Development of a Surrogate Safety Assessment Framework Incorporating Traffic Simulator, Vehicle Dynamics, Driver Warning, GPS/INU, and V2V/V2I

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Jaehyun (Jason) So

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AUTHOR

The dissertation has been read and approved by the examining committee:

Byungkyu (Brian) Park

Advisor

Michael J. Demetsky

William T. Scherer

John S. Miller

Michael D. Fontaine

Accepted for the School of Engineering and Applied Science:

Dean, School of Engineering and Applied Science

August

2013

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ABSTRACT

This dissertation developed an integrated surrogate safety assessment framework to proactively assess traffic safety using realistic vehicle trajectories as well as potential positioning errors and V2V/V2I communication delays on the vehicle safety applications. To this end, the following simulators were developed and integrated into the surrogate safety assessment framework: 1) vehicle dynamics model-integrated traffic safety simulation environment, 2) V2V/V2I communication delays simulator, 3) GPS/INU positioning error simulator, and 4) driver warning generator.

First, a vehicle dynamics model (i.e., CarSim) was integrated with a microscopic traffic simulation model (i.e., VISSIM) for a surrogate safety assessment, based on more realistic vehicle trajectories. This idea was initiated from the fact that the microscopic traffic simulation model can generate various traffic situations and the vehicle dynamics model has an extensive capability of modeling the vehicle dynamics including pitch, yaw, and roll and generating realistic vehicle trajectories. To take advantage of these capabilities, the two simulation models (i.e., VISSIM and CarSim) were integrated and used to estimate the number of traffic conflicts. In addition, a driver aggressiveness model derived from the Next Generation Simulation (NGSIM) project's lane change vehicle trajectories was incorporated to the lane change vehicles in VISSIM. The resulting VISSIM vehicle trajectories were processed through CarSim to account for the vehicle dynamics and the traffic conflicts were identified through the Surrogate Safety Assessment Model (SSAM). The VISSIM-CarSim integrated simulation environment

resulted in 9.5% fewer traffic conflicts compared with the existing VISSIM-only approach.

Second, the results of the two conflict estimation approaches, that is, from the proposed approach (i.e., VISSIM-CarSim) and the existing approach (i.e., VISSIM-only), were analyzed to estimate their correlation with the actual traffic crashes. These correlations were then used to assess and compare the effectiveness of these two approaches for assessing traffic safety. This correlation analysis was based on the number of traffic crashes and traffic conflicts from two freeway corridors (i.e., I-495 and SR-267) during a peak hour (i.e., from 5 P.M. to 6 P.M.). This analysis showed that the traffic conflicts obtained from the proposed approach exhibits a stronger correlation (i.e., 0.72 of correlation coefficient) with traffic crashes than the existing approach did (i.e., 0.61 of correlation coefficient). Both traffic conflicts computed for both approaches showed a statistically significant relationship with the actual traffic crashes. In addition, a cross-validation test on the confidence intervals of the correlation coefficients showed that the correlation coefficients have very tight confidence intervals (i.e., 0.02 for both cases). This indicates that traffic conflict can be used as a traffic safety estimator but also the newly developed vehicle dynamics model-integrated traffic safety simulation environment was found to be a superior, valid alternative for assessing the surrogate safety.

In addition, the V2V/V2I communication connection probability model reflecting that communication performance can be degraded according to the number of transceivers (i.e., vehicles) in a specific area and the distance between transceivers was developed. The GPS/INU simulator, which simulates the VISSIM X and Y coordinates according to the assumed positioning system corresponding to the positioning accuracy, was also developed. When the driver warnings are triggered in VISSIM, the V2V/V2I communication delays simulator potentially delays the warnings, and the GPS/INU simulator provides GPS/INU erroneous vehicle trajectories on the fly. A perception-reaction time (PIEV) was adopted in the middle of driver warnings and actual vehicle response (i.e., deceleration) to reflect a realistic driver response.

Consequently, although the driver warnings reduced 28% to 35% of dangerous conditions under no-communication delays and positioning errors, the communication delays degraded the effect of driver warnings ranging from 8% to 15%. In addition, the effectiveness of driver warnings based on various GPS/INU technologies improves as the accuracy level of the GPS/INU devices increases. Therefore, two important findings are highlighted: 1) the probability of false alarm would decrease as the high-accuracy positioning system is deployed in the vehicle safety applications, and 2) the traffic safety estimation result can be different according to the accuracy level of the positioning systems assumed. Accordingly, this dissertation research conveys to the traffic safety research community that potential positioning errors need to be considered when the traffic safety is estimated under advanced vehicle safety applications scenarios (e.g., Connected Vehicles applications)

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Chapter 1

INTRODUCTION

1. Research Motivations

Today, traffic safety is considered a major social issue due to the millions of crashes every year. According to the 2009 National Highway Traffic Safety Administration (NHTSA) report [1], 30,797 deaths, 1,517,000 injuries, and $230.6 billion in economic loss were due to traffic crashes throughout the United States. In 2012, NHTSA reported that motor vehicle traffic crashes were the leading cause of death for those between 13 and 30 years of age [2]. Given such circumstances, several research efforts have been made to enhance traffic safety.

Traditