Vehicular Safety and Operations Assessment of Reserved Lanes using Microscopic Simulation

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ABSTRACT

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Evaluation of roadway safety via the analysis of vehicular conflicts using microscopic simulation shows increasing preference among transportation professionals, mostly due to significant advances in computational technology that allows for better efficiency when compared with other traffic safety modeling approaches. In addition, since modeling vehicular interactions via simulation is intrinsic to the methodology, one may assess various impacts of safety treatments without disrupting vehicle movements and before proceeding with real-world implementations. VISSIM, a microscopic traffic simulation model, is used in this thesis to reproduce vehicular interactions of an urban High Occupancy Vehicle (HOV) arterial in Québec. The model is calibrated to reflect the observed real-world driving behavior. Vehicle conflicts are assessed using the Surrogate Safety Assessment Model (SSAM) developed by Federal Highway Administration (FHWA). The experimental results indicate that the existing study area has a significant safety problem, mostly due to high interactions between buses and passenger cars. Alternative geometric and control designs are evaluated to ameliorate traffic safety. It is shown that the proposed alternative solutions can be used to either efficiently eliminate many vehicular traffic conflicts, or to significantly reduce public transit delay while ameliorating traffic safety. It is expected that this methodology can be successfully applied to other similar reserved lanes facilities.

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AX	Desired distance between two vehicles in standing queue in Wiedemann car-following model
a_0	Intercept of driver reaction model, or estimated model parameters of two-phase collision prediction model
α_1	Estimated model parameters of two-phase collision prediction model
a_i	Coefficient for *i*th independent variable of driver reaction model
ax	Stand still distance (m)
BX	Minimum following distance in Wiedemann car-following model
bx_add	Additive part of safety distance (m)
bx_mult	Multiplicative part of safety distance (m)
CC_{field}^{i}	Number of field observed conflicts for time interval$i$
CC_{sim}^{i}	Number of simulated conflicts for time interval$i$
CLDV	Action point at short distance where the higher speed than the leading vehicle is perceived in Wiedemann car-following model
d	Safety distance (m)
E	Number of crashes estimated by empirical Bayes safety estimation model
H_{1i}	Observed average hourly traffic volume for major approaches at site *i* of two-phase collision prediction model
H_{1i}	Observed average hourly traffic volume for minor approaches at site *i* of two-phase collision prediction model

KE_s	Kinetic energy (j)
m_s	Mass (kg)
n	Number of independent variables of driver reaction model, or number of sites in two-phase collision prediction model
OPDV	Action point at short distance where the lower speed than the leading vehicle is perceived in Wiedemann car-following model
$P_n(j)$	Probability of existence of evasive maneuvers before crash predicted by driver reaction model
SDV	Action point at long distance where the speed difference is perceived by the driver in Wiedemann car-following model
SDX	Maximum following distance in Wiedemann car-following model
t	Time (s)
v	Speed (m/s)
x_i	ith independent variable of driver reaction model
X_{ji}	Geometric-related covariate for site i of two-phase collision prediction model
α	Estimated weight given to expected number of crashes (λ) of empirical Bayes safety estimation model
β_j	Estimated model parameters of lognormal model for geometry j of two-phase collision prediction model
λ	Expected number of crashes in empirical Bayes safety estimation model, or amount of collisions estimated by collision regression model
γ	Recorded number of crashes in empirical Bayes safety estimation model

γ_0 Model parameters of two-phase collision prediction model

γ_1 Model parameters of two-phase collision prediction model

μ_i Predicted number of collisions of two-phase collision prediction model

c_i Number of observed conflicts with severity level i of collision regression model

π_i Ratio of collision to conflict with severity level i of collision regression model

ΔV_s Vehicle speed change estimated by Newtonian Mechanics (km/h)

θ_i Predicted number of conflicts at site i of two-phase collision prediction model

List of Abbreviations

AADT	Annual Average Daily Traffic
CPI	Crash Potential Index
ETSC	European Transport Safety Council
FHWA	Federal Highway Administration
GA	Genetic Algorithm
GP	General Purpose
HCM	Highway Capacity Manual
HOV	High Occupancy Vehicle
ISS	Injury Severity Score
MAPE	Mean Absolute Percent Error
PET	Post-encroachment Time
SSAM	Surrogate Safety Assessment Model
TTC	Time to Collision
VAP	Vehicle Actuated Programming

CHAPTER 1: INTRODUCTION

1.1 Background

Traditionally, most traffic safety studies employed statistical analysis of accident records within a given study area. For example, some studies proposed equations that relate the number or frequency of crashes to some traffic operations independent variables (e.g. Annual Average Daily Traffic (AADT), average vehicle speed, etc.) (Persaud, Retting, Garder & Lord, 2001; Elvik, 2008; Srinivasan, Haas, Alluri, Gan & Bonneson, 2016). There are several limitations of the accidents-based analysis on road safety evaluation. For example, obtaining reliable accident data is a complex and difficult task, the non-replicability of the crash process limits the thoroughness of the analysis, while there is a limited transferability to other existing or future/new facilities (Older & Spicer, 1976; Brown, 1994; Gettman & Head, 2003; Laureshyn, Svensson & Hydén, 2010).

On the other hand, the microscopic simulation-based safety evaluation approach presents some significant advantages. For example, different safety performance indicators can be generated and are readily available from microscopic simulation models (Archer, 2004). Furthermore, the evaluation can be established within a short time, for large study areas, once a simulation model is developed. Moreover, the safety modeling approach has the ability to test the modifications on the traffic systems without disrupting the existing traffic. Additionally, the process of traffic failure can be reproduced without real-world consequences through microscopic simulation (Archer, 2000; Young, Sobhani, Lenné & Sarvi, 2014). While the reliability of the results depends largely on the quality of the simulation model, many of the previously mentioned characteristics make simulation-based safety evaluation more and more preferred among transportation practitioners.

One of the significant advantages of simulation based safety evaluation is the ability to generate measureable safety performance indicators, typically, vehicular conflicts as well as a series of associated surrogate safety measures such as Time to Collision (TTC), Post-encroachment Time (PET), etc. A dedicated tool namely Surrogate Safety Assessment Model (SSAM) was developed by Federal Highway Administration (FHWA) to automatically identify, classify, and evaluate the severity of the simulated traffic conflicts (Gettman, Sayed & Shelby, 2008).

1.2 Problem Statement

High Occupancy Vehicle (HOV) lanes were implemented on both freeway and urban arterial sections during the recent 30 years in North America, aiming at operation improvement by promoting carpooling and usage of public transit, and generally reducing the single-occupancy riding for commuting purposes. More recently, HOV lanes have also been used as an incentive to contribute to the reduction in greenhouse gas emissions, by allowing electric and/or hybrid vehicles that do not meet the required occupancy regulation.

Research indicates that there are safety issues related to HOV lane facilities due to the arbitrary lane changes and the major speed difference of road users traveling on HOV lane and adjacent General Purpose (GP) lane. Some studies indicate that HOV lane might have negative impacts on the operating efficiency of adjacent GP lane (Tao, Foomani & Alecsandru, 2015). This condition is mainly due to the lack of uniform standard of geometry implementation and control strategy for HOV lanes.

Bus reserved lane is a specific type of HOV lane which is specifically designed for exclusive bus use with the purpose to maximize the operation efficiency of public transit. Such kind of HOV lanes tend to present more safety issues and operation problems on the arterials, especially near the public transit terminals, where the terminating buses travel across the undivided road and cause more delay and conflicts.

To evaluate the safety of the HOV or bus reserved lanes, the traditional statistics-based accidents analysis method is less preferred, not only due to the previously mentioned limitations, but also because HOV lanes are relatively new facilities, therefore the reported accident records related to HOV lanes are usually very limited. Consequently, alternative methods, such as the simulation-based analysis, might be better tools to evaluate the safety of the HOV lanes. However, there is very limited studies proposed systematic procedures that focus on the HOV lane safety simulation. It is necessary to develop an integrated method aims at the HOV lane safety and operational efficiency evaluation thus benefits the future researches on this area.

1.3 Research Objectives

This thesis proposes an integrated simulation-based analysis method to evaluate the safety and operational efficiency of HOV lanes, especially the bus-reserved lanes. Several possible geometry and control implementations aimed at improving the performance of the HOV lanes are also proposed.

A calibrated VISSIM microsimulation model is built to test the safety and operational efficiency of an urban HOV facility in Québec. Two alternative network designs are proposed for comparison analysis (i.e. one modifies the existing road geometric alignment; another proposes a change in the existing traffic control strategy). To assess the road safety impact of the proposed alternative designs, SSAM is used to compare the simulated vehicle conflicts between the existing network and the alternative solutions. The results indicate that the status-quo of the study area exhibits a safety problem due to high interactions between buses and passenger cars. The proposed alternative geometry design efficiently eliminates the traffic conflict. In addition, the alternative control design scheme significantly reduces the public transit delay.

1.4 Thesis Organization

This thesis is organized in five major sections:

The first chapter introduces the problem related to HOV lanes and identifies the research objectives.

The second chapter reveals the available literature pertinent to reserved-lanes, traffic simulation and traffic safety analysis.

The third chapter provides the details of the methodology used in this study to investigate traffic safety using a microscopic traffic simulator.

The fourth chapter describes the case study of an arterial HOV lane. It includes the operational efficiency and traffic safety evaluation; as well, it presents two possible improvement strategies.

The last part summarizes the work developed in this thesis, provides the concluding remarks and makes specific recommendations for future research undertaking.

CHAPTER 2: LITERATURE REVIEW

2.1 Microsimulation Modeling Based Road Safety Evaluation

2.1.1 Road Safety Statistical Analysis

Traditionally, traffic safety analysis of various road facilities applied statistical study tools on encountered or reported accidents within the study areas. For example, Gettman and Head (2003) established regression equations to relate the number of crashes or the crash rate with some operational independent variables (i.e. AADT, average vehicle speed, etc.).

Srinivasan et al. (2016) established several negative binomial regression models to estimate the number of crashes. The proposed models were developed based on a five-year accident dataset for Washington, California and Florida. The AADT, road length and left shoulder width were the variables used in the models. The models were used to estimate the number of yearly crashes at certain freeway HOV facilities. However, the models were developed based on the accident data of only three states, and their feasibility to highways in other states is not proven. In other words, creating generalized models for crash prediction is difficult due to limitation of accident data and other traffic performance parameters.

Another safety estimation method is empirical Bayes estimation of safety. This method estimates the number of crash within certain road section by using both the recorded crashes and the expected crashes calculated by a prediction model. The crashes estimated by this method can be given by:

$$E = \alpha\lambda + (1 - \alpha)\gamma \tag{2.1}$$

where E denotes the estimated number of crashes, λ represents the expected crashes calculated by the prediction model, γ represents the recorded crashes, and α is the estimated weight given to λ (Elvik, 2008). This method is very sensitive to the recorded accident data within the study area, and the longer the estimation period, the bigger the dataset needs. Moreover, the development or calibration of the needed crash prediction model is usually complex.

Persaud et al. (2001) utilized the Empirical Bayes estimation method to test the safety effects of roundabout conversions. In total 23 previous four-leg or three-leg intersections that were converted to roundabouts in the U.S. were studied. Empirical Bayes method was applied to estimate the safety of each intersection suppose that they are not converted to roundabouts, and the results were compared to the recorded accidents happened at each corresponding converted roundabout. The accident data involved in this study were extracted from the police reports. However, the police reported data is sometimes not easy to inquire. Furthermore, the police reported accident data mainly focus on property lost, which usually contains limited information about the detailed crash positions for safety study (Tao et al., 2015).

Gettman et al. (2008) summarized the drawbacks of using authority reported crash data for safety evaluation. It pointed out that the rareness and randomness of field traffic accidents leads to the slowness of establishing analysis; and the lack of ability to evaluate the safety of traffic facilities yet to be built or the traffic remediation yet to be applied in the field, are the main weakness of the statistical methods for road safety analysis. Brown (1994) pointed out that the lack of precision in databases and the small size of accident samples lead to the statistical problems for safety analysis based on accident data. Laureshyn et al. (2010) concluded that an accident is the result of a series of small probabilistic behaviors, while the lack of information makes it difficult to study the safety on behavioral aspect based on the reported accident data. Young et al. (2014) also concluded that the lack of ability to deduce the crash process through the accident data is the reason that prevents the statistical studies of accidents to be properly applied to road safety evaluation.

2.1.2 Microsimulation Modeling on Road Safety Evaluation

On account of the aforementioned drawbacks of the traditional statistical analysis for road safety evaluation, an alternative safety evaluation approach which includes the computer microsimulation modeling of vehicle interactions is developed.

Simulation modeling has been applied generally in evaluation of traffic systems' operations. While the idea of using microsimulation models for road safety assessment was developed recently. Archer (2000) concluded that the lack of micro-simulators for safety evaluation in the past was mainly due to limitations in modeling reliably road users' behaviors. Along with the advancements in computing technologies as well as the improved reliability of new data collection techniques during the recent decades, traffic simulation models have also been promoted and rapidly developed. With focus on road safety, the newly enhanced traffic simulation models have been able to replicate the vehicle interactions from micro perspective through modeling the complicated driving behaviors (Young et al., 2014).

A significant advantage of simulation based safety analysis is that microsimulation models can easily generate and measure various safety performance indicators (Archer, 2004). Safety performance indicators are the measurements that casually related to crashes, and can be observed more frequently than crashes (European Transport Safety Council (ETSC), 2001). Microsimulation enables the directly output of various safety performance indicators. Through the evaluation of such output data, the safety performance of certain road facilities under different traffic measures can be determined. The microsimulation output used most frequently for safety analysis is the vehicle trajectory data. They can be used to estimate crash probability related measures such as TTC and PET. These parameters have been promoted by many studies as surrogate measures of safety rather than crash (Brown, 1994; Gettman et al., 2008; Laureshyn et al., 2010).

Compared with the traditional statistical analysis of road safety, microsimulation based safety evaluation possesses several advantages. Firstly, the analysis can be established in a short period using microsimulation. Secondly, various safety performance indicators can be output directly from microsimulation model for surrogate safety assessment. Thirdly, the feasibility of modifications to traffic systems can be tested without disrupting the existing traffic using microsimulation (Archer, 2000). Finally, it is possible to reproduce the process of traffic failure using the microsimulation model (Young et al., 2014). These characteristics make microsimulation based safety analysis accepted by traffic safety analysts, especially during the last decade.

While some questions related to microsimulation safety are proposed, for example what kind of microsimulation model is suited for traffic safety simulation? How realistically real traffic conditions can be modeled by the simulation? To answer these questions, Young et al. (2014) studied the structures of up to eighteen traffic simulation models built for safety evaluation from

1976 to 2014. These models are usually established for analyze the safety of specific traffic scenarios, such as the unsignalized T-intersection, the signalized four leg intersection, etc. Some of the models are developed based on computer programming languages; others are built on dedicated traffic simulation software. The authors revealed that the models that provide surrogate safety measures that relate to crash probability and severity are more applicable for safety evaluation, because the crash is a result of a process that involves various safety factors. The authors concluded that the simulation models must be able to reflect stochastic diver behavior properties including those observed real world "unsafe" actions, rather than a fixed vehicle driving behavior so that to reproduce the complicated driving scenarios in practice. Moreover, the level of reliability is depends on the flexibility of the adjustable model parameters to reflect gap acceptance or car following behaviors.

Sobhani, Young and Sarvi (2013) combined microsimulation, numerical modeling and statistical analysis to evaluate the safety performance of certain road locations. The authors used a VISSIM model to generate vehicle conflicts. The conflicts with required breaking rate more than -4 m/s² were deemed as serious conflicts and were used in the analysis. The characteristics of serious conflicts were used as the input of a potential crash severity estimation model so that to determine the relative safety level of the simulated road location. The mathematical model component of this method included two steps. In the first step, a statistical model named driver reaction model was utilized to estimate the probability of whether the drivers involved in the simulated conflicts were sufficiently alert, since the drivers' reactions closely related to the possibility and severity of crashes. The equation of the reaction model is:

$$P_n(j) = \emptyset\ (a_0 + \textstyle\sum_{i=0}^{n} a_i\, x_i) \tag{2.2}$$

where $P_n(j)$ represents the probability of existence of evasive maneuvers before crash, a_0 denotes the intercept, a_i represents the coefficient for each independent variable, and x_i represents the independent variables including the speed limit at the scene of the crash (km/h), the weather, etc. In the second step, the characteristics of the simulated conflicts and the probability of drivers' evasive maneuvers were used conjunctively to estimate the vehicle speed changes (ΔV_s) during the conflicts. Once ΔV_s was determined, the kinetic energy (KE_s) of the conflict vehicles was calculated using Newtonian Mechanics:

$$KE_s = \frac{1}{2} \times m_s \times \Delta V_s \tag{2.3}$$

where m_s represents the mass of the subject vehicles. At last, the expected Injury Severity Score (ISS) of the object conflict was estimated using the measured kinetic energy, given that kinetic energy applied to subject vehicles is directly proportional to crash severity. The average expected ISS as well as the average kinetic energy of all the simulated serious conflicts were used to represent safety conditions along the simulated road location.

This method overcomes the need to obtain the real crash data for safety analysis; instead, it utilizes the conflicts output from the simulation model to estimate the potential number and severity of crashes in order to evaluate the safety of the simulated traffic facilities. The limitation of this method is that it is very specific to the study area. The development and calibration of the driver reaction model was still depended on a database of real recorded crashes and the interview of the injured drivers about their reactions before crashes.

Archer (2000) believes that the behavior of individual driver directly contributes to the traffic accident; therefore, the microsimulation models have to be able to reproduce the high diversity of road users' behaviors. In other words, the behavioral models must allow some "errors" to occur so that to reproduce the failures expected in real world. Most simulation models only generate a small behavioral variance of vehicles, and this is not sufficient to reflect the "uncommon" situations in real world, such as the crash occurrences. Based on the above-mentioned assumption, a microsimulation model namely SINDI was developed to evaluate the safety of a four-leg road intersection. In this model, the drivers' behaviors, when they approached the intersection or interacted with other road users, were modeled in three stages: the perception stage, the decision making stage and the action stage. The characteristics related to each stage were assigned randomly to individual driver based on the distribution from empirical data. For example, in the perception stage, the visual sample of different directions and the visual limitations were assigned randomly to each driver. These factors have impacts on the estimation of gaps and speeds of moving objects. The corresponding decisions, such as lane change or turning maneuver, were also randomly assigned to the drivers in the second stage, based on the information gathered from the previous stage. Finally, the resulting actions, such as the continually straight driving on the link or waiting before the stop line, were assigned randomly to the road users. Some general types of characteristics such as the vehicle acceleration capacity, the driver's reaction time were also assigned randomly to each simulated vehicle to reproduce the diversity of driving behaviors in reality. Moreover, to make the simulated driving behaviors more realistic, the errors were introduced in each stage through probability factors that were assigned to road users on basis of empirical data. For example, the incorrect estimation of gaps in the perception stage, which in real world usually caused by fatigue or some other factors. Once the model was established, the output safety indicators from vehicle interactions, such as the TTC and PET, were analyzed to indicate the safety of the simulated road location.

