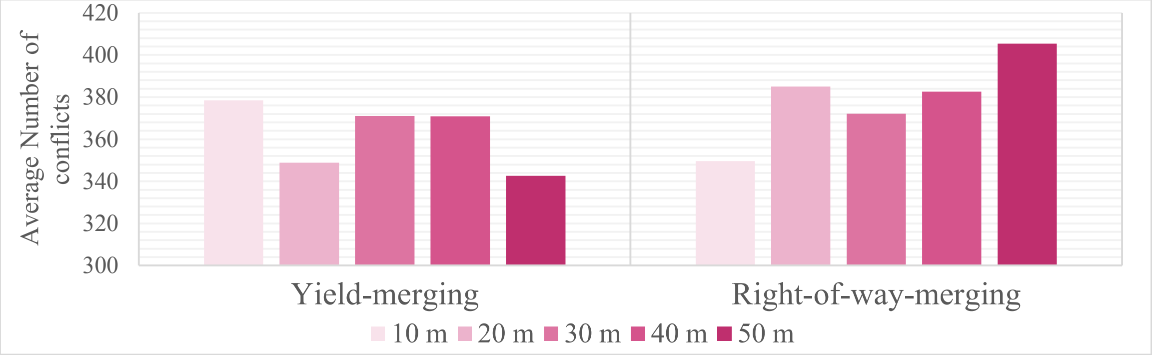


(c) Difference of expected conflicts

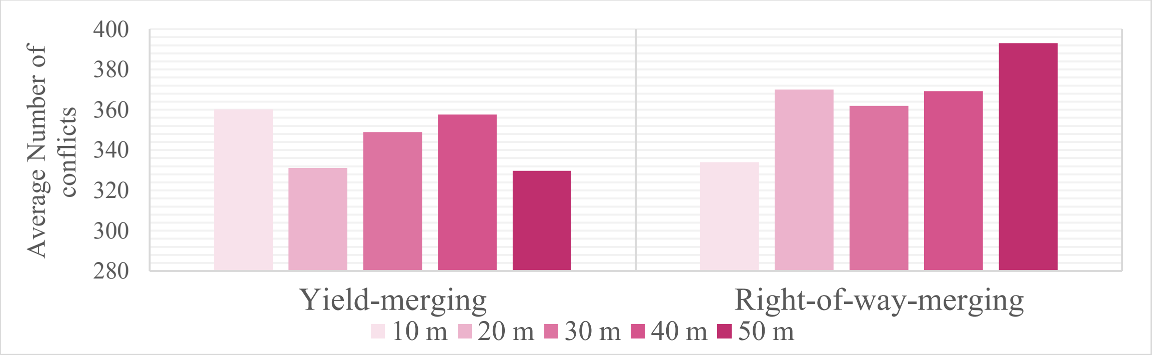


(d) Relative change

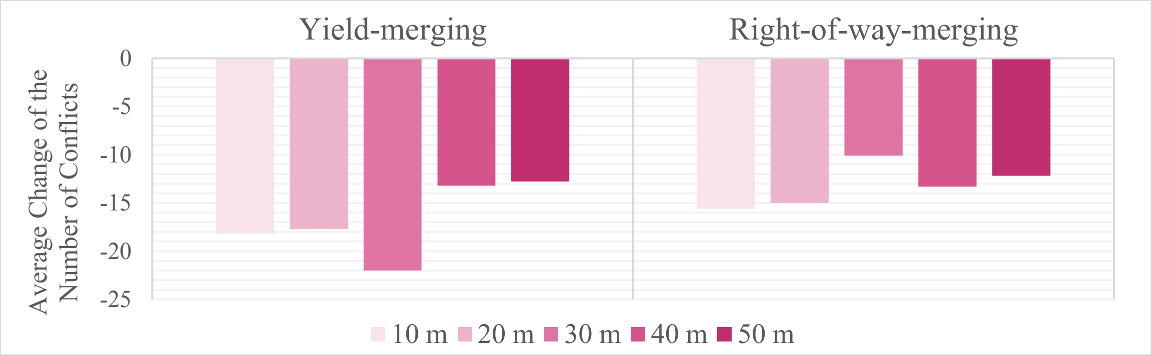
Figure 40. Effects of calibration for crossing conflicts in non-merging zones