This SINDI simulation model succeeded in reproducing multiple vehicle behaviors to reflect the real traffic conditions. However, the complexity of the behavior models is limited to be applied to only a component of the traffic system, rather than the whole traffic system. Furthermore, the large variability in driving behaviors makes it hard to calibrate and validate the model due to the difficulty in collecting the necessary field data.

Tao et al. (2015) developed a simulation-based approach to test the safety of an existing reserved lane facility under various geometrical modifications. In this study, an eight-lane arterial including a HOV lane was modeled in VISSIM using the field collected traffic flow and existing geometry. The model was calibrated by the observed vehicle headway distribution. Several geometrical modifications to the existing system were introduced including different length of weaving sections at road access points, and a new designed external lane, which allowed the vehicle to merge into the main road via the signaled intersection instead of the original access points. Surrogate safety assessment was then applied to analyze the vehicle trajectory data output from the simulation model. The conflicts generated from the original network and the new geometrical designs were recorded to indicate the safety of each simulated traffic condition, given that vehicle conflict reflects the risk of crash. The conflicts from each design were compared to determine which design is safer. The result showed that the network with modified 30-meter length weaving section generated the minimum conflicts, and the new designed lane had positive impact on safety as well. The safety performance of the network was also estimated by increasing the input traffic flow by 10% to 30% respectively.

This study tested the safety performance of a traffic network with a set of expected geometrical modifications without disturbing the existing traffic. The result gives an indication of whether the alternative developments should be implemented to improve the network. This is mainly beneficial in estimating the safety impact of the network elements that have yet to be introduced. However, the model was calibrated based on the original traffic network, whether the calibrated driving behavior is sufficient to reflect the network with new introduced design elements is to be validated.

In conclusion, microsimulation based traffic safety analysis has been generally promoted by traffic researchers in the recent decade, due to its ability to provide surrogate safety measures to reflect the safety of road facilities, which overcomes the difficulty in obtaining real accident data for safety evaluation. Furthermore, it gives a way to estimate the safety of traffic facilities have yet to be built or traffic network modifications have yet to be implemented. The reliability of the microsimulation models established for safety analysis is highly dependent on their ability of reproducing realistic driving behaviors.

2.2 Traffic Surrogate Safety Assessment

2.2.1 Safety Performance Indicators for Road Safety Evaluation

Road safety analysis based on accident data is usually associated with the problems of data availability, data quality and pool timeliness, thus a method less preferred by researchers (Zheng, Ismail & Meng, 2014). To overcome these problems, the road safety evaluation requires the identification and measurement of safety performance indicators that imply accident probability (Archer, 2004). Laureshyn et al. (2010) summarized the advantages of developing safety performance indicators (e.g. evaluating traffic safety more efficiently, the potential to indicate the impacts of design elements on risk, the potential of indicating the relationships among driving behaviors and risk, the potential to show the process involved in the normal behavior and the critical situations, etc.).

Svensson (1998) concluded that safety performance indicators must have validated statistical relationship to accidents, should complement accident data, and show more frequently than accidents. Archer (2004) specified that the ability to reveal the severity of accidents (e.g. slight injury, severe injury, fatal, etc.) is also necessary for safety indicators. Hence, safety performance indictors can be classified into two categories, the surrogate measures of traffic accident occurrence, and accidents severity, respectively. Traffic conflict, which is a surrogate measure of traffic accident occurrence, can be considered as a “near-accident”. Laureshyn et al. (2010) assumed the collision course is a continuous process over time and space, therefore the accident severity indicators used to describe this process should also allow for continuous description. Several accident severity indicators were suggested, including time gap, speed, etc. Other accident severity indicators proposed were maximum vehicle speed, speed differential of interacting entities, road user type, collision angle, etc.

2.2.2 Traffic Conflict Technique

The concept of traffic conflict was formalized in the late 1960s as an alternative to crash analysis, given that such scenario could be observed more frequently than crash and is related to crash occurrence (Young et al., 2014). Brown (1994) proposed that traffic safety issue is multidimensional; therefore, it is necessary to search for not only roadway elements but also human factors to explain the failure mechanism. Traffic conflict is a good candidate to account for human factors; hence, it can serve to model the crash mechanism.

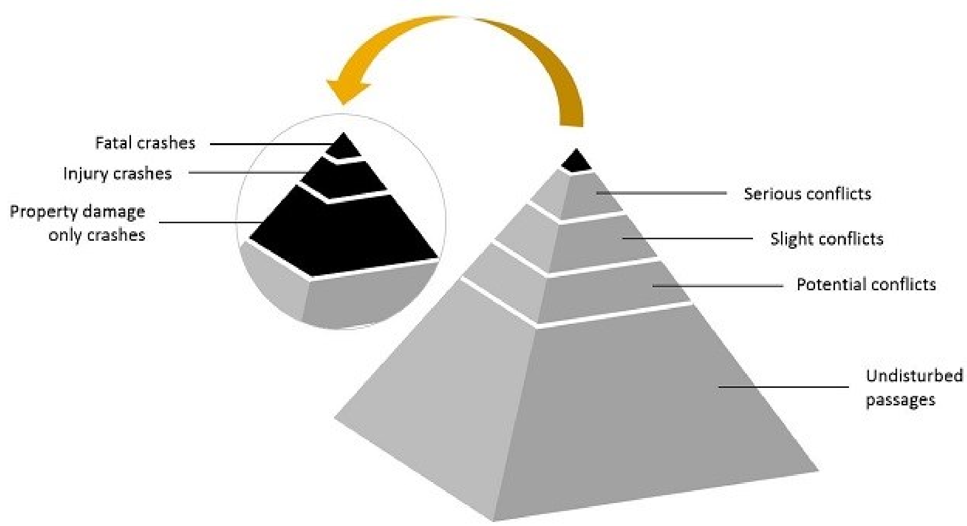


Figure 2.1. Safety pyramid proposed by Hydén (Hydén, 1987)

Traffic safety is presented as a continuum on which the standard safe driving behavior is situated at one end while the accident is located at the other end (Archer, 2004). In other words, traffic accident is an extreme situation of errors in driving behavior. Traffic conflict is considered to identify the occurrence of “near accident” conditions on the continuum. This is because “near accident” conditions represent less error in driving behavior, but are highly related to accidents and occur more frequently than accidents. Figure 2.1 shows the traffic safety pyramid developed by Hydén (1987), which shows the relationship between standard and unsafe driving behaviors. Traffic conflicts are located at a relatively higher level that approaches the top hierarchy (i.e. accidents).

The definitions of conflict could be categorized into two types (Zheng et al., 2014). One type emphasizes the evasive action involved in the road users’ interaction, a representative of such evasive action based conflict definition is “An event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision” (Parker & Zegeer, 1989). This definition implies the conflict and collision are similar errors in driving behavior, and the difference is weather a successive evasive action existing. Figure 2.2 shows a conflict scenario caused by lane change of road users. In order to avoid collision, the effected vehicle must take an evasive action to yield the lane change vehicle.

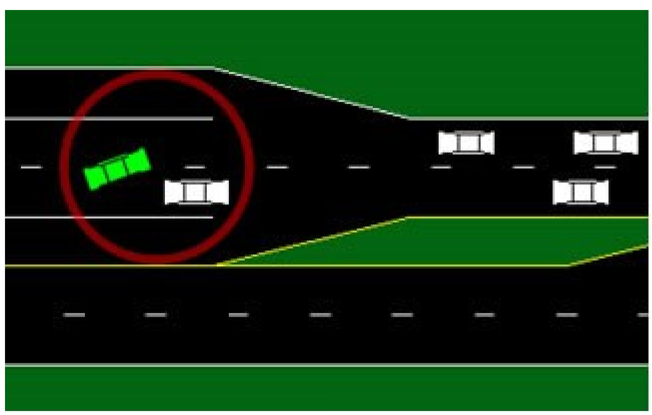


Figure 2.2. Conflict scenario caused by lane change vehicle (Gettman et al., 2008)

Another conflict definition focuses on the temporal and spatial progress of errors in driving behavior. The space-time based 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 collision if their movements remain unchanged” (Amundsen & Hyden, 1977). This definition abandons the distinct boundary between conflict and collision, instead, collision is deemed as an extreme result of conflict. Furthermore, this definition provides a potential to quantify the conflict by setting threshold values on temporal and spatial dimensions, therefore the conflicting and normal conditions can be distinguished (Zheng et al., 2014).

Various studies have proposed models to validate the statistical significance and correlation between conflict and accident. For example, Hauer & Garder (1986) proposed a regression equation to model the relationship between conflict counts and accidents occurrence. According to their study, the estimation of collisions through conflicts can be given by the following equation:

$$\lambda = \sum_i \pi_i \mathrm{c}_i \tag{2.4}$$

where λ denotes the estimated amount of collisions, $\mathrm{c}_i$denotes the number of observed conflicts with severity level i, and π_i represents the ratio of collision to conflict with severity level i, which can be estimated using various regression techniques.

El-Basyouny and Sayed (2013) proposed a two-phase model to correlate conflicts with accidents. In the first phase, a lognormal model was established to estimate the number of conflicts at site i, see the equation below:

$$\ln(\theta_i) = \ln(\alpha_0) + \alpha_1 \ln\sqrt{H_{1i}H_{2i}} + \sum_{j=1}^{m} \beta_j X_{ji} \tag{2.5}$$

where θ_i denotes the predicted number of conflicts at site i, H_{1i} and H_{2i} denote the observed average hourly traffic volume for major and minor approaches at site i respectively, X_{ji} denotes the geometric-related covariate for site i, and α_0, α_1 and β_j are estimated model parameters. In the second phase, the predicted conflicts were adopted to estimate the number of accidents at site i using the following equation:

$$\ln(\mu_i) = \ln(\gamma_0) + \gamma_1 \ln(\theta_i) \tag{2.6}$$

where μ_i denotes the predicted number of accidents, γ_0 and γ_1 are the model parameters. The model was applied to a database contains geometrical and accident data of 51 signalized intersections, and the comparison results showed significant consistency. Through this study, the proportional relationship between conflicts and accidents was showed.

Brown (1994) compared the conflict counts and accident counts at 11 intersections, for each intersection, the observed traffic conflicts were recorded during 16 hours, and the accident data covered 5 years. The results showed that at eight out of eleven intersections the conflicts and accidents were correlated significantly at 95% confidence level, and the average accident-conflict ratio was 2.95 with standard deviation at 1.10. In addition, the conflicts and accidents were categorized into eight types (e.g. left turn/opposing, right turn, rear end, etc.), and the result indicated that four of them (i.e. left turn/opposing, right turn, crossing and left turn/crossing) significantly correlated at 95% confidence level.

Based on the occurrence of a conflict, some other safety performance indicators can be measured, among which the most studied are TTC, PET, deceleration rate, maximum speed and speed differential. The former three parameters are treated as conflict-severity indicators that may be used to estimate the probability of collision occurrence based on conflicts, while the latter two parameters are used as surrogate measures to quantify the severity of a potential collision that might result from the analyzed conflict (Gettman & Head, 2003).

TTC, by definition, "the time required for two vehicles to collide if they continue at their present speed and along the same path" (Hayward, 1971), is the most notable surrogate measures of conflict severity (Gettman & Head, 2003). A lower TTC value implies a higher opportunity of collision. The minimum TTC during the entire conflict event is usually measured to indicate the conflict severity (Archer, 2004). Many studies used TTC values of 1.5 seconds or less to indicate a high risk of collision (Brown, 1994; Gettman et al., 2008).

PET, by definition is, "the time between when the first vehicle last occupied a position and the time when the second vehicle subsequently arrived to the same position" (Gettman et al., 2008). A lower PET value implies a higher opportunity of collision.

Deceleration rate reflects the evasive action taken by the driver to avoid a collision (Gettman & Head, 2003). A higher deceleration rate implies a higher risk of collision.

Maximum speed and speed deferential are surrogate measures of potential collision severity. These data are usually combined with the mass of the interacting vehicles in order to give a better estimation of the collision severity, given that heavier vehicles usually causes more damages than the lighter vehicles (Gettman & Head, 2003).

Some studies showed that conflict with low TTC value is likely to result in collision, while the potential collision may only lead to property damage if the maximum speed or speed deferential of the vehicles involved in the conflict event is relatively low. On the contrary, a higher TTC or PET value implies the low risk of collision, but once the collision happens, it could be severe (i.e. fatality) if the involved vehicle speed or speed differential is high enough (Brown, 1994; Laureshyn et al., 2010; Zheng et al., 2014).

2.2.3 Surrogate Safety Assessment based on Traffic Simulation Models

Traditionally, traffic conflicts were captured and identified in the field by trained observers, and the severity of each conflict can be judged based on the severity of the observed evasive actions (Older & Spicer, 1976). This method used to assess conflicts has some limitations. Firstly, to observe conflicts accurately, an observer with objective judgement skills is required; otherwise, different observers might record different number of conflicts at same study area, since interpretation of vehicle interaction could be subjective. While, it usually takes a substantial amount of time to train a qualified observer. For example, in a research proposed by Brown (1994), two teams of observer were trained for five days to reach only 77% accuracy for conflict identification and conflict severity proximity. Secondly, this method needs to utilize video technology to process some measures, such as the TTC value, since the field observers cannot identify such surrogate safety measures (Gettman & Head, 2003; Archer, 2004). To address the above-mentioned problems, the simulation based surrogate safety assessment, which could quantify the conflict identification and its associated surrogate safety measures, was proposed (Young et al., 2014).

One of the significant advantages of simulation-based traffic safety evaluation is the ability to generate measureable safety performance indicators, typically the vehicle conflict and a series of associated surrogate safety measures (e.g. TTC, PET, etc.) (Gettman et al., 2008). Compared with the subjective measures taken by human observers, the microsimulation model can update road user's condition at small time-intervals (e.g. 0.1 seconds or more frequently if needed); therefore, the measures generated from simulation models are much more detailed and precise

(Gettman & Head, 2003). In addition, the automated extraction and evaluation of needed measures from microsimulation models contribute to time and labor saving; therefore, the evaluation can be established more efficiently.

Gettman and Head (2003) studied the requirements for microsimulation models in order to coordinate surrogate safety measures. The microsimulation models must possess the following advantages that contribute to generating surrogate safety measures properly. Firstly, the interactions of road users can be modeled on the behavioral basis. Secondly, detailed data can be output for analysis (e.g. vehicle trajectory data, conflict, etc.). Thirdly, the model input parameters can be selected and calibrated by the users to accommodate various traffic scenarios. Fourthly, the smaller simulation time step can be selected thus more precise time related measures can be obtained. Finally, different time headways can be generated, and the road users that accept "unsafe headways" to make lane change or crossing actions can be simulated to reflect different aggressive driving behaviors.

Through the review and comparison of various prevailing traffic simulation models, the microsimulation model VISSIM, TEXAS, Paramics and AIMSUN are determined to satisfy the requirements of coordinating the surrogate safety assessment (Gettman & Head, 2003; Gettman et al., 2008).

A dedicated tool namely SSAM was developed by FHWA to automatically identify, classify and evaluate the severity of the simulated traffic conflicts (Gettman et al., 2008). SSAM was designed to supplement several prevailing microsimulation models (e.g. VISSIM, AIMSUN, Paramics. etc.).

By providing vehicle trajectory data output from the simulation models, the simulated vehicle interactions are analyzed by SSAM, and vehicular conflict events can be extracted when the processed vehicle interactions satisfy the predetermined criteria to form conflicts. The vehicle-to-vehicle interaction is identified as a conflict when the TTC or PET value exceeds the predetermined threshold.

When a conflict is determined, SSAM calculates surrogate safety measures associated with the conflict for severity analysis; these measures include minimum TTC, minimum PET, maximum speed, speed differential, initial decelerate rate, etc.

Three types of conflicts (rear-end, lane-change and crossing) can be identified by SSAM through estimating the intersection angle of the projected vehicle trajectories. The angle thresholds are usually settled by the user according to the geometrical condition of the simulated site. Several studies proposed to calibrate the angle thresholds of different conflict types utilizing the link and lane information of the vehicles involved in the conflict events (Gettman et al., 2008; Tao et al., 2015).

SSAM was validated under various traffic scenarios, and the conflicts identified by SSAM were significantly correlated with the historical accident data collected on the fields. The conflict-to-collision ratio was found to be 20,000 to 1 (Gettman et al., 2008).

2.3 Microsimulation Modeling of Traffic Network

2.3.1 Field Study of Driving Behavior

In order to properly model the traffic network, not only the geometrical elements and traffic flow but also the road users' driving behaviors within the objective site must be captured, so that the model can be adjusted from both the macroscopic and microscopic aspects to accurately reflect the real traffic conditions. The typical driving behavior models include car following, lane change, and gap acceptance models. Modeling of car following and lane changing are usually the core of various traffic simulation systems (Panwai & Dia, 2005).

Modeling traffic flow is essential for traffic simulators; therefore, the quality of the modeled car following behavior, which indicates the interaction between each pair of vehicles, directly influences the quality of the simulation (Panwai & Dia, 2005; Vissim, 2014). Real-world car-following behavior is influenced by two categories of factors. The first category comprises individual factors, including age, gender, driving skill, vehicle condition, etc. The second category includes conditional factors consisting of the environment, weather, road condition, etc. (Panwai & Dia, 2005).

Wiedemann (1974) developed a psycho-physical perception car following model to describe the longitudinal car following behavior. This model is well known since it is the adopted built-in car following model of simulator VISSIM. According to this model, the road user will be under one of the following four driving states:

- **Free driving**: in this state, the vehicle is run without influence from other preceding vehicles, and the driver seeks to maintain a prescribed (desired) speed.
- **Approaching**: in this state, the driver succeeds the front vehicle, and a deceleration is made to adapt the speed with the lower speed of the preceding vehicle. Once the desired safety distance is reached, the speed differential of the two vehicles is zero.
- **Following**: in this state, the driver follows the preceding vehicle and keeps the safety distance more or less constant by accelerating or decelerating slightly.
- **Braking**: in this state, the driver breaks at medium to high deceleration rates to avoid collision, when the distance to the preceding vehicle falls below the desired safety distance.

The driver switches from one state to another when a threshold of speed or distance is reached, and the acceleration is the result of speed, speed differential, distance headway and characteristics of the driver. Figure 2.3 shows the process of a faster vehicle approaching a slower vehicle described by Wiedemann car-following model. From the figure, the driving states switched when the following individual thresholds reached:

- **SDV**: the action point at long distance where the speed difference is perceived by the driver who is approaching a slower vehicle, is a function of speed difference and distance headway
- **BX**: the minimum following distance
- **SDX**: the maximum following distance
- **CLDV**: the action point at short distance where the higher speed than the leading vehicle is perceived
- **OPDV**: the action point at short distance where the lower speed than the leading vehicle is perceived
- **AX**: the desired distance between two vehicles in standing queue

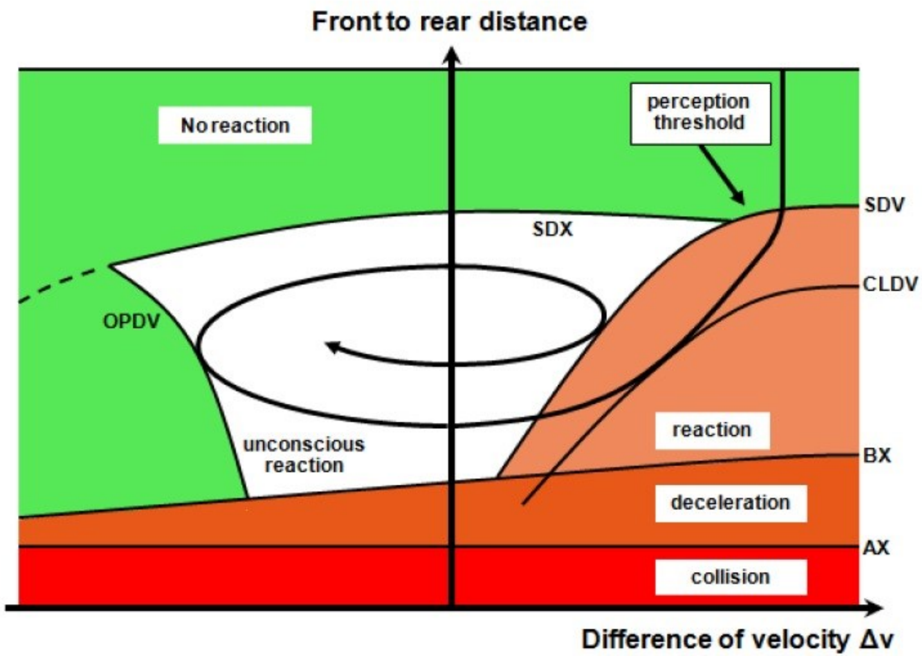


Figure 2.3. Preceding process described by Wiedemann car-following model (Vissim, 2014)

When a faster vehicle approaches a slower vehicle, the driver begins to decelerate as soon as his or her individual threshold (i.e. SDV) is reached. The driver then maintains the speed in order to follow the leading vehicle. As a small speed differential is not perceivable, the driver decelerate to a speed that lower than the leading vehicle in order to ensure the distance headway is sufficient, until the opposite threshold (i.e. OPDV) reached, when the driver accelerates again to reduce the gap. This is an iterative process and it can be observed from most of the car-following conditions (Fellendorf, 1994; Panwai & Dia, 2005). Such psychophysical-physical car-following models are adopted as the core models of some traffic simulators.

Accurate road safety analysis depends on how well traffic simulators can replicate the observed vehicle headways. Vehicle headway by definition is the time lapse between two consecutive vehicles traveling in the same lane as they pass an observation point. Accurately generating headway distribution of objective site from simulation is one essential characteristic for safety as well as capacity analysis studies.

Al-Ghamdi (2001) studied the daytime headway distributions of 20 urban sites; where in total more than ten thousands of observed headways were recorded. Chi-square test was applied to compare the collected sample of each site with various candidate distributions to obtain the best fitting, and the distribution that gave the minimum chi-square value would be selected. The result showed that the negative exponential distribution, shifted exponential or gamma distribution, and Erlang distribution are reasonably fit the low flows (less than 400 vehicles per hour), medium flows (400 ~ 1200 vehicles per hour), and high flows (above 1200 vehicles per hour) conditions, respectively.

Lane change and gap acceptance behaviors are highly related to safety. An abrupt lane change or errors on gap acceptance are likely to cause serve conflict even collision. As long as a driver travels slower than his or her desired speed, due to the slower leading vehicle, he or she is probably searching for opportunities to change lane so that to improve the present situation (Barceló, 2010, P. 77). A study showed that the conflicts at weaving section are mainly caused by mandatory lane changes, and the suddenly deceleration of the approaching vehicle on the target lane to evade the lane-changing vehicle might also lead to collision with the following vehicle (Uno, Iida, Itsubo & Yasuhara, 2002).

Lane change is usually associated with gap acceptance, a driver needs to find a suitable gap to complete a successful (safe) lane change. The gap size depends on the speed of the lane-changing vehicle and the speed of the approaching vehicle from behind of the desired lane (Vissim, 2014). The lane-changing driver is willing to accept that the approaching vehicle on the desired lane is forced to decelerate so that to cooperate the merging (Barceló, 2010, P. 81).

Gap acceptance behavior is also associated with left turning movements. To complete a left turn successfully, the driver must estimate the adequacy of gaps available on the opposite flows. The rejection of an adequate gap causes unnecessary delay, while adopting an inadequate gap leads to conflict even collision (Davis & Swenson, 2004).

Davis and Swenson (2004) studied the gap acceptance behavior at a signalized intersection. In this study, in total 74 left turning actions involving 212 gap decisions were recorded and reviewed. As expected, the results showed that the gap distance strongly influences the decision of gap choice. In addition, the gap time and the speed of the opposite oncoming vehicle also make a significant influence on the decision of gap acceptance. A limitation of this study is the collection of left turning movements were only at a 4-way intersection, whether the finding can represent the gap acceptance behavior at different type of locations, for example a t-intersection, has to be validated.

Most studies agree that reliable modeling of driving behaviors is of great importance for perceiving the essential mechanism of traffic accident and provides the theoretical basis for traffic safety simulation.

2.3.2 Video Based Vehicle Tracking Technique

The vehicle speed is an important input parameter of microsimulation models. Accurate modeling of vehicle speeds directly influences the car following as well as lane change models, thus affecting road safety performance. Some parameters such as the maximum vehicle speed, speed difference and deceleration rate, are generally used as severity related surrogate safety measures. Therefore, a realistic modeling of the speed distribution of vehicles in the simulation model contributes to accurately reflecting the safety performance of the study area.

There are many methods to measure and collect speed distribution along different types of roads (e.g. radar, laser, loop detectors, etc.). Depending on the type of data needed and the application, one may select the most suitable method. The advantage of video-based speed processing method is that it may provide additional driving behavior information.

Saunier and Sayed (2006) summarized the advantages of monitoring traffic based on video sensors. Firstly, video sensors are easy to use and install compared with the loop detectors. Secondly, video-based assessment provides the possibility to obtain various measures of traffic parameters. Thirdly, small number of video sensors can cover large study areas. Finally, the price of image processing devices is relatively lower.

A critical advantage of applying video-based assessment to obtain traffic parameters is it clearly improves processing time and outputs results that are more accurate. A study compared the vehicle speeds extracted from video with that measured by laser gun, and the result indicated the video extracted results were accurate to about one mile per hour (Davis & Swenson, 2004).

A method to measure the vehicle speeds efficiently and automatically is the video vehicle tracking technique. Typically, video-based speed processing implies detecting and tracking vehicles over space and time. From vehicle trajectories, parameters such as the vehicle speed within each time interval can be measured. Compared with the measurements from point detectors, video-based vehicle tracking provides results that are more consistent, and shows the changes of vehicle speeds from one period to another, which contributes to detailed traffic flow modeling (Coifman, Beymer, McLauchlan & Malik, 1998).

The common video based vehicle tracking method can be classified into four categories according to their tracking strategies, namely *model based tracking*, *region based tracking*, *active contour based tracking* and *feature based tracking* respectively.

Model based tracking method utilizes the 3D model of certain vehicles, and the recognition of vehicles is achieved by matching the video image with the pre-given 3D models. It provide high accuracy on the tracking of certain vehicle types, while the main weakness of this method is that it is impossible to provide all kind of vehicle models that can be seen on the road.

In the region based tracking method, the foreground vehicle is detected by subtracting the incoming video background from the current video image. However, this method is unsuited to be applied to congested traffic conditions.

The active counter based tracking method tracks the counter of the moving vehicles. In this method, the road users can be recognized accurately by detecting the boundary curves of the moving objects. However, it cannot separate the partially occluded vehicles thus not suit for congested traffic conditions as well.

Feature based tracking method abandons the idea of tracking certain moving object as a whole, instead, the sub-features of the object are tracked. These features can be distinguishable points or lines on the object that showed on the video image. Since the object can be identified and tracked as long as some features of it remain on the video image, this method overcomes the problem of partial occlusion of the object thus generally accepted by traffic researchers. Figure 2.4 (A) shows the movements of two vehicles. The partial occlusion of vehicle 1 happens at time t_3. Figure 2.4 (B) shows the simplified feature based tracking algorithm of the same two vehicles, although part of the features of vehicle 1 are occluded and lost, the remain of the features are still tracked.

Feature grouping is an important component of feature based tracking method. After the features are tracked, those rigidly moving together are grouped to represent each individual object. The motion of one representative feature of the object is selected to represent the trajectory of that object, which is shown in figure 2.4 (C).

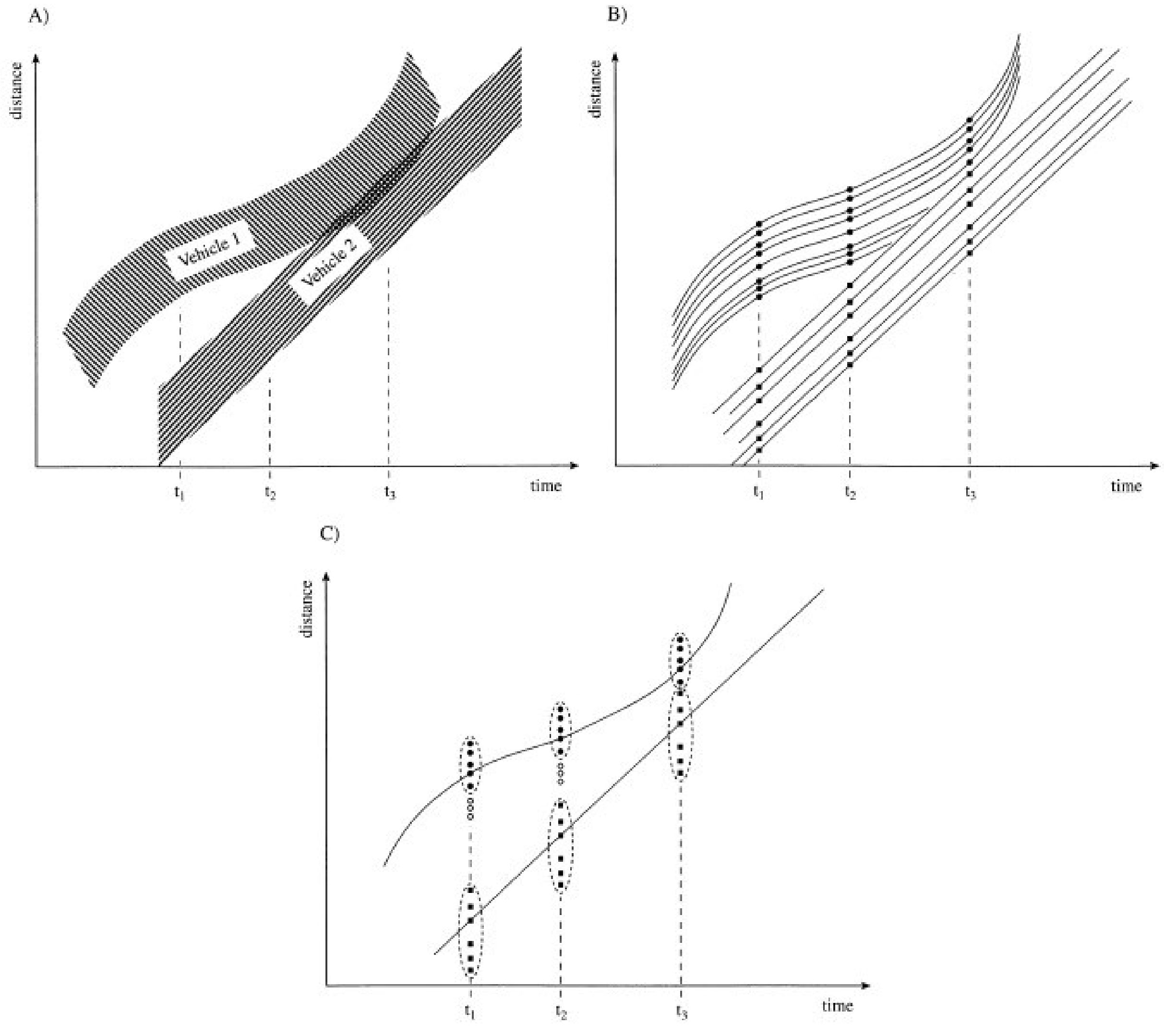


Figure 2.4. Simplified feature based tracking algorithm of two vehicles (Coifman et al., 1998)

Coifman et al. (1998) proposed a complete feature based vehicle-tracking method. Because the camera is usually not aiming at the right above of the tracked traffic stream, which causes error on distance based measures. In this method, the camera is calibrated firstly so that the tracking area showed on the video is correspondent to the world coordinates with known scale. In other words, a projective transform, or homography, is computed between the video image coordinates and the satellite map coordinates. This transformation allows the moving objects to be tracking on the satellite map plane with known distance between the vehicle entering and exiting point, which achieves the calculation of distance based measures such as the velocity. The corner features of the vehicles where brightness various in more than one direction are then detected and tracked over time within the predefined tracking area. The positions of the tracked features are predicted on the world coordinates frame by frame utilizing the homography. Features from the same moving object follow the similar track, so individual vehicle can be distinguished from each other by grouping the features that rigidly move together. Finally, one representative track from each group is selected as the vehicle trajectory, and the parameters such as the vehicle average speed can be computed from the trajectory. A weakness of this method is the small error comes from the impact of the shadows of the tracked vehicles.

Saunier and Sayed (2006) proposed an improved feature-grouping algorithm. By this algorithm, the detected features that within a threshold distance are connected and tracked together. For each pair of connected features, their relative distance are updated every time step. If the relative motion (the subtraction of maximum and minimum distance) of the pair of features exceeds the feature segmentation threshold, they are then disconnected. Each connected component is identified as a vehicle hypothesis, and its characteristics such as the centroid position, speed, etc. are computed. As long as the movements of features show consistency, they will be connected as one component; this study efficiently overcomes the problem of partial occlusion on the tracked objects through connecting features time by time. The advantage of this algorithm is that it can be applied to complex traffic conditions, for example, to monitor the vehicle movements at the intersections. Based on this algorithm, a vehicle tracking program namely *Traffic Intelligence* was developed (Jackson, Miranda-Moreno, St-Aubin & Saunier, 2013), which is assorted with various parameter measuring sub-programs that significantly facilitate the acquisition of input parameters for simulation models.

2.3.3 Microsimulation Model VISSIM

The microscopic simulation tool VISSIM is designed to model the traffic network at a high level of details (Fellendorf, 1994). This model has been used in the thesis for modeling vehicular data. The basic network elements include links and connectors, signal heads, stop signs, speed limit signs, road user detectors, public transit stop, parking lot, and specific driving speed areas (Barceló, 2010, Chapter 2). Multiple types of road users with different dimensional and acceleration characteristics can be modeled within a given network, and they follow either predetermined or random routes.

The simulation system of VISSIM consists of two separate programs, the traffic flow model and the signal control model. VISSIM adopts Wiedemann's psycho-physical car following model to implement the longitudinal vehicle movement, and a rule-based algorithm to model the lateral vehicle movement thus achieves the modeling of realistic driving behaviors. The signal control system can be either fixed cycle or externally triggered. Vehicle arriving time can be generated randomly by setting different simulation random seeds. The stochastic noise can be added to the model in order to reflect the randomness of the traffic.

Vehicular conflict areas are automatically generated in VISSIM links at intersection zones, and road user priority rules can be defined to control traffic progression according to real-world setups. The results of the simulation can include online animation of the traffic flow and offline reports of various measurements such as the vehicle delay, vehicle trajectories, etc. (Fellendorf, 1994). Depending on the comprehensiveness on modeling of driving behaviors and the diversity of detailed output, VISSIM is being used by many transportation researchers and practitioners.

2.3.4 Calibration of VISSIM

Model calibration involves the adjustment of model parameters to improve the model's ability of reproducing local driving behaviors and traffic performance. Calibration is necessary since every model must adapt to various traffic conditions, and adjustments are needed to model reliably different real-world conditions (Dowling, Skabardonis, Halkias, McHale & Zammit, 2004).

A properly calibrated simulation model contributes to accurately reflecting the modeled real world traffic flows and observed driving behavior. On the other hand, a simulation model with non-calibrated parameters, may lead to unreliable results thus mislead the decision (Shahrokhi Shahraki, 2013). To address this issue, real-world data must be collected and used to calibrate simulation models, so that to suit the studied traffic conditions.

Microscopic simulation tool VISSIM includes a variety of model parameters that can be calibrated using measurement data from driving experiments. Fellendorf and Vortisch (2001) validated VISSIM on both microscopic and macroscopic levels. By adjusting the model parameters, VISSIM was applied to a German and a US freeway respectively, where there were different traffic rules, and consequently different driving behaviors. The simulated speed variations of individual vehicle at both sites were compared with that of the field measured data recorded by a probe vehicle. The result showed that VISSIM properly reproduced the field measured data on both sites, which was referred to as microscopic validation. Also, the flow rate distributions were compared well with the field measured data on both German and US freeways, which was referred to as macroscopic validation.

Various processes aiming at calibrating VISSIM were proposed. Dowling et al. (2004) developed a procedure through which the model parameters were classified and calibrated successively. According to this research, the model parameters should be divided to the adjustable parameters which influence the desired performance, and the parameters that do not need to be calibrated. In order to minimize the calibration effort, the parameters without analytic information are treated as non-adjustable parameters as well. The adjustable parameters are then subdivided so that those has direct influence on capacity should be calibrated prior to those related to route decision. In addition, in each set of parameters, those with impact on network wide performance should be adjusted prior to those affects the link-specific performance. At last, the system performance calibration should be proposed to fine tune the model.

Park and Qi (2005) developed a procedure for microsimulation tool calibration. In this study, the model parameters that have relevant impact on the simulation results were identified, and the acceptable ranges of the selected parameters were determined on the basis of a review of the literature. An experimental design method was then applied to reduce the number of parameter combinations to a practical amount while covering the entire parameters' ranges. For each parameter set obtained from the experimental design, multiple simulation runs were conducted to reduce the stochastic variability. The feasibility test was then applied to determine whether the simulation result compared well with the field measured result. Several statistical analyses were conducted to determine whether the selected each individual parameter type had significant impacts on the results, if not, the parameter type should be replaced by other newly selected parameter type and the previous procedure should be repeated. At last, the Genetic Algorithm (GA) was applied to generate the optimized population of parameter sets that gave the best fitness of results.

Park and Schneeberger (2003) proposed a nine step procedure for microscopic simulation modeling calibration and validation. The procedure starts with determination of a performance measure, for example, the travel time between two locations in the network, and identifying uncontrollable parameters (e.g. existing geometry, traffic counts, etc.) and controllable input parameters (e.g. lane-changing distance, minimum headway, etc.). Once the performance measure and the uncontrollable input parameters are determined, their field values should be collected. Followed with data collection, all the calibration parameters that could influence the performance measure should be identified and the acceptable range of each parameter should be determined. The experimental design was then introduced to reduce the number of possible combinations of the parameters to a reasonable value. Multiple simulation runs with each of the previous determined parameter sets are then conducted to reduce the stochastic variability. The next step focuses on developing a surface function using the calibration parameters and the measure of performance, for example, the linear regression function, with the calibration parameters to be the independent variables and the corresponding performance measure as the dependent variable. Depending on the surface function, by applying the field performance measure, the optimal parameter set can be found. The next step is to run the simulation model with the identified parameter sets from the previous step, and checking whether the output performance measure compared well with the field collected data. Finally, the validation process should be introduced by comparing an alternative type of output measure of performance with that collected from the field. The study showed that by applying this calibration procedure, the model can output a more realistic measure of performance than that from the model with the default parameters.