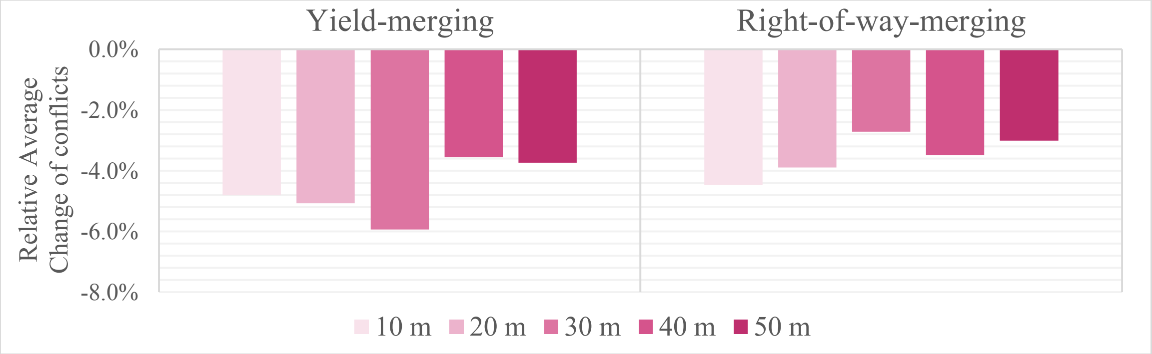
(a) Before calibration



(b) After calibration

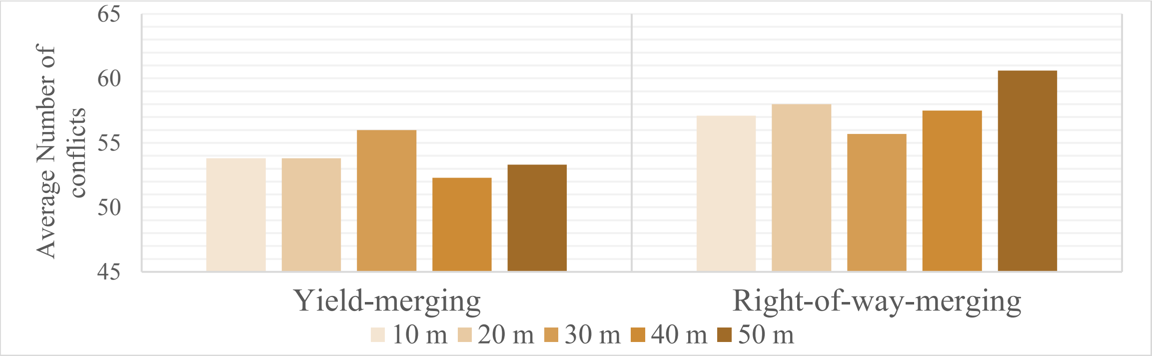


(c) Difference of expected conflicts

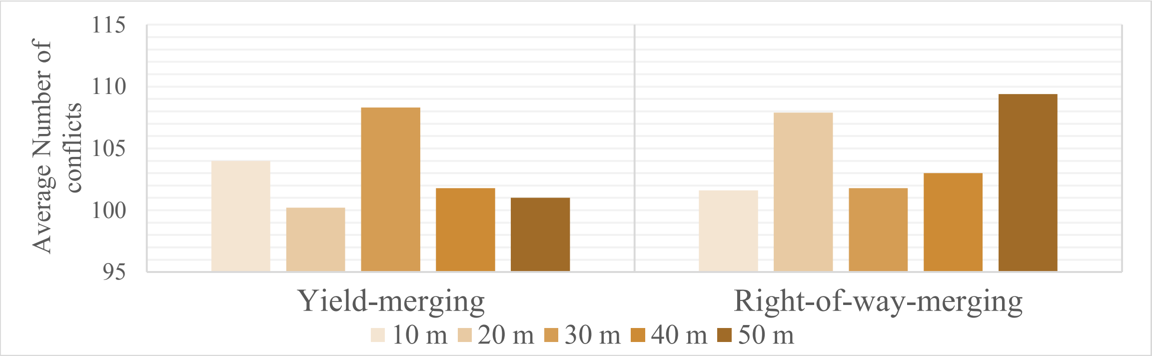


(d) Relative change

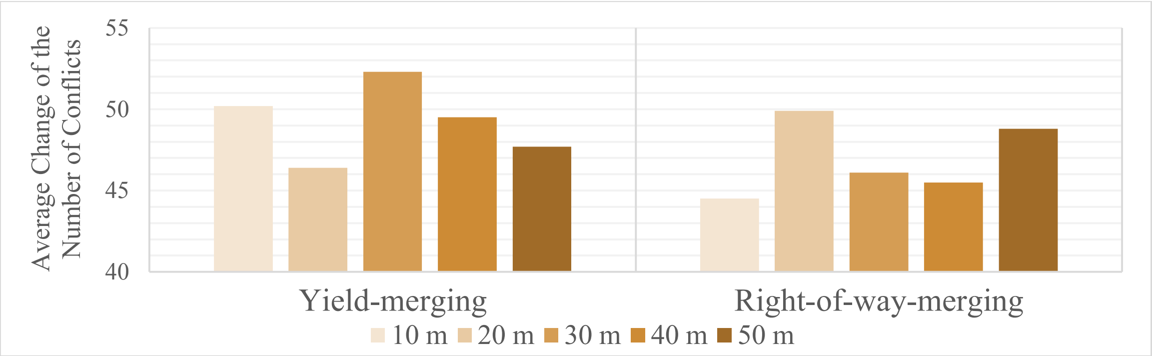
Figure 41. Effects of calibration for lane change conflicts in non-merging zones



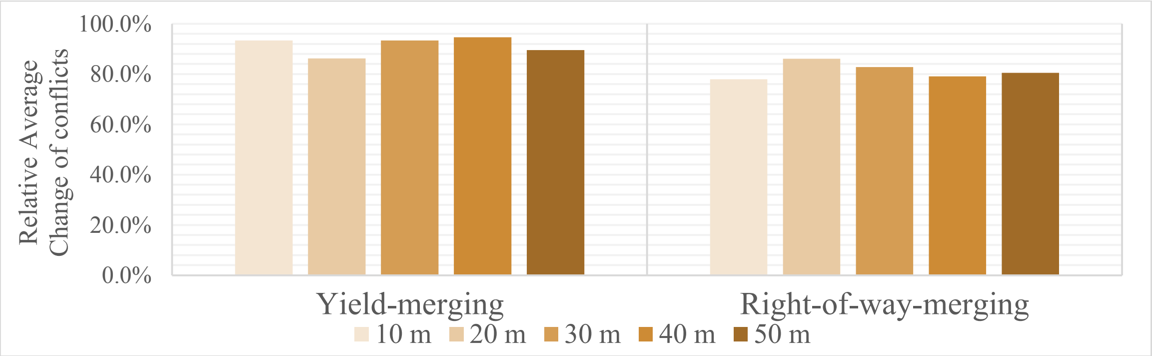
(a) Before calibration



(b) After calibration



(c) Difference of expected conflicts



(d) Relative change

Figure 42. Effects of calibration for rear end conflicts in non-merging zones

Bus-on-Shoulder is one of the popular transit operation strategy mainly because it provides a more reliable service schedule, especially during peak hour under congested traffic condition. However, several locations where buses have to merge/diverge into/from the adjacent traffic lanes more safety issues arise. Modifying the existing geometric alignment, without adding new lanes it is considered a cost-effective solution. This chapter studied on a typical BoS highway segment in Laval, Quebec area, it found out that by adding a 50-m long yield-merging section the operation and safety performance could be improved.