Menneni, Sun and Vortisch (2008) proposed a model calibration method based on matching the speed-flow graphs from the simulation and that from the field. The study emphasized that taking the average capacity as the only criteria to calibrate the model is not sufficient because of the stochastic nature of the simulation. Instead, it is suggested to match as many measures as possible to achieve higher modeling accuracy. In this research, the VISSIM car following model parameters CC1-CC5 were chosen to be adjusted. The calibration aimed to match the flow-speed graph output from the simulation and that collected on the field. The results were generated every five minutes. To compare whether the flow-speed plot from the simulation was matching to that from the field data, the pattern recognition method was applied. The output graph with the maximum fit to that of the field, in other words, the minimum difference in plot cover area, was identified, and the corresponding input parameter set was chosen for the model. The calibrated parameter set was validated by applying it to a larger scale traffic simulation model, and the result showed that it was able to generate the realistic flow rate distribution.

Kim, Kim and Rilett (2005) introduced a microscopic simulation calibration method using nonparametric statistical techniques. According to the authors, to generate aggregated performance measures from the simulation that can reproduce the field collected data is not sufficient to prove reliability of the model. Instead, it is preferred to build statistical similarity between the performance measures estimated from the simulation and that from the observed field data. The authors used a combination of various statistical methods including the Moses test, the Wilcoxon rank-sum test and the Kolmogorov-Smirnov test to identify whether the selected parameter sets can generate similar travel time distribution with the field measured travel time distribution. Only those parameter sets that passed all three tests were reserved for the next modeling stage. In the next step, GA was used to obtain the optimal parameter sets. Then the optimal parameter sets were used in the simulation, and the output mean travel time from each parameter set was compared with the observed field average travel time. The parameter sets that generated both similar travel time distributions and similar mean travel times with the field collected data were selected as the model input parameters. To validate this method, the simulation was run with the selected parameter set, and the result showed the output flowrate was compared well with that provided by the *Highway Capacity Manual* (HCM).

Cunto and Saccomanno (2008) proposed a method that focuses on calibrating the simulation model built for signalized intersections. It should be noted this method assumes that there exists a relationship between the safety performance measures and the rear-end crash probability. The authors identified an initial set of thirteen input parameters that could influence the safety performance, and their ranges of values were determined. A predefined *Crash Potential Index* (CPI) was defined as an objective safety performance measure. Based on several statistical tests, the significant parameters that significantly influence CPI were reduced to six. Then the fractional factorial analysis was used to further reduce the six parameters to three first order effects and two second order interactions. The CPI was defined as functions of remaining significant parameters. Using the CPI functions, different possible parameter combinations was determined. Finally, GA was applied to optimize the parameter sets. The method was validated by applying the calibrated parameters to model the same intersection at a different time interval, and the result showed that the simulation-based estimated CPI can reproduce that value based on the observed field measurements.

Zhou, Li, Sun and Han (2010) proposed a two-stage calibration and validation procedure for traffic safety simulation based on experimental optimization. The authors emphasized that compared with the traffic operations simulation; more precision is required for safety simulation calibration since small change of model parameters may lead to significant results differences. Their study used vehicle delay and conflicts that were collected from three intersections and the data were divided into two groups. The first group was used for model calibration. The feasibility test was conducted to identify the input parameter sets with which the simulation can output the delay and conflicts that cover field measured data. The experimental optimization was then conducted to identify the parameter set that generates the minimum error on the delay and number of conflict compared with the field data. The second group of collected data was used for validation. The result showed that through this procedure, the error of delay and conflict output from the simulation model were significantly decreased.

To conclude, calibration can be described as a process of optimization which aims at minimizing the deviation between the observed and simulated measurements (Aghabayk, Sarvi, Young & Kautzsch, 2013). To achieve this objective, the proper model input parameter set must be found, and the core of the procedure is a trial-and-error approach, which it may be a time-consuming task (Shahrokhi Shahraki, 2013). To overcome this issue, typically various statistical methods are introduced to reduce the workload. Recently, certain study incorporates the procedure with the VISSIM COM interface thus the trial-and-error can be automatically done by the programming, which significantly reduced the calibration time (Aghabayk et al., 2013). Studies showed that through adequate calibration, the traffic simulation model can reflect more realistic driving behaviors and output more accurate measurements.

2.3.5 Validation of VISSIM and SSAM for Road Safety Evaluation

Several traffic safety studies combined VISSIM and SSAM analysis (Zhou et al., 2010; Tao et al., 2015). However, any safety analysis needs calibration with real-life data to ensure reliable results. Therefore, the validation of using VISSIM and SSAM for traffic safety analysis must be conducted.

Fan, Yu, Liu and Wang (2013) studied the consistency between the SSAM identified conflicts generated from VISSIM and the field observed conflicts. The geometric characteristics and traffic data of in total 88 hours were collected at seven freeway intersections. The field traffic conflicts were extracted from the recorded videos by identifying vehicles' evasive actions. The following information related to the identified conflicts was also collected for comparison:

- The time of each conflict, which is defined as the time when the first vehicle involved in the conflict event takes evasive action
- The distance between the conflicting vehicle and the conflict point
- The conflicting angle
- The speed of the conflicting vehicle
- TTC of the conflict

A calibrated VISSIM model was built, and SSAM thresholds were adjusted based on the field collected data. The Mean Absolute Percent Error (MAPE) between the simulated and observed conflicts was calculated using the following equation:

$$MAPE_{cc} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{CC_{field}^{i} - CC_{sim}^{i}}{CC_{field}^{i}}\right| \tag{2.7}$$

where CC_{field}^{i} represents the number of field observed conflicts for time interval$i$, and CC_{sim}^{i} represents the number of simulated conflicts for time interval$i$. The result showed the MAPE value for the total conflict is 19.9%, which was considered an acceptable value. In addition, the different types of conflicts (e.g. rear-end conflict, lane change conflict, etc.) also showed reasonable goodness-of-fit. Several other types of statistical tests such as the linear regression analysis and the Spearman rank correlation coefficient were applied to test the correlation between the simulated and observed conflicts, and the results indicated similar high consistency.

Huang, Liu, Yu and Wang (2013) applied the similar method to test whether the VISSIM simulation model and SSAM can provide acceptable estimates for field observed conflicts under more complex driving environments. In this study, the field conflict data was collected at ten signalized intersections. The model was calibrated by adjusting the three parameters of Wiedemann 74 car following model such that the simulated vehicle headway distribution was statistically matching the field measured headway distribution using the Chi-square test. The consistency test indicated the model could provide reasonable estimates for both the rear end and total conflicts.

In general, all the reviewed studies showed that combining VISSIM and SSAM is a reliable tool used for traffic safety evaluation if a consistency between the field observed and simulated conflicts is observed.

2.4 HOV Lane Safety and Operational Efficiency Analysis

HOV lane, by definition represents a restricted usage traffic lane reserved for exclusive use of vehicles with a driver and one or more passengers, including carpools, vanpools and authorized transit buses. The implementation of a HOV lane system targets mobility improvement of both current and future roadway. Over thirty years of deployment of HOV lanes proved that reserved lanes might contribute to mitigating traffic congestion in urban areas, and reduce the person-hour delay effectively (Fuhs & Obenberger, 2002; Menendez & Daganzo, 2007). However, many problems related to the implementation of HOV lanes have been identified. These problems can be roughly classified into two categories, the reduction of capacity (for the non-HOV users) and potential traffic safety issues respectively. The former category may include increased congestions on the adjacent GP lanes, and/or reduction of vehicle speeds due to the merging maneuvers of high occupancy vehicles into the GP lanes. The latter category mainly concerns illegal lane changes (Guin, Hunter & Guensler, 2008).

Currently, efforts are continually made to explore new ways to improve the operation and safety of HOV facilities. However, there is no universally accepted method to evaluate the effectiveness of safety of certain HOV facilities (Bauer, McKellar, Bunker & Wikman, 2005).

Golob, Recker and Levine (1989) focused on the HOV safety evaluation based on the statistical analysis of accidents data during long periods (i.e. six years). Several studies examined the safety of HOV facilities with respect to different types of geometrical design based on the collision and driving behavior (i.e. lane-changing) data (Jang, Chung, Ragland & Chan, 2009; Qi, Wu, Boriboonsomsin & Barth, 2015). As previously mentioned in this chapter, the accident-based analysis methods are usually inefficient thus not suitable for current urban traffic system development which needs rapid assessments of road facilities.

Qi et al. (2015) emphasizes that the geometrical configuration of HOV facility has significant impacts on the safety performance. For example, based on the before and after studies of lane change along a HOV roadway segment that was converted from continuous access to limited access, the conclusion was reached that lane-changing conflicts along the continuous-access HOV facility occur more frequently. Therefore, the HOV facilities with limited access are safer than those with continuous access. To support such conclusion, more studies must be conducted, however, in reality there is limited opportunity for researchers to conduct before and after studies of road facilities respect to geometrical conversion. Figure 2.5 shows the HOV lanes configured with different types of access.

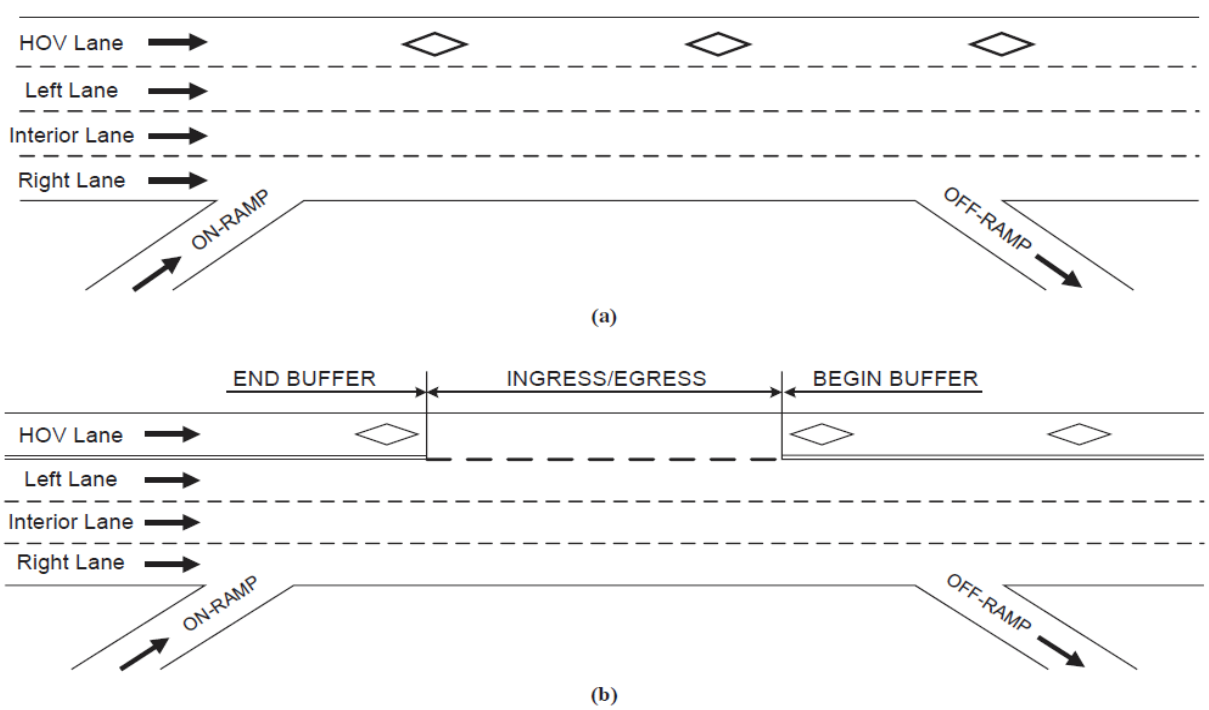


Figure 2.5. HOV lane configured with continuous (a) and limited (b) access (Jang et al., 2009)

Focusing on the problems associated with the HOV lane safety and operational efficiency evaluation, using simulation tools may be an effective remedial measure to overcome the limitation of data availability, and to evaluate the impacts of geometrical alignment modifications than before-after studies. Several studies have introduced the evaluation of safety or capacity of HOV facilities utilizing microsimulation (Guin et al., 2008; Tao et al., 2015), while another study focused on the simulation study of bus reserved lane (Arasan & Vedagirl, 2010). However, such kinds of researches are mainly focusing on the analysis results of the study areas. It is necessary to develop a systematical method for HOV lane evaluation based on microsimulation thus benefitting future practitioners and researchers.

CHAPTER 3: METHODOLOGY

3.1 Microsimulation Modeling of Traffic Network using VISSIM

3.1.1 Modeling of Geometry and Flow

Typically, more detailed information contained in the simulation model contributes to more realistic reflection of the traffic at the study area. This is especially important for safety simulation model, which requires highly accuracy on both simulated capacity and vehicle performance. In order to build precious model to reflect the study area, some basic model parameters must be collected from the field.

The basic model input is the geometry of the road, including the number of lanes on each direction, the lane separation type, the position of access, etc. Such kind of information can be easily gathered from the field. Microsimulation tool VISSIM is able to toggle an aerial photo of the study area as a frame, and the road network can be built based on the frame, which significantly improves the accuracy of the represented road segment. In this thesis, the links and connecters of the studied network were built in VISSIM by togging an aerial photo from Google® map. Some details of the geometry, for example the access position of the public transit terminal, were measured on the field using tapes, and compared with that from the field-recorded videos to ensure the accuracy. Other kinds of basic geometry, for example the position of the reserved lane, were collected on the field and included in the simulation.

Traffic flow is another important input parameter. To simulate the flow accurately is crucial for the capacity related evaluation. Typically, traffic flows were measured manually from the video recorded on the field. Such kind of information including the vehicle counts of each lane, vehicle routes, and road user types. In this thesis, in order to ensure the precision, the vehicle counts were recorded and input to the model in every five minutes. An additional five-minutes period without vehicle input was include at the end of each simulation, this “clean up” period ensures that no loss to analysis of every simulated vehicle. To model the vehicle composition, road users were identified and classified into three categories, passenger car, bus and truck respectively. The basic vehicle characteristics, for example the acceleration rate, vehicle length and vehicle weight of each vehicle type can be modeled separately in VISSIM so that to reflect the traffic more realistically. To determine individual vehicle routes, vehicles were tracked in from the videos generated by three cameras that were used to cover the whole study area. The route of each vehicle in the simulation was assigned in strict accordance with that encountered from the video to ensure a realistic representation of the study area.

3.1.2 Modeling of Traffic Signal

The peak hour traffic signal cycle length as well as the red, amber and green time intervals on each direction were collected on the field and modeled in VISSIM. VISSIM provides a separated signal design program to achieve the high precision of signal-based control. Once a signal program is designed, it can be used to control the indications of the signal heads built in the model, and the signal-timing plan is executed automatically with the simulation. In this thesis, a fix-cycled signal program was built and set at the intersection in strict accordance with the signal type and length encountered on the field.

Some additional signal control strategy was used in this study to improve the network performance; including a fix signal cycle contains a protected left turn phase at the intersection, and a pulse-triggered signal at the public transit terminal.

To improve the efficiency of public transit, a pulse triggered signal control was implemented by adding a detector at the exit of the terminal and a signal heads linked with the detector near the terminal. An add-on signals design model namely Vehicle Actuated Programming (VAP) was programmed to control this actuated signal. The switchable signal phases created using this model can be controlled by the linked detectors. Typically, a signal phase of permanent green on the main street and permanent red on the minor road is toggled when bus is not in the proximity of the detector. While, when the existing buses are detected by the sensor, the signal would switch to the complementary phase (i.e. green signal on the minor road and red on the main road), thus protecting the movements of buses passing through multiple lanes. The signal type and time elapse of the triggered phase can be easily programmed and edited using VAP.

3.1.3 Modeling of Right-of-way without Signal Control

In VISSIM, for non-signalized intersections and merging links, the right-of-way can be modeled via either the *priority rules* or *conflict areas*.

Priority rules are required for the conflicting traffic flows that are not controlled by signals. In this thesis, the priority rules were set at the entry and exit of the bus terminal, in order to realistically model the access and excess movements of buses that encountered from the video. Typically, the buses travel to or from the terminal, yielding the vehicles traveling along the artery and stop in position near the access or exit until acceptable gaps occur on both directions on the main road. In VISSIM, the *priority rule* algorithm is using a *stop line marker* for the vehicles approaching the conflict area and that must wait, and therefore a *conflict marker.* Two thresholds are set for the p*riority rules* to confine the crossing of the yielding vehicles*,* respectively are *minimum headway* and *minimum gap time*. According to the VISSIM user's manual, the headway represents "the distance from the conflicting marker against the movement direction up to the first vehicle that is moving towards the conflicting marker". The available time gap is "the time that the first upstream vehicle will require in order to reach the conflicting marker with its present speed". A yielding vehicle will stop before the stop line until both predetermined thresholds are achieved. The values of the thresholds are determined by reviewing all the accepted gaps and headways by the crossing buses from the video. Figure 3.1 shows the graphical representation of priority rule set in VISSIM.

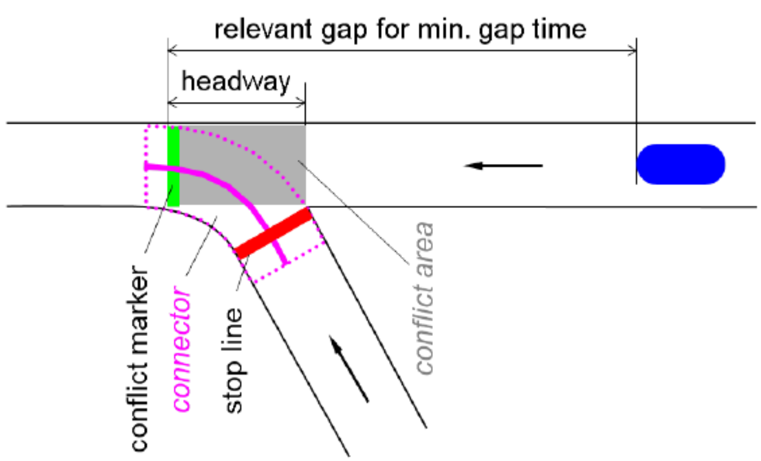


Figure 3.1. Graphical representation of priority rule (Vissim, 2014)

The right-of-way (logic controlling the movements of vehicles through a conflict area in general – merging, diverging, etc.) can be set via *conflict area* algorithm as well. The conflict areas are automatically generated in VISSIM where links or connectors overlap. In this thesis, the priority rules at the conflict areas were set thus the vehicles approaching the conflict area from the minor road yield those from the main road as generally observed in the field. The gap time needed for crossing at the conflict area was determined similarly by reviewing the video.

A noticeable parameter set via conflict area is the *avoid blocking*, which defines the ratio of vehicles that do not stop in the middle of a junction. This value is default to be 100% in VISSIM, in other words, all the vehicles will follow the rule that not to block the junctions if there is stopping traffic ahead. However, by reviewing the video recorded at the study area, no vehicle obeyed this rule. Therefore, to reflect the real conditions, this value is set to 0% for all the conflict areas in simulation models used in this thesis.

3.1.4 Modeling of Driving Behavior

Properly modeling of the field observed driving behavior is critical for road safety evaluation, since it directly influences the vehicle interactions in a micro level. Microsimulation tool VISSIM adopted Wiedemann car following model as the main portion for modeling the vehicle longitudinal movement, and rule-based laws for modeling of vehicle lateral movement and lane change behavior.

Wiedemann car following model is a classic psycho-physical perception model which has been introduced in previous chapter. In this thesis, the Wiedemann 74 model is selected to simulate the urban motorized traffic as suggested by the VISSIM user's manual. This model contains three adjustable parameters, respectively the *average standstill distance*, the *additive part of safety distance*, and *multiplicative part of safety distance*.

Average standstill distance defines the average desired distance between two cars. *Additive part of safety distance* and *multiplicative part of safety distance* represent the values used for the computation of the desired safety distance (Vissim, 2014).

According to the VISSIM user's manual, the desired safety distance between vehicles can be express by the following equation:

$$d = ax + (bx\_add + bx\_mult * z) * \sqrt{v} \tag{3.1}$$

where *ax* represents the *standstill distance*, *bx_add* and *bx_mult* represent the *additive part of safety distance* and *multiplicative part of safety distance* respectively, *v* represents the vehicle speed in meters per second, and *z* is a value ranges from zero to one, which is normally distributed around 0.5 with a standard deviation of 0.15.

For the initially simulation, the values of these three parameters are usually defined with the default value. However, they must be calibrated later to suite for the real driving behaviors of the study site.

In addition to the Wiedemann model, some basic parameters are also included in the car following model to define the longitudinal driving behavior, for example, the *look ahead distance*, *observed vehicles,* etc. Such kinds of parameters are generally adopted as the default values in this thesis since they usually change slightly respect to different study sites.

The lane change behaviors are defined by a rule-based model in VISSIM. In this model, the critical parameter that decides whether a lane change would be conducted is the *minimum headway.* A vehicle can only changes lane when there is a distance gap arrival at the adjacent lane that is bigger than the predetermined minimum headway. Otherwise, it has to either travel continuously or stop and wait until the arrival of an enough gap for it to merge in order to follow a predefined route. In this thesis, the value of the *minimum headway* was determined by reviewing the videos.

Another noticeable parameter defined in the lane change model is the *advanced merging*, this option is selected in this thesis thus more vehicles can change lanes earlier when following their routes, as encountered in the videos.

3.1.5 Measurement of Vehicle Speed Distribution by Feature-based Tracking

Vehicle speed distribution is an important input parameter for safety simulation. While potentially more accurate, individual vehicle speeds on multiple lanes is usually difficult to measure on the field simultaneously with radar devices. Therefore, an alternative method was applied in this thesis to measure the vehicle speed, which is the video-based feature tracking.

An open sourced software project namely *Traffic Intelligence* was used to automatically track and measure the speed of the vehicles caught by the video at the study site (Jackson et al., 2013). *Traffic Intelligence* consists of a set of tools that work cooperatively for traffic data processing and analysis, including camera image calibration, feature tracking and trajectory data analysis.

The videos evaluated in this study were recorded by GoPro HD video cameras, which utilize fisheye lenses to expand the perspectives thus providing wider cover ranges. However, the fisheye effects must be removed before the video analysis to enhance the accuracy. A program contained in *Traffic Intelligence* was first applied to undistort the video images by reading the original camera matrix. Figure 3.2 shows the comparison of a sample video frame before and after distortion removal.

Figure 3.2. Sample video frame before and after distortion removal

The feature-based tracking algorithm utilizes a homography file that projects the camera image space to the real world ground plane. The homography file was created by utilizing a video frame and a corresponding aerial photo with known scale (pixels per meter). In this thesis, an aerial photo of the study site from Google® map with known scale of 0.21 pixels per meter was adopted. In total ten non-collinear visible points on the video frame were positioned on the aerial photo, thus the video image was projected to the aerial photo, and the vehicles tracked in the video were deemed to be tracked in the real world plane with their speeds. Figure 3.3 shows the points projected to the aerial photo from the video frame.

Figure 3.3. Points selected on the video frame to compute homography file

Based on the computed homography file, the feature-tracking program can be run. The predetermined number of features of each vehicle in the video were detected and tracked frame by frame until the vehicle is away from the video. In order to suppress the interference of the shadows, a mask image was created and toggled with the video image, therefore only the features within the white range of the mask image can be detected, and the shadows can be filtered out. The features that moves consistently were then grouped together to generate the trajectory file of each vehicle, and all the trajectories generated from the video were written into a database. The average speed of each vehicle can be easily read by processing their trajectories. Figure 3.4 shows the feature tracking process by *Traffic Intelligence*.

Figure 3.4. Feature tracking process by *Traffic Intelligence*

3.1.6 Model Calibration

The westbound vehicle gap distribution on the GP lane near the bus terminal was taken as the criterion to calibrate the model, because the vehicle time gap directly reflects the car following behavior. The real vehicle gaps were observed manually from the video using the *MPC player* that provides milliseconds accuracy. Because the vehicles travel westbound pass through a signalized intersection before they enter the cameras field of view, to eliminate the impact of the red time at intersection, the time gaps bigger than 5 seconds were ignored. The distribution of all the observed gaps that are smaller or equal to 5 seconds was recorded in a histogram with a sample rate of 0.3 second. Figure 3.5 shows the observed vehicle gap distribution.

In VISSIM, by inserting the *Data Collection Point* at the position where the real vehicle gaps were collected, the time when each vehicle passed the point can be reported, thus the time gaps can be easily obtained. The three parameters of the Wiedemann 74 model were adjusted such that a Chi-square test comparing the average simulated vehicle gap distribution and the observed gap distribution showed statistically matching distributions at 90% confidence level. A MATLAB program was used to automatically test the effects of different parameter sets and to run the chi-square test. The parameter set that yields the minimum average chi-square value is treated as the optimal choice and is adopted as the model parameter set (Al-Ghamdi, 2001). Figure 3.6 shows the chi-square test results of three possible parameter sets.

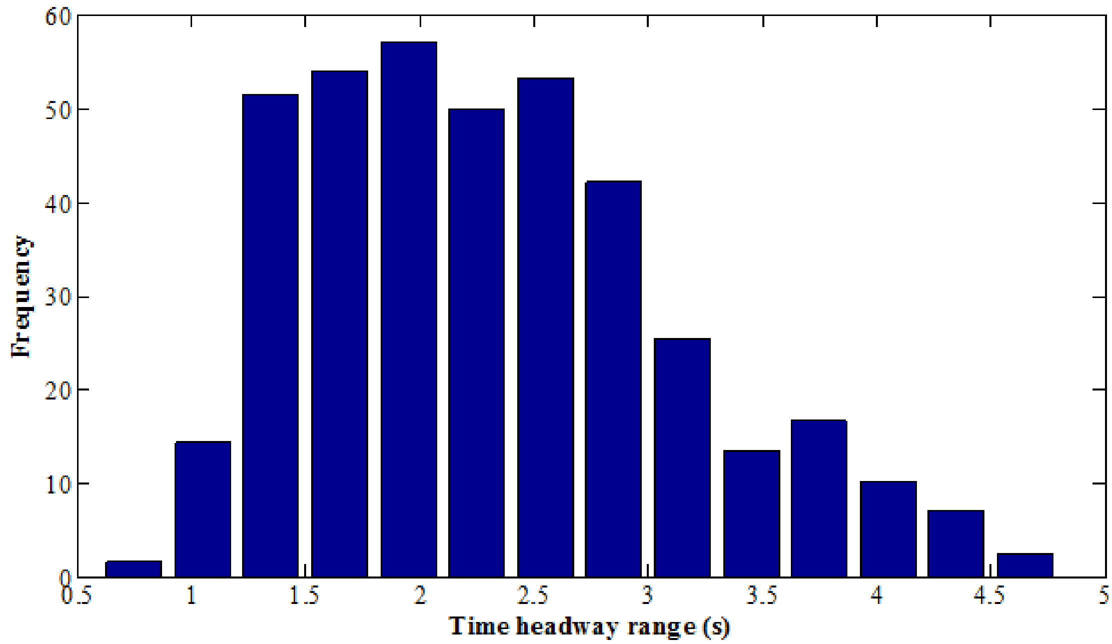


Figure 3.5. Observed vehicle gap distribution

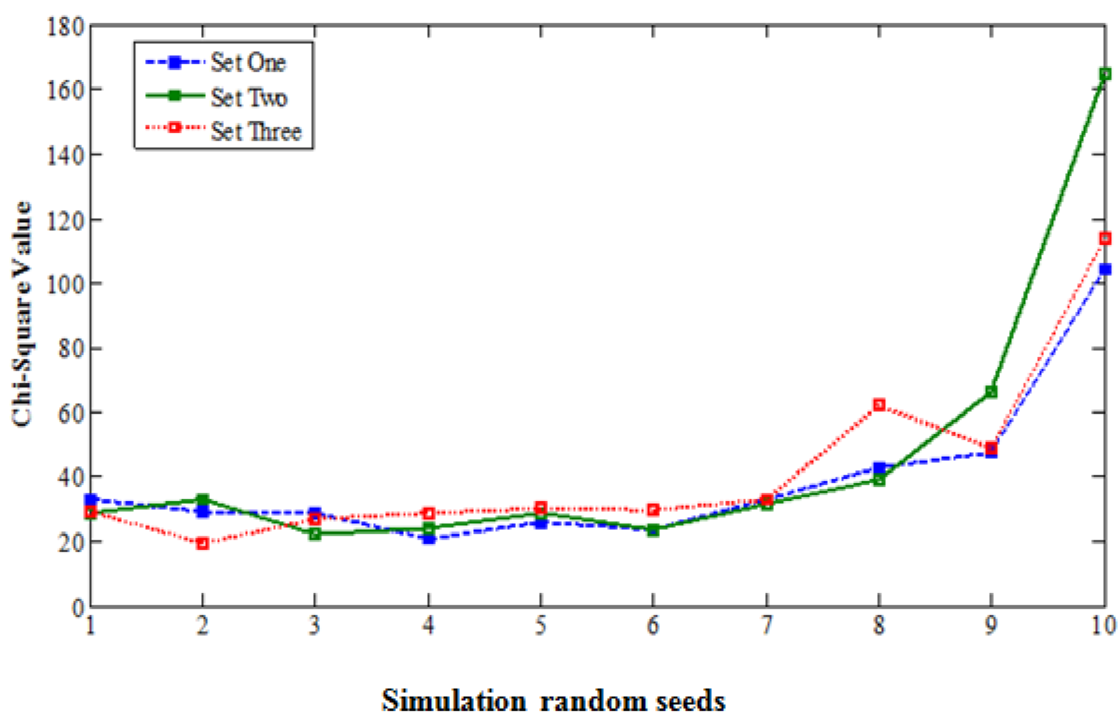


Figure 3.6. Chi-square test results of three possible parameter sets

The lateral movements of buses that merge into the main traffic from HOV lane or travel across the road when an acceptable gap was identified, was also calibrated by adjusting the parameters of the priority rule. The minimum gap time and distance headway were set to 6 seconds and 20 meters respectively, similar to the values observed in the recorded videos. It is noticeable that a part of the terminating buses changed lanes between the reserved HOV lane and the adjacent GP lane before the intersection, this behavior is reflected in the simulation model.

3.1.7 Simulation Output

VISSIM provides direct output of various kinds of simulation results. In this thesis, the vehicle delay and trajectory were analyzed to evaluate the operational efficiency and safety of the study area.

Vehicle delay data can be generated by setting *Vehicle Travel Time* on the vehicle routes. This tool contains a *Starting Point* that was set at the beginning of the vehicles' routes, and an *End Point* that was set at the end of the vehicles' route. For the vehicles that passed though the *Starting Point* and then the *End Point*, VISSIM calculates and generates their travel time delays within these two points automatically. The vehicle delays of the interested vehicle routes were then analyzed to evaluate the operational efficiency of the network.

The trajectories of all the simulated vehicles can be generated and output by VISSIM, and the trajectory data were then analyzed using SSAM to evaluate the vehicle conflicts within the network.

For each simulation, different simulation random seeds were applied, and the output results were taken the average value, this simulation setup scenario accounts for the stochastic properties of the simulation model, thus reflecting traffic more realistically.

3.2 Analyzing Vehicle Conflicts using SSAM

SSAM was used to assess the vehicle conflicts detected in the study area for safety evaluation, by utilizing the vehicle trajectory data collected from microscopic simulator VISSIM. Most studies, evaluate traffic safety through two surrogate measures, TTC and PET. Values bellow a commonly accepted threshold of either TTC or PET value indicates a higher probability of collision. SSAM is able to automatically estimate the TTC and PET values of each vehicle interaction thus to record all potential conflicts. In this study, the TTC and PET were set to 1.5 seconds and 5 seconds, respectively - the values commonly established by previous research studies (Brown, 1994; Gettman et al., 2008).

The detected conflicts were classified to three types, based on the predetermined conflict angles, namely *crossing conflict*, *lane change conflict* and *rear end conflict,* respectively. The thresholds of the conflict angles were adjusted to 2 degree and 45 degree as suggested by previous studies (Tao et al., 2015). Basically, detected conflicts at an angle less than 2 degree, it is classified as *rear end conflict*; if the conflict angle is between 2 and 45 degree, it is detected as *lane change conflict*; while the conflict angle is bigger than 45 degree, it is recorded as *crossing conflict*. However, due to the peculiarity of geometry of each study area, the link information of all the output conflicts, which was also detected by SSAM, was manually checked to properly determine their type. The three types of conflicts were recorded for subsequent comparative safety analysis.

A built-in filter of SSAM can be applied to screen out the conflicts caused by each measured movements by reading the corresponding link information. The spots where conflicts were detected can be plotted automatically on the toggled network image by positioning the VISSIM network coordinates. The conflicts of different types can be showed in different shapes or colors on the togged map to give a visual impression of the conflicts frequently occurred regions.

3.3 Summary

The methodology presented in this thesis introduces a simulation-based approach to evaluate road network safety and efficiency. To apply this methodology, the field traffic conditions are collected, and the detailed information including the field geometry, control strategy, flow and driving behavior are reviewed. Such basic information is then integrated in a VISSIM simulation model. An important model parameter, the vehicle speed distributions are obtained using a feature tracking program namely *Traffic Intelligence*. The model is properly calibrated until the output vehicle time gap distribution compared well with the field observed vehicle gap distribution by applying the chi-square test. The model output vehicle delays are reviewed for network operational efficiency analysis, and the model output vehicle trajectory files are analyzed by SSAM to determine the conflict within the study area thus giving the safety level of the site. Figure 3.7 shows the flow chart of the methodology used in this thesis for traffic safety and operational efficiency evaluation.

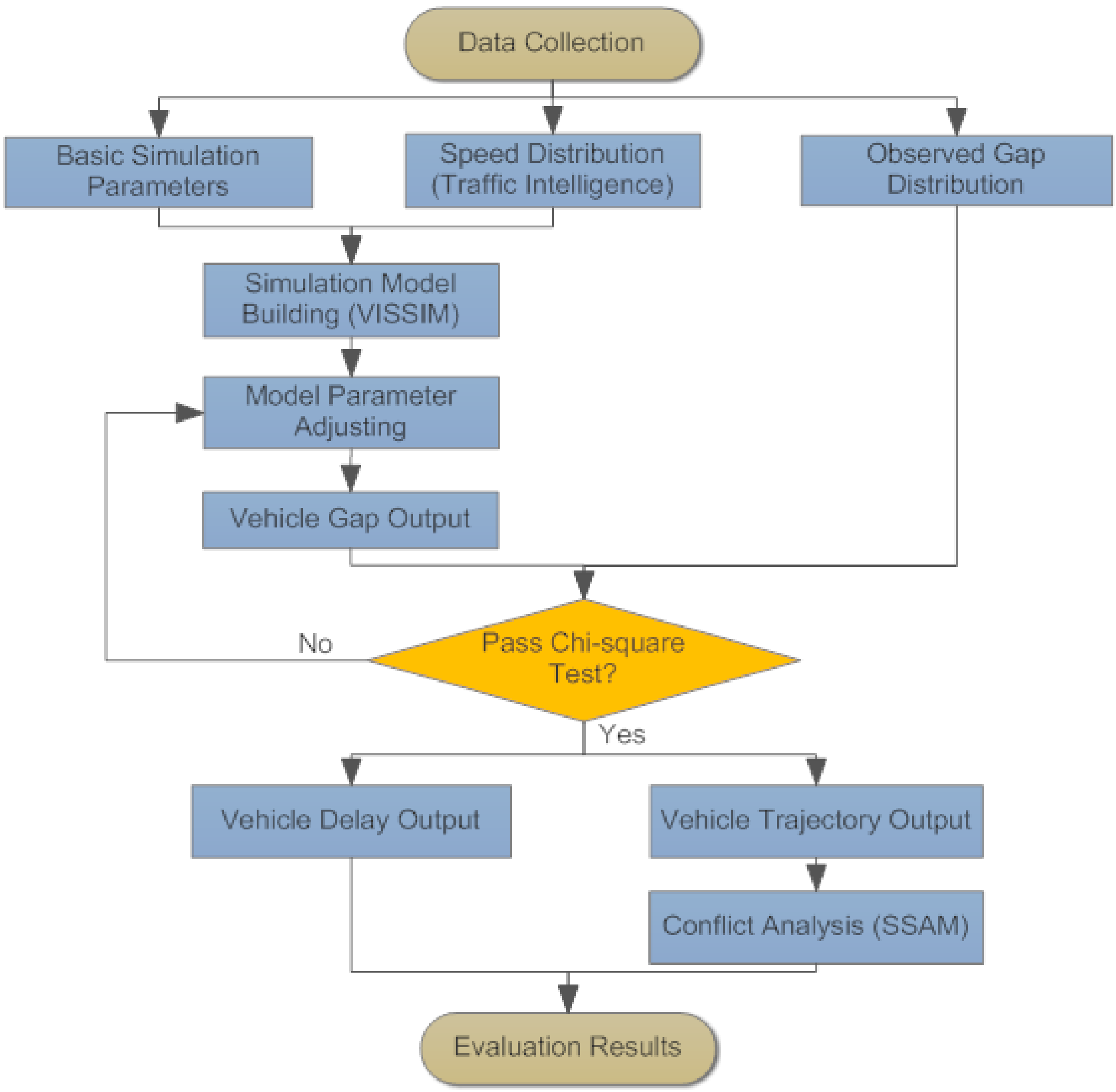


Figure 3.7. Framework of evaluation procedure

CHAPTER 4: CASE STUDY

4.1 Study Area Description

The study area used in this study is a segment of Rte-116, a suburban highway that passes across Levis area in Québec. Evaluations of traffic safety and operations were made at a specific location along the four-lane east-west arterial segment that includes one GP lane and one HOV lane, in both directions. The reserved lane running east allows buses and passenger cars with three or more passengers. The reserved lane running west allows only buses. Potential traffic safety issues have been identified due to the proximity of the public transit terminal used by buses terminating their routes or transiting the area.