Chapter 7.

Conclusions

7.1 Summary

The traffic operations of reserved-lanes may lead to negative impact on the average travel time of vehicles on the minor streets. This problems occurs typically when there is a high density of merging/weaving sections, regardless of the type of facility where they are implemented (e.g. arterial, highways, etc.). In addition, depending on the geometric alignment, the users of reserved lanes may be exposed to an increased number of conflicts with the vehicles on the adjacent lanes due to merging/diverging and crossing maneuvers. In this thesis, a two-step microscopic safety evaluation model had been proposed to present vehicular interactions using microscopic traffic simulator VISSIM and Surrogate Safety Assessment Model (SSAM).

This thesis deployed access management into network design by proposing several counter measures in order to improve operation and safety performance. Another contribution of this thesis is a new conflict classification method using a binary matrix principle. This lead to a more accurate estimation of conflicts classification using an existing SSAM software. This thesis applied the proposed measure using two case studies, an arterial reserved lane facility and a bus-on-shoulder facility. The case studies were analyzed with real-world collected traffic data, which was used processed to calibrate a traffic simulation model and safety analysis model. The analysis procedure used in this thesis is generally independent of the type geometric alignment so that it can be deployed to other similar reserved-lane facilities..

7.2 Findings and Concluding Remarks

Microscopic traffic simulation models provide a fast and efficient way for researchers to analyze safety transportation related problems. This thesis combined VISSIM and SSAM to evaluate the traffic operations and safety of two case studies with a reserved lane, an arterial and a highway. The proposed two-step methodology to enhance the conflict classification output of SSAM was shown to be effective for the analysis of traffic safety and operation on different geometric alignments of reserved lane facilities. For example, in the tested case studies it was found that a 30-m merging section is the best geometric alignment configuration for the bus lane facility along an arterial. Also it was found that the highest reduction in the number of conflicts along a BoS facility can be achieved with by using a 50-m yield-merging section.

This thesis also attempted to identify if alternate geometric alignments can be used to increase traffic operations and safety performance. For example, it was found that for the arterial bus-lanes the reduction of vehicle interactions opportunities (i.e. proving alternative routes for vehicles to merge onto the arterial) did not significantly affect the traffic safety, but it lead to better network average travel time. This can be explained by the reduction in the random component of vehicular delay due to accommodation via the neighbouring traffic lights. In the other case study, the highway BoS facility, a different merging principle was tested to accommodate the vehicular conflicts at the end of the facility (i.e. the righ-of-way merging). However, it was found that while the impact on travel was not expected to be affect, the impact on vehicular traffic was negative (i.e. the expected number conflicts increased, mainly due to the high volume on the lanes adjacent to the BoS).

Finally, the proposed conflict assessment method has been tested with the selected case studies. It was found that the proposed binary matrix conflict calibration method leads to more accurate estimation of conflicts classification regardless of the type of facility used (i.e. arterial or highway). The analysis of the tested scenarios showed that the proposed conflict classification method enhances the accuracy of the SSAM output. Therefore, this approach is highly recommended for further studies comparing observed conflicts and simulated conflicts as well as studies that are focusing on conflict and accident regression.

7.3 Future Work

Microscopic traffic simulation is an efficient way for transportation engineers to model a zonal traffic network. However, simulating a realistic traffic environment it is critical to the reliability of any analysis. In this study, only a few numbers of simulation parameters had been tested. More efforts could be done to calibrating and validating safety performance, such as the minimum TTC, and minimum PET, in order to explore a diversified set vehicular interaction conditions. Also, using the conflict analysis results, one could also establish a regression model between simulated conflicts can real accidents. This study did not focus on historical accident data analysis, mainly because it this kind of data is not available for specific reserved lanes. Therefore, improving the existing surrogate performance analysis methods represents an alternative solution to the lack of data problem.

Also, specifically related to the case study presented here, additional efforts are suggested to determine feasible alternatives to enhance and improve traffic operation and safety performance for BoS facilities.

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