The current design of this facility is such that the westbound buses arriving to or departing from the terminal have to travel across the four-lane undivided road. The terminal is located about 100 meters west upstream of the intersection with Rue des Perce Neige, which during congestion hours spills back traffic into the access path of the buses to/from the terminal. Additionally, between the bus terminal and the intersection, there is a commuter parking lot (mainly used by public transit users). Buses from both directions access the terminal on west entrance, while the egress maneuvers are accommodated through the east entrance on either direction. Figure 4.1 shows the current paths of the buses using the terminal.

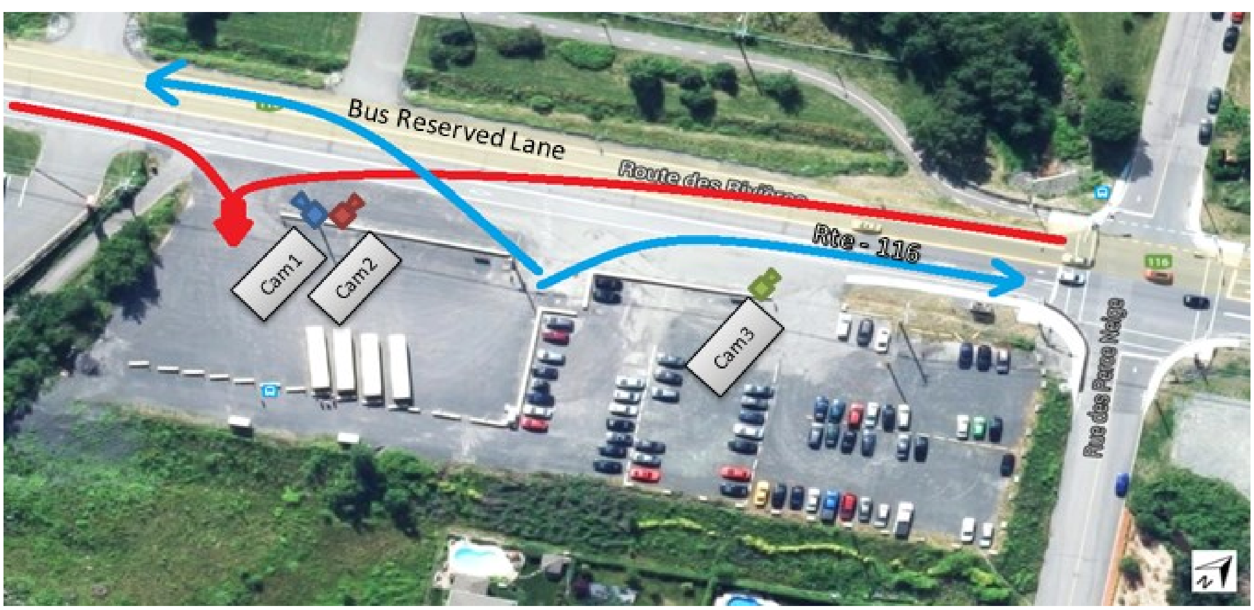


Figure 4.1. Paths of the terminating buses

4.2 Data Collection and Processing

Traffic data at this study area was collected during several sessions, in April 2014, June 2015 and September 2015. The most reliable four hours of video traffic data were used in the final analysis of this study. The traffic video feeds of vehicles accessing the terminal, the commuter parking lot and traveling along Rte-116 were collected via GoPro HD video cameras that were installed on top of extendable masts along the roadway. Camera 1 and 2 were both installed at the same location with views opposing form each other. The orientations of these two cameras were adjusted to capture east-west traffic that interacts with both access points into and out of the bus terminal. Camera 3 was installed at the proximity of the commuter parking lot entry/exit gate, to capture interactions between main road traffic and vehicles to and from the parking. The positions of the cameras are shown in Figure 4.1. Both morning and afternoon peak periods were recorded. However, preliminary evaluation of vehicular traffic interactions showed that the PM peak traffic has the highest dynamics, both from safety and traffic operations perspectives.

In order to synchronize the vehicles passed across all three recording areas, the video files recorded by each camera were merged and then trimmed to about 3.5 hours of afternoon peak period, from 2:30 pm to 6:00 pm. A probe vehicle was driven several times along the study segments with an arbitrarily selected constant speed. The known speed values were used to calibrate the post processing speed detection measuring software, namely *Traffic Intelligence*. A fixed 88-seconds cycle of the traffic signal along Rte-116 at the adjacent intersection (i.e. 40 seconds red, 40 seconds green and 4 seconds yellow) was measured in the field and used in the simulation model of the study area.

In order to build a traffic simulation model of the study area, distribution of vehicle flows and speeds were estimated by processing the video recordings. To ensure that automated video detection is accurate, a manual validation of the results was performed. In this case, the video files from each camera were processed in 5-minute increments to determine the distribution of traffic flows during the analysis period. The recordings from camera 1 were used to estimate the flow of buses accessing the terminal from both directions. The recordings from camera 2 were used to determine the flow of west/east traffic along the highway, as well as the egress flow of buses leaving the terminal. The recordings processed form camera 3 was used to estimate the interactions between the vehicles accessing the commuter parking lot and the vehicular flow on the highway.

Data from the complete afternoon period was used to determine that during 4:30 pm ~ 5:30 pm interval, the hourly traffic flow of westbound and eastbound traffic reached a maximum. During this peak hour the westbound traffic volume was approximately two times higher than that of eastbound traffic volume, it also found that during the same hour buses using the terminal exhibited a high rate of access and egress maneuvers. Table 4.1 and Table 4.2 show a classification of westbound and eastbound traffic flows along the highway, as well as the distribution of access/egress of the buses using the terminal during the 4:30 pm ~ 5:30 pm peak period. The traffic volume in these two tables distinguishes between four types of users, passenger cars (on the GP lane), buses, trucks, and reserved lane users. This separation of traffic flow was necessary to be able to model more reliably vehicle interactions in the traffic simulation model build in VISSIM (different vehicle types exhibit different driving behaviors in terms of acceleration, minimum headway, etc.).

It is noticeable that there is no westbound access parking car observed during the afternoon peak hour, instead the westbound egress parking cars achieved a high volume at 37 during this period. In other words, most commuter parking lot users access the facility from west (i.e. travelling eastbound towards Québec city) in the morning, and leave the parking lot to travel westbound in the afternoon. Similar usage behavior was detected during all three data collection sessions. While the vast majority of the parking lot is filled up in the morning by the same users, during the morning peak there are less traffic interactions due to a spread in vehicle arrivals as well as less traffic volume. These facts were used to justify the decision to evaluate traffic safety only during the more critical period, the afternoon peak hour.

Traffic Intelligence was utilized to measure the vehicle speed. The peak hour video recorded by camera 1 was used to determine speed measurement of the vehicles along the arterial. The video frames were preprocessed (undistorted) prior to running the software for speed measurements, because the wide-rage field of view feature of the cameras used also includes a fisheye effect.

Table 4.1. Observed traffic flow during the peak hour (4:30 pm ~ 5:30 pm)

Time	Vehicle Counts							
	Westbound				Eastbound			
	Car	Bus	Truck	HOV	Car	Bus	Truck	HOV
4: 30 pm - 4: 35 pm	48	1	1		36	1		2
4: 35 pm - 4: 40 pm	69	1		1	27		1	2
4: 40 pm - 4: 45 pm	72	1		1	22	1	1	3
4: 45 pm - 4: 50 pm	62				27			5
4: 50 pm - 4: 55 pm	48	6	1		50			1
4: 55 pm - 5: 00 pm	38	2		2	25			2
5: 00 pm - 5: 05 pm	64	1	1		24	2		4
5: 05 pm - 5: 10 pm	52				26	1		2
5: 10 pm - 5: 15 pm	53	2		1	24		1	4
5: 15 pm - 5: 20 pm	63	2			20			8
5: 20 pm - 5: 25 pm	43			2	26			1
5: 25 pm - 5: 30 pm	51				31		1	2
Total	663	16	3	7	338	5	4	36

Table 4.2. Access and egress vehicles during the peak hour (4:30 pm ~ 5:30 pm)

Time	Vehicle Counts							
	Westbound				Eastbound			
	Bus		Parking Car		Bus		Parking Car	
	Access	Egress	Access	Egress	Access	Egress	Access	Egress
4: 30 pm - 4: 35 pm		1		8	1		1	2
4: 35 pm - 4: 40 pm		3		2				
4: 40 pm - 4: 45 pm								
4: 45 pm - 4: 50 pm	1	1			1			1
4: 50 pm - 4: 55 pm	1	1		3				
4: 55 pm - 5: 00 pm	1				2			2
5: 00 pm - 5: 05 pm	2	1		17		1		9
5: 05 pm - 5: 10 pm				3		1		2
5: 10 pm - 5: 15 pm		3		1				
5: 15 pm - 5: 20 pm	1			1			3	
5: 20 pm - 5: 25 pm		1		1	1			1
5: 25 pm - 5: 30 pm	4	3		1	2	1		1
Total	10	14	0	37	7	3	4	18

The vehicle trajectories were detected using the feature-tracking algorithm of the video analysis software. An undistorted video frame and its corresponding aerial photography with known scale were used in the algorithm to generate the individual trajectories of each moving vehicle. The trajectory data was written into a database for speed analyzing. Calibration of the video analysis software was performed using various mask pictures to filter the shadows of the moving vehicles until the measured speeds of the probe vehicle were identical to the observed values. After the calibration of the video analysis software, the vehicle speed distributions of both westbound and eastbound vehicles were recorded every five minutes and used as simulation input parameters. The westbound and eastbound main traffic aggregated speed distributions were also recorded and are shown in Figure 4.2. This information is needed to model more realistically vehicles traveling speeds in the microscopic traffic simulator, considering that the posted speed limit at this location is 50 km/h (i.e. it can be seen that 80% of the drivers travel at speed up to 65 km/h).

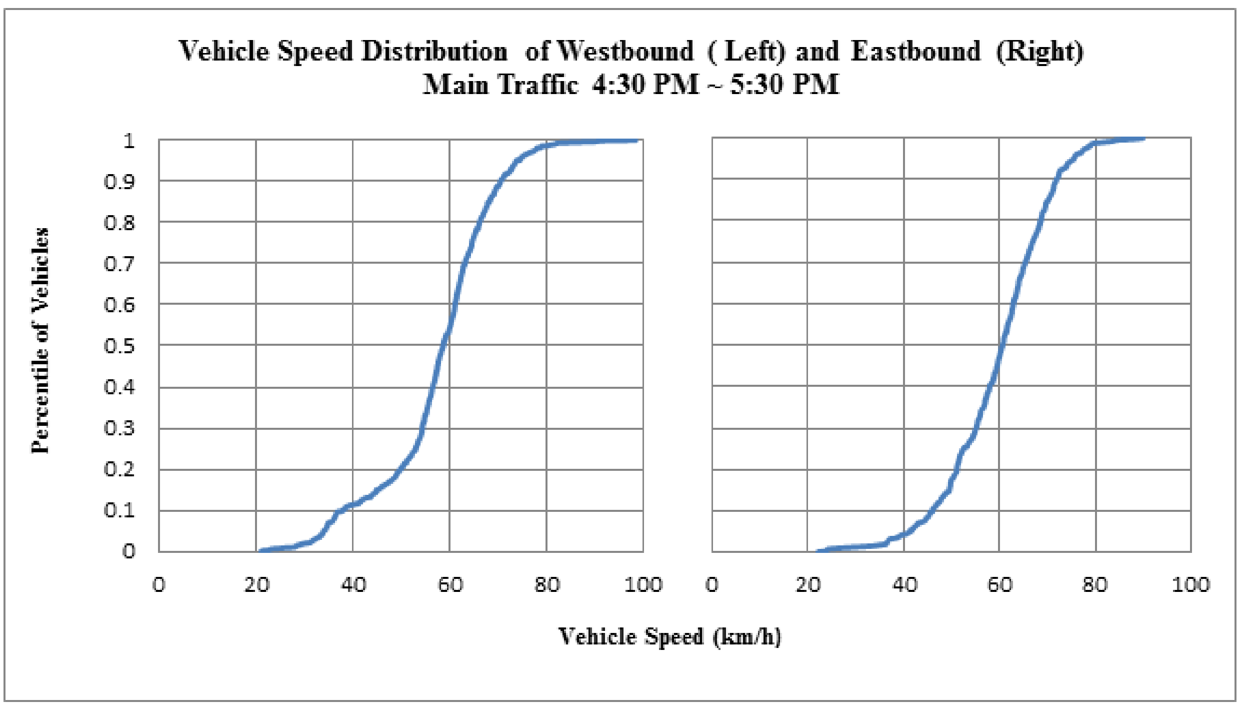


Figure 4.2. The westbound and eastbound main traffic speed distributions during peak hour

4.3 Modeling Existing Configuration and Traffic Conditions (Status Quo)

Processed data pertaining to traffic operations, geometric alignment and signal control was used to simulate the peak hour traffic using the microscopic traffic simulator VISSIM. The observed traffic flow and vehicle speed distributions were input to the microscopic simulator to represent real world driving behavior and traffic conditions. The Wiedemann 74 car following model was used as suggested by VISSIM User's Manual for urban arterial's car following behavior simulation. The model parameters were calibrated until the output vehicle time headway distribution of the westbound main traffic showed insignificant difference with that observed from camera 1, near the bus terminal.

The peak hour traffic (4:30 pm ~ 5:30 pm) was modeled to evaluate traffic safety and operations of the observed arterial segment. The existing geometry and intersection signal timing of the study area were built in VISSIM to model the current conditions (i.e. status quo). Figure 4.3 represents a snapshot of the VISSIM simulation model using the existing geometric alignment and traffic operations conditions.

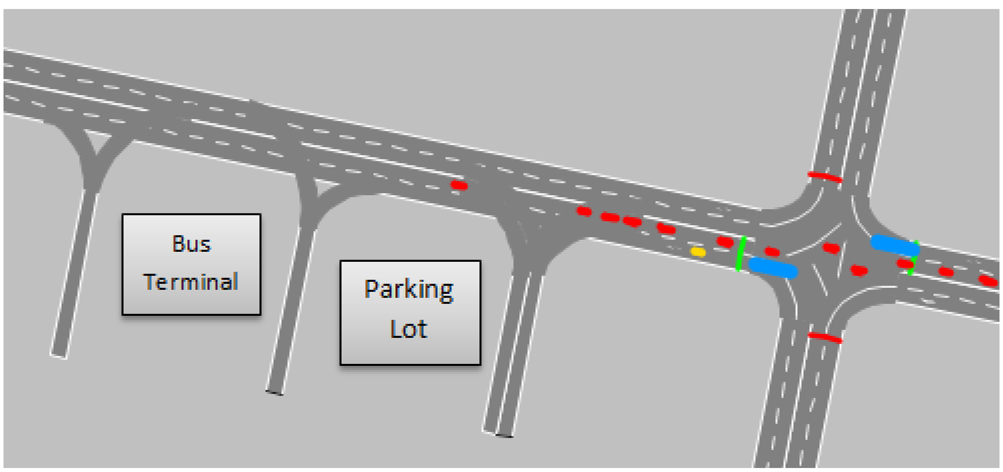


Figure 4.3. The status quo network modeled in VISSIM

To account for the effects of stochastic variation of the model's parameters (e.g. different vehicles are modeled with different preferred headways, free-flow speeds, etc.) ten different simulation random seeds were applied and the average values of observed outputs were considered for the analysis.

From the VISSIM model, the average vehicle delay (excluding signal waiting time at the upstream intersection) was measured for the three types of movements, as shown in Figure 4.4, using the *vehicle travel time measurements* tool. *Movement 1* identifies the westbound traffic on the GP lane. *Movement 2* is associated with westbound buses entering the terminal (i.e. buses merging from HOV lane into the GP lane then crossing the two eastbound lanes). *Movement 3* represents westbound buses leaving the terminal (i.e. buses that cross all the four lanes to enter the highway). Vehicle trajectory files were also output for later conflict analysis.

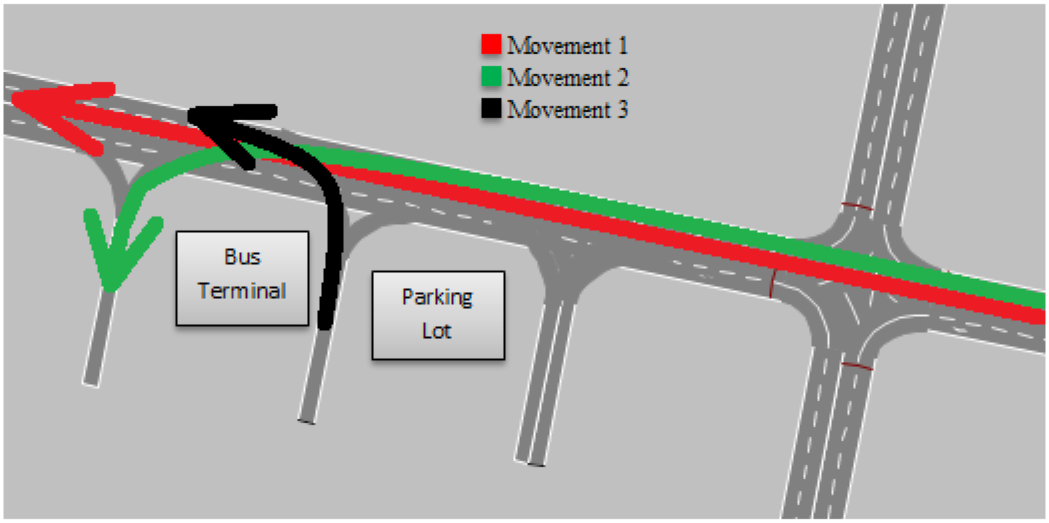


Figure 4.4. Sketch of the measured movements

In addition, the same simulation model was used to evaluate the impact on traffic operations (i.e. average vehicle delay) assuming the traffic volume increases in the future by 10%, 20% and 30% from the current values. For all three additional traffic demand volumes, the same methodology was used, 10 simulation runs with different random seeds and the average traffic delay of the three movements together with individual vehicle trajectory files were collected for comparison analysis.

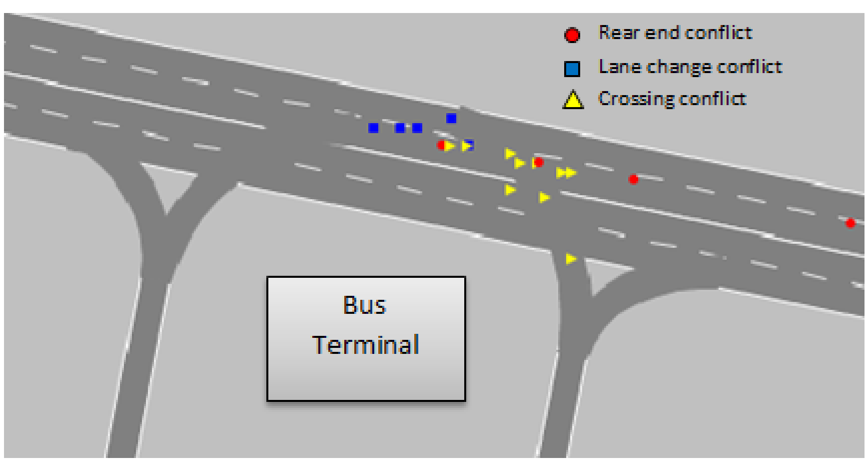


Figure 4.5. Conflicts near bus terminal plots on original network

SSAM was applied to assess the vehicle conflicts detected in the study area for safety analysis, the built-in filter of SSAM were applied to screen out the conflicts caused by each measured movements. The spots where conflicts detected were showed on the toggled network image. The conflicts of different types were showed in different shapes and colors. Figure 4.5 shows the spatial distribution of conflicts caused by measured movements near the bus terminal plotted on the original network.

4.4 Simulations of Alternative Geometry/Control Designs

The main concern related to traffic safety at the investigated study area pertains to the placement of the reserved lanes on the outside lanes. This configuration leads to multiple lanes crossing when left turns are needed and high occurrence of vehicle interactions were observed especially during congested traffic conditions, as shown in Figure 4.6.

Figure 4.6. Sample vehicle interactions at the study area

Two alternative designs have been tested to evaluate their potential to mitigate traffic safety and operations issues. One solution proposes a modification of the geometric alignment (assuming that the highway has a physical separation barrier between the directions). Another alternative proposes a traffic control strategy (i.e. a dedicated traffic control signal) with provisions for a protected left turn of the buses exiting the terminal, assuming automatic detection. Both alternatives were also modeled in VISSIM for comparison analysis with respect to traffic safety and operations.

Figure 4.7 shows the VISSIM network layout of the first proposed alternative design (i.e. the modified link geometry). In this model, westbound buses were prohibited to enter or exit the terminal/parking by crossing the highway directly. Instead, an adjacent roadway segment was inserted along the south side of bus terminal, which is directly connected to the minor road. To serve the terminating buses, ten seconds of left turning signal phase was provided at the signalized intersection on the main road.

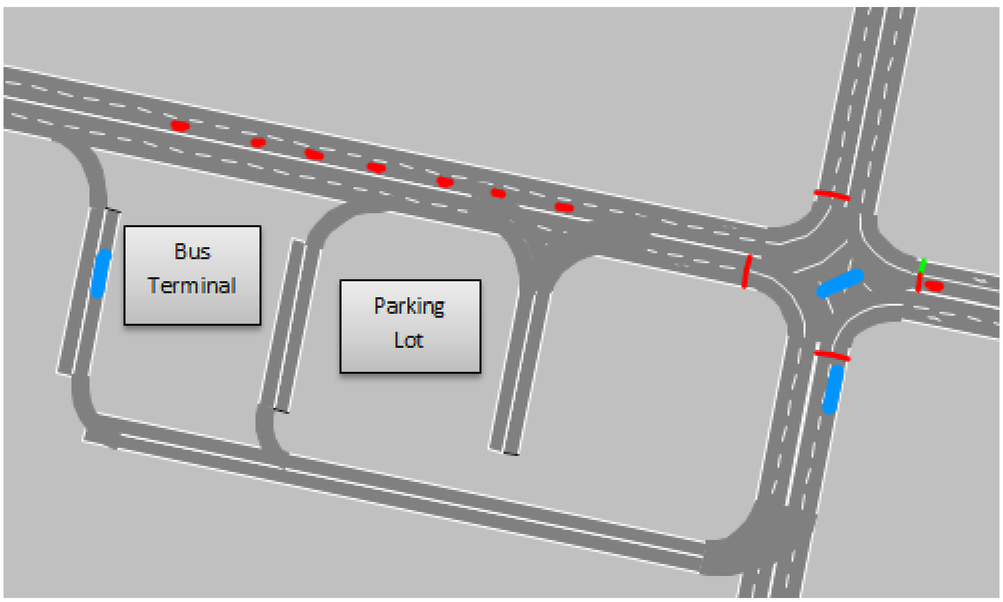


Figure 4.7. VISSIM network with modified link geometry

Similarly, for each traffic demand alternative (i.e. current condition, 10%, 20%, and 30% increments of vehicular demands), the collected peak hour vehicle flows and speed distributions were used to model the network using ten simulation random seeds. The individual vehicle trajectories and delay measurements of the same kinds of movements as evaluated in the status-quo configuration were collected and used for comparison analysis. Figure 4.8 shows a sketch of the movements evaluated for traffic safety and operations in this alternative solution.

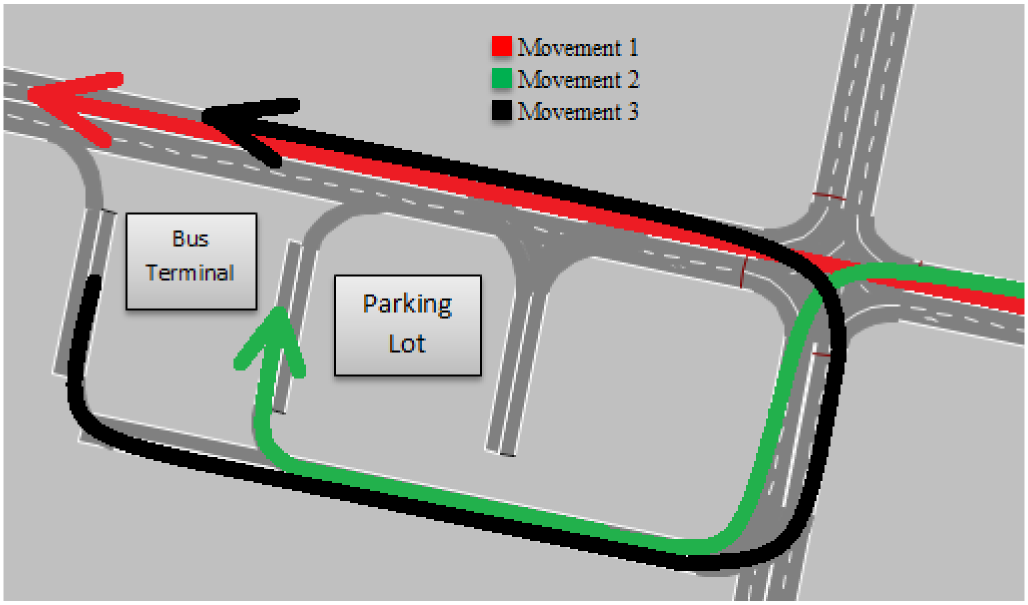


Figure 4.8. The sketch of the movements been measured for modified geometry

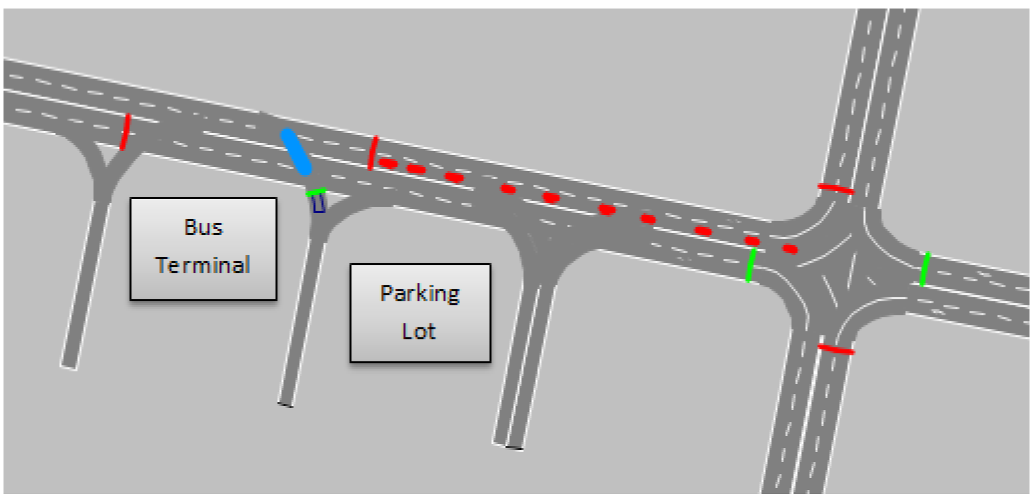


Figure 4.9. VISSIM network with modified control

Figure 4.9 shows the VISSIM network layout of the second alternative design (i.e. this solution includes a bus actuated traffic control signal). In this model, a loop detector that controls a signal set was added to the existing network. This system was used to control the westbound egress of buses as they leave the terminal. An add-on signal control model VAP was created to program the signal timing. The detector was set near the exit of the bus terminal. When bus is detected near the terminal exit, the signal indicates green for the main road to allow east-west traffic and red for the bus exit to prevent the egress buses from travelling across the road directly. When approaching buses are detected at the terminal exit, the signal turns green for them and red for traffic on the main road, which allows for protected turns. The red signal on the main road lasts for 10 seconds from the last bus detected and then turns back to green until the next detection. There is no minimum green set for the main road in order to allow the buses departing from the terminal to have a reliable schedule. The same vehicle demands previously processed were used in this simulation scenario, and the same ten different simulation random seeds were applied. The delay measurements of the same kinds of movements as shown in Figure 4.4 and trajectory data were collected for comparative analysis.

4.5 Comparison Analysis of Safety and Operation

This section presents a sensitivity analysis with respect to the effect of different levels of traffic demand (i.e. current conditions, and incremental increases by 10%, 20% and 30% of the observed vehicular volume) on existing geometric alignment and on the proposed alternative scenarios. Figure 4.10 and Figure 4.11 represent the impact of different traffic volumes on traffic operations (delay) and safety (conflicts).

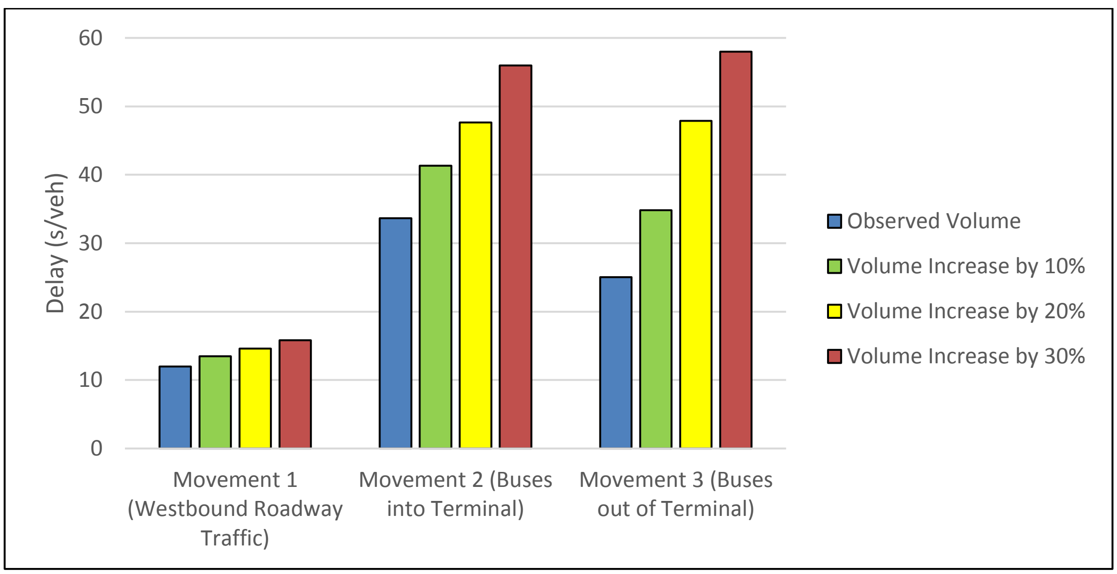


Figure 4.10. Effects of increasing traffic flow on average delay per vehicle

It can be seen that, as intuitively expected, more traffic demand leads to increased average delay. It also shows that of the three types of vehicle interactions analyzed, movements labeled 2 and 3 (i.e. associated with buses entering and leaving the terminal) are affected by significantly higher delay than the vehicles moving along the east-west roadway. This is explained by the fact that buses have to make left turns from/into the roadway, and consequently, they do not have the default right-of-way. In addition, traffic safety analysis (i.e. evaluation of vehicular interactions through the SSAM tool) shows that, for all levels of traffic demand, the majority (more than 85%) of vehicular conflicts were crossing conflicts associated with the same movements of buses that enter or leave the terminal facility. Also, lane-changing conflicts were observed between buses moving from the reserved lane into the GP lane to engage in left-turning maneuvers towards the terminal.

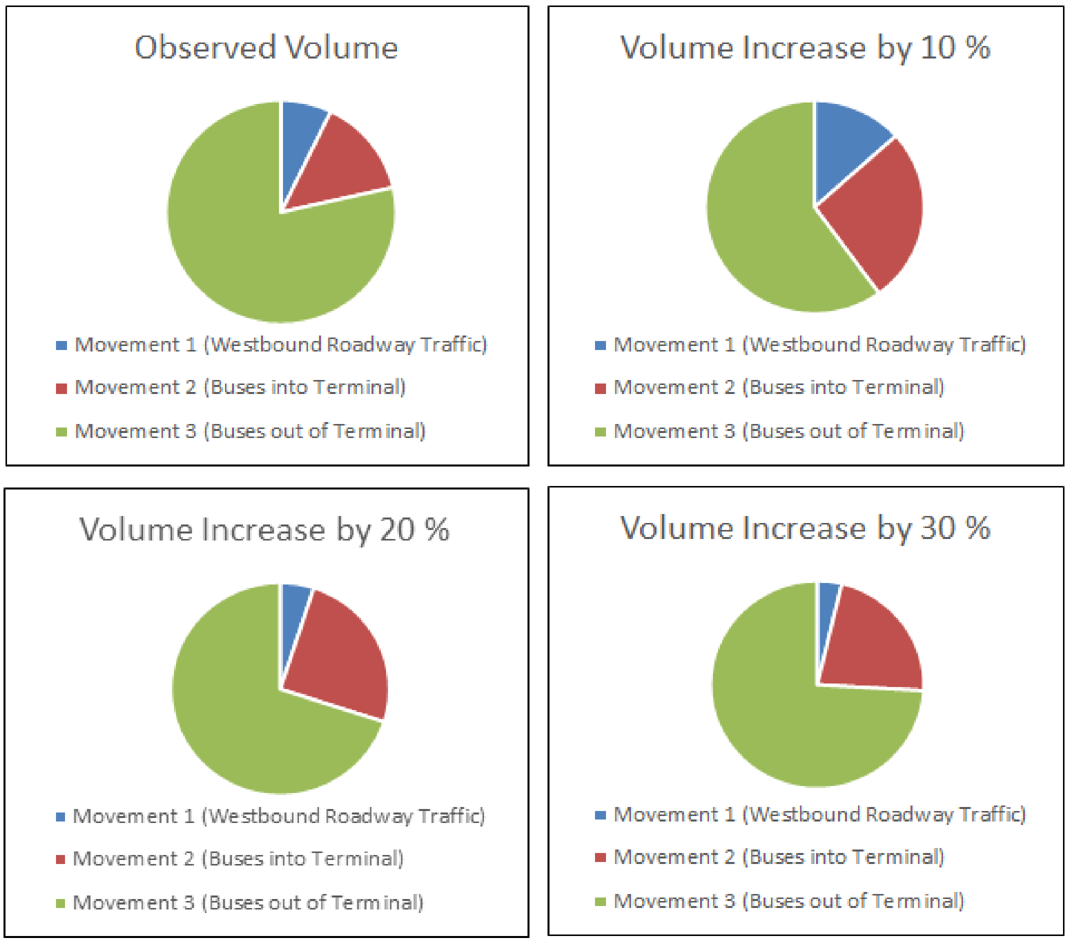


Figure 4.11. Sensitivity analysis of conflicts distribution (current configuration)

Based on the observed prevailing conditions and the sensitivity analysis with respect to increased demands, the effects of the two alternative scenarios were evaluated.

Figure 4.12 shows the effects of different traffic volumes on traffic operations (magnitude of delay) and safety (frequency of conflicts) when the first alternative scenario was used. As expected, by including a separation median between the two directions of traffic, all vehicular conflicts associated with left turn movements into and out of the terminal are eliminated. The sensitivity analysis demonstrates that traffic operations are not impacted by this design. It can be seen that, there is a minor positive effect on the average vehicular delay for movement 1 (vehicles traveling west-bound on Rte-116), but there is a significant positive effect on the average delay of buses accessing the terminal (i.e. a reduction in delay of about 85%). However, this alternative scenario brings a trade-off for the movements of buses exiting the terminal that are hindered for most traffic demands. The additional delay encountered by buses leaving the terminal is due to the fact that, for this design, the westbound egress buses must use the nearby intersection, and the traffic signal timing was not optimized to accommodate left turning buses from the minor street.

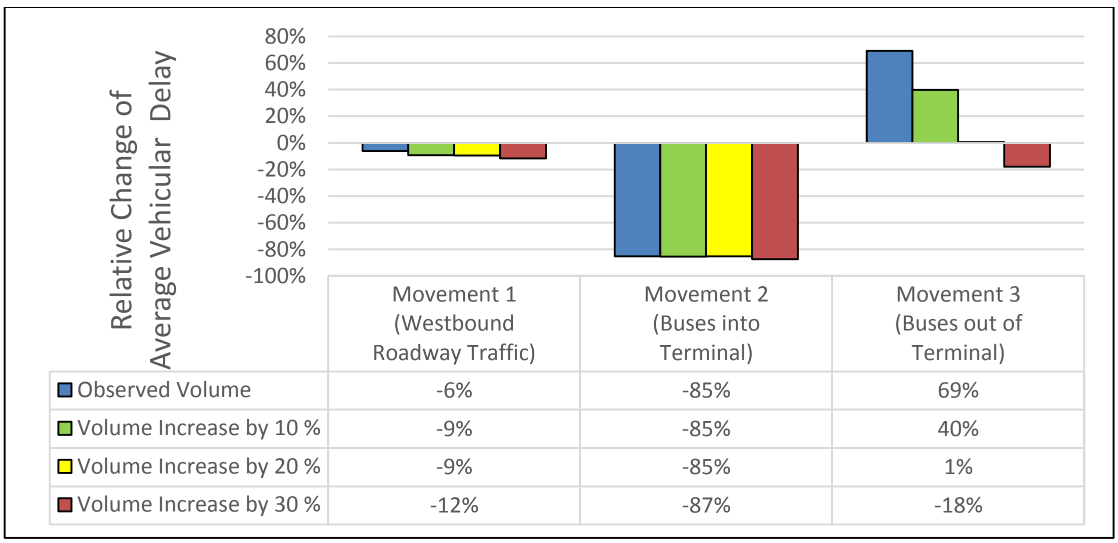
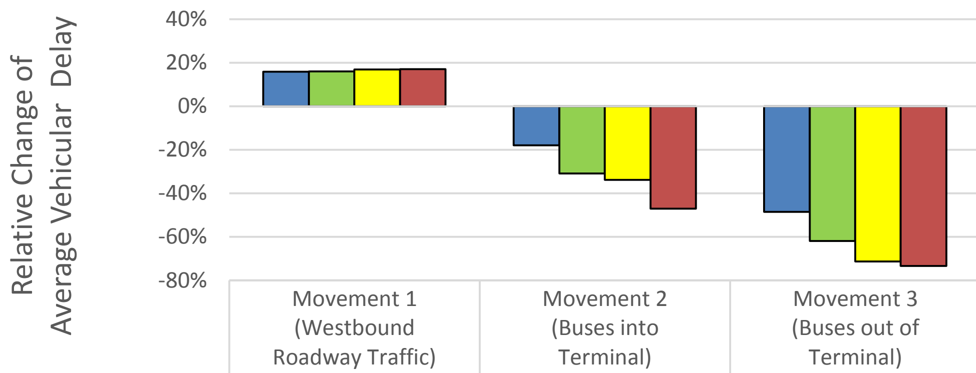


Figure 4.12. Effects of first alternative design on the average delay (separation median)

The results for the second alternative design (i.e. controlling the access/egress of buses for movements 2 and 3 via a public transit-triggered traffic control signal, in order to reduce the vehicle interactions with the buses) are shown in Figure 4.13. It can be seen that this alternative design reduces considerably the delay of buses in and out of the terminal (Movements 2 and 3), while it increases by less than 17% the delay of vehicles traveling westbound along the arterial (Movement 1).

More importantly, the vehicular conflict analysis of these results shows the elimination of the crossing conflicts (Movements 2 and 3) related to buses accessing/leaving the terminal by turning left across the HOV and GP lanes. In addition, this design has no impact on the low conflict occurrence of Movements 1 (vehicles moving westbound on the arterial).



	Movement 1 (Westbound Roadway Traffic)	Movement 2 (Buses into Terminal)	Movement 3 (Buses out of Terminal)
Observed Volume	16%	-18%	-49%
Volume Increase by 10 %	16%	-31%	-62%
Volume Increase by 20 %	17%	-34%	-71%
Volume Increase by 30 %	17%	-47%	-73%

Figure 4.13. Effects of second alternative design on the average delay (traffic control)

Several aspects of the proposed alternative designs are discussed at the end of this section. The delay of the traffic flow moving westbound on the arterial during the peak period was compared across all three simulation scenarios (i.e. current design, separation barrier, and traffic control alternative). It was found that the traffic control alternative leads to the most negative impact on the vehicular delay. In addition, conflict occurrence between the current design and the proposed traffic control design is not significantly different, due to breaking at red light, it is expected that rear end conflicts might be more severe. On the other hand, re-routing busses through the intersection via the minor street seems to be the best option, because it eliminates completely all conflicts of left turning vehicles while its impact on traffic operations might not be significant, since it can be mitigated with optimizing the traffic signal timing plan at the intersection.

To conclude, the existing geometric and traffic signal configurations show that there is a high occurrence of vehicular conflicts for left-turn buses that yield to east-west traffic to approach the terminal. It can be seen from the results that using the alternative designs, these types of conflicts are eliminated. In addition, the proposed alterations to existing alignment provide benefits for traffic operations because they reduce significantly the average vehicular delay. However, when traffic signals are used to control for protected left-turn buses that are re-routed through the adjacent intersection, an additional analysis of signal delay and optimization is necessary.

Similarly, the analysis of the measured movement 3 (i.e. westbound buses leaving from terminal) identifies a large number of crossing conflicts within the east-west traffic on the main arterial. Elimination of these conflicts can be achieved if this movement is protected either through the traffic signal sensitive to the buses present at the terminal exit, or by using the barrier separated geometry that re-routes the buses via the adjacent intersection. The results indicate that the network with alternative control design is the best for departing buses (i.e. the delay is the smallest).

As expected, the sensitivity analysis shows that an increased main arterial traffic volume leads to negative effects on the conflict frequency and average vehicular delay, regardless the design used, while the alternative designs provide elimination or significant reduction in conflicts.

CHAPTER 5: CONCLUDING REMARKS

5.1 Summary of the Road Safety Evaluation using Microsimulation

The traditional traffic safety evaluation method using statistical analysis of accidents occurrence is usually associated with some drawbacks. For example, it was shown by many studies that obtaining reliable accident data is difficult, that there is a problem of non-replicability of the crash process, and that there is a limited applicability of such methods to other existing or new facilities. These issues render such methods less effective for traffic safety evaluation of a generic road segment that needs the quick and reliable assessment.

Because of the dependency of the historical accident data, such accident analysis based methods are even inapplicable to the new alignments of traffic facilities, for example, the HOV lanes. HOV lanes exist in North America for less than thirty years, and studies showed that there are severe safety problems associated with such kind of lanes due to their geometrical or operational characteristics. However, there are very limited studies that focus on the vehicle behavior or traffic performance on HOV lanes, and the reported accident data rarely covers the detailed information needed and associated with HOV lanes.

An alternative safety analysis method for accidental statistics is the surrogate measures based traffic safety analysis. This method identifies the safety indicators that highly related to accidents and are more frequently observed on the road. Vehicular conflict is one of the most accepted surrogated safety measures and started to be frequently studied by traffic researchers. Some studies indicated that the number of conflicts within an area directly reflects the potential accidents. However, to identify a conflict even by a trained observer could be time-consuming and subjective task. It is necessary to develop a method to quantifying the conflict identification.

An efficient way to measure the conflict is utilizing a microscopic simulation model. Microscopic traffic models can generate various measureable outputs, for example, the vehicle trajectory information. A model namely SSAM was developed by FHWA and used in this thesis to analyze the vehicle trajectories output from typical microscopic simulation models, thus leading to quick and efficient assessment of the vehicle conflicts.

While microscopic simulation based conflict analysis contributes to completing the safety and operational efficiency tests of certain road facility in a relatively short time, the reliably of such method is highly dependent on the validity and precision of the provided model parameters that reflect the simulated real traffic conditions. In other words, the model input parameters; especially the driving behavior related parameters (e.g. vehicle speed, vehicle gaps, etc.) must be properly calibrated first, before the model is used for traffic safety evaluation.

Another advantage of simulation-based traffic analysis is that it provides the opportunity to test the traffic network designs or modifications not yet deployed at the analyzed study site. This characteristic significantly provides convenience to traffic practitioners who intend to modify the traffic network, and to test the modified designs without interrupt the current traffic.

To sum up, a systematic method using microscopic traffic modeling that includes the building of simulation mode for traffic safety and operation efficiency analysis is more and more accepted among the transportation researchers and practitioners, due to the readiness of the computations technology and the advancements in modeling vehicular interactions reliably.

5.2 Conclusion of the Case Study

This thesis analyzed a study area with the proposed microscopic simulation-based road safety and operational efficiency analysis procedure, which utilizes a series of analysis tools. This procedure was applied to test the safety and operational efficiency of a HOV road segment in Levis, Québec.

In this methodology, a VISSIM simulation model was built using the observed field geometry, control strategy and vehicle flows, and the vehicle priority rules and driving behaviors were calibrated to reflect correlated parameters observed on the field. An important model parameter, the vehicle speed distribution was measured by feature-based tracking using an open-sourced program namely Traffic Intelligence. The model was calibrated using the field measured vehicle gap distributions. The output delay data was used for operational efficiency analysis, and the output trajectory data was analyzed by SSAM to define the number of vehicle conflict within the study area therefore the safety of the site.

Using the proposed methodology, this thesis analyzed the peak hour safety and operational traffic conditions of the status quo and of two alternative scenarios (i.e. geometry and control designs). The analysis assessed the critical vehicular movements and the output vehicle delay and conflicts were estimated for operation and safety comparison. The results indicate that the existing network configuration exhibits significant safety issues due to the crossing conflicts along the path of buses approaching the terminal across the four-lane arterial road. It was shown that one of the investigated alternative designs may enable the terminating buses to travel on different path to efficiently eliminate critical vehicular conflict. In addition, it was shown that the alternative control design can be used to reduce the bus delay by giving priority to public transit.

5.3 Future Works

In this study, the safety of a HOV lane segment was tested using a microsimulation model. SSAM was applied to detect and quantify the vehicle conflict by directly reading the simulated vehicle trajectory data. By defining the TTC and PET value, the conflict can be identified rapidly, therefore the safety analysis of a study area can be conducted within a short time.

The model is properly adjusted to reflect the real traffic conditions on the field, and the model input is limited to every five minutes, in other words, the conflict is measured every five minutes with the real time vehicle speed distribution and flow. In addition, the stochastics were added by changing the simulation random seeds for ten times, and the results were taken as the average value. These conditions ensured the accuracy of the analysis results. However, the number of simulated conflicts should be validated with those observed of the field. In the future, a trained observer should review all the vehicle interactions in the videos within the same peak hour, and using the same TTC and PET thresholds to determine the real conflicts. Because the determination of the TTC and PET value for each observed vehicle interaction is a time-consuming event, the validation process can be a long and tedious process. Automatic detection of conflict parameters can also be employed, using a better placement of the cameras and enhanced video analysis algorithms.

REFERENCES

Aghabayk, K., Sarvi, M., Young, W., & Kautzsch, L. (2013). A novel methodology for evolutionary calibration of vissim by multi-threading. Paper presented at the *Australasian Transport Research Forum,* 1-15.

Al-Ghamdi, A. S. (2001). Analysis of time headways on urban roads: Case study from riyadh. *Journal of Transportation Engineering, 127*(4), 289-294.

Amundsen, F., & Hyden, C. (1977). The swedish traffic conflict technique. Paper presented at the *Proceedings of First Workshop on Traffic Conflicts, Institute of Transport Economics, Oslo,* 1-5.

Arasan, V. T., & Vedagiri, P. (2010). Microsimulation study of the effect of exclusive bus lanes on heterogeneous traffic flow. *Journal of Urban Planning and Development, 136*(1), 50-58.

Archer, J. (2000). Developing the potential of micro-simulation modelling for traffic safety assessment. Paper presented at the *Proceedings of the 13th ICTCT Workshop, (Vol. 44)*.

Archer, J. (2004). Methods for the assessment and prediction of traffic safety at urban intersections and their application in micro-simulation modelling. *Royal Institute of Technology*.

Barceló, J. (2010). *Fundamentals of traffic simulation* Springer.

Bauer, J. I., McKellar, C. A., Bunker, J. M., & Wikman, J. (2005). High occupancy vehicle lanes-an overall evaluation including brisbane case studies.

Brown, G. R. (1994). Traffic conflicts for road user safety studies. *Canadian Journal of Civil Engineering, 21*(1), 1-15.

Coifman, B., Beymer, D., McLauchlan, P., & Malik, J. (1998). A real-time computer vision system for vehicle tracking and traffic surveillance. *Transportation Research Part C: Emerging Technologies, 6*(4), 271-288.

Cunto, F., & Saccomanno, F. F. (2008). Calibration and validation of simulated vehicle safety performance at signalized intersections. *Accident Analysis & Prevention, 40*(3), 1171-1179.

Davis, G., & Swenson, T. (2004). Field study of gap acceptance by left-turning drivers. *Transportation Research Record: Journal of the Transportation Research Board,* (1899), 71-75.

Dowling, R., Skabardonis, A., Halkias, J., McHale, G., & Zammit, G. (2004). Guidelines for calibration of microsimulation models: Framework and applications. *Transportation Research Record: Journal of the Transportation Research Board,* (1876), 1-9.

El-Basyouny, K., & Sayed, T. (2013). Safety performance functions using traffic conflicts. *Safety Science, 51*(1), 160-164.

Elvik, R. (2008). The predictive validity of empirical bayes estimates of road safety. *Accident Analysis & Prevention, 40*(6), 1964-1969.

ETSC. (2001). Transport safety performance indicators. *European Transport Safety Council, ISBN 90-76024-11-1, Brussels*.

Fan, R., Yu, H., Liu, P., & Wang, W. (2013). Using VISSIM simulation model and surrogate safety assessment model for estimating field measured traffic conflicts at freeway merge areas. *IET Intelligent Transport Systems, 7*(1), 68-77.

Fellendorf, M. (1994). VISSIM: A microscopic simulation tool to evaluate actuated signal control including bus priority. Paper presented at the *64th Institute of Transportation Engineers Annual Meeting,* 1-9.

Fellendorf, M., & Vortisch, P. (2001). Validation of the microscopic traffic flow model VISSIM in different real-world situations. Paper presented at the *Transportation Research Board 80th Annual Meeting*.

Fuhs, C., & Obenberger, J. (2002). Development of high-occupancy vehicle facilities: Review of national trends. *Transportation Research Record: Journal of the Transportation Research Board,* (1781), 1-9.

Gettman, D., & Head, L. (2003). Surrogate safety measures from traffic simulation models. *Transportation Research Record: Journal of the Transportation Research Board,* (1840), 104-115.

Gettman, D., Pu, L., Sayed, T., & Shelby, S. G. (2008). *Surrogate Safety Assessment Model and Validation: Final Report* (No. FHWA-HRT-08-051).

Golob, T. F., Recker, W. W., & Levine, D. W. (1989). Safety of high-occupancy vehicle lanes without physical separation. *Journal of Transportation Engineering, 115*(6), 591-607.

Guin, A., Hunter, M., & Guensler, R. (2008). Analysis of reduction in effective capacities of high-occupancy vehicle lanes related to traffic behavior. *Transportation Research Record: Journal of the Transportation Research Board,* (2065), 47-53.

Hauer, E., & Garder, P. (1986). Research into the validity of the traffic conflicts technique. *Accident Analysis & Prevention, 18*(6), 471-481.

Hayward, J. (1971). *Near misses as a measure of safety at urban intersections* Pennsylvania Transportation and Traffic Safety Center.

Huang, F., Liu, P., Yu, H., & Wang, W. (2013). Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections. *Accident Analysis & Prevention, 50*, 1014-1024.

Hydén, C. (1987). The development of a method for traffic safety evaluation: The swedish traffic conflicts technique. *Bulletin Lund Institute of Technology, Department,* (70).

Jackson, S., Miranda-Moreno, L., St-Aubin, P., & Saunier, N. (2013). Flexible, mobile video camera system and open source video analysis software for road safety and behavioral analysis. *Transportation Research Record: Journal of the Transportation Research Board,* (2365), 90-98.

Jang, K., Chung, K., Ragland, D., & Chan, C. (2009). Safety performance of high-occupancy-vehicle facilities: Evaluation of HOV lane configurations in california. *Transportation Research Record: Journal of the Transportation Research Board,* (2099), 132-140.

Kim, S., Kim, W., & Rilett, L. (2005). Calibration of microsimulation models using nonparametric statistical techniques. *Transportation Research Record: Journal of the Transportation Research Board,* (1935), 111-119.

Laureshyn, A., Svensson, Å., & Hydén, C. (2010). Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and first implementation. *Accident Analysis & Prevention, 42*(6), 1637-1646.

Menendez, M., & Daganzo, C. F. (2007). Effects of HOV lanes on freeway bottlenecks. *Transportation Research Part B: Methodological, 41*(8), 809-822.

Menneni, S., Sun, C., & Vortisch, P. (2008). Microsimulation calibration using speed-flow relationships. *Transportation Research Record: Journal of the Transportation Research Board,* (2088), 1-9.

Older, S. J., & Spicer, B. R. (1976). Traffic conflicts—a development in accident research. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 18*(4), 335-350.

Panwai, S., & Dia, H. (2005). Comparative evaluation of microscopic car-following behavior. *IEEE Transactions on Intelligent Transportation Systems, 6*(3), 314-325.

Park, B., & Qi, H. (2005). Development and evaluation of a procedure for the calibration of simulation models. *Transportation Research Record: Journal of the Transportation Research Board,* (1934), 208-217.

Park, B., & Schneeberger, J. (2003). Microscopic simulation model calibration and validation: Case study of VISSIM simulation model for a coordinated actuated signal system. *Transportation Research Record: Journal of the Transportation Research Board,* (1856), 185-192.

Parker Jr, M., & Zegeer, C. V. (1989). *Traffic Conflict Techniques for Safety and Operations.Observers Manual* (No. FHWA-IP-88-027).

Persaud, B. N., Retting, R. A., Garder, P. E., & Lord, D. (2001). Observational BeforeAfter study of the safety effect of US. Paper presented at the *Transportation Research Board, National Research Council*.

Qi, X., Wu, G., Boriboonsomsin, K., & Barth, M. J. (2015). Empirical study of lane-changing characteristics on high-occupancy-vehicle facilities with different types of access control based on aerial survey data. *Journal of Transportation Engineering, 142*(1), 04015034.

Saunier, N., & Sayed, T. (2006). A feature-based tracking algorithm for vehicles in intersections. Paper presented at the *The 3rd Canadian Conference on Computer and Robot Vision (CRV'06),* 59-59.

Shahrokhi Shahraki, H. (2013). *An Efficient Soft Computing Based Method for Calibration of Vehicular Microscopic Simulation Models* (Doctoral dissertation, Concordia University).

Sobhani, A., Young, W., & Sarvi, M. (2013). A simulation based approach to assess the safety performance of road locations. *Transportation Research Part C: Emerging Technologies, 32*, 144-158.

Srinivasan, S., Haas, P., Alluri, P., Gan, A., & Bonneson, J. (2016). Crash prediction method for freeway segments with high occupancy vehicle (HOV) lanes. Paper presented at the *Transportation Research Board 95th Annual Meeting,* (16-6333).

Svensson, Å. (1998). *A Method for Analysing the Traffic Process in a Safety Perspective*.

Tao, H., Foomani, M. G., & Alecsandru, C. (2015). A two-step microscopic traffic safety evaluation model of reserved lanes facilities: An arterial case study. Paper presented at the *Transportation Research Board 94th Annual Meeting,* (15-3635).

Uno, N., Iida, Y., Itsubo, S., & Yasuhara, S. (2002). A microscopic analysis of traffic conflict caused by lane-changing vehicle at weaving section. Paper presented at the *Proceedings of the 13th Mini-Euro Conference" Handling Uncertainty in Transportation Analysis of Traffic and Transportation Systems,* 143-148.

Vissim, P.6.0 user manual, 2014 PTV AG. *Karlsruhe, Germany*.

Wiedemann, R. (1974). Simulation des strassenverkehrsflusses.

Young, W., Sobhani, A., Lenné, M. G., & Sarvi, M. (2014). Simulation of safety: A review of the state of the art in road safety simulation modelling. *Accident Analysis & Prevention, 66*, 89-103.

Zheng, L., Ismail, K., & Meng, X. (2014). Traffic conflict techniques for road safety analysis: Open questions and some insights. *Canadian Journal of Civil Engineering, 41*(7), 633-641.

Zhou, S., Li, K., Sun, J., & Han, P. (2010). Calibration and validation procedure for intersection safety simulation using SSAM and VISSIM. Paper presented at the *Proceedings of the 10th International Conference of Chinese Transportation Professionals*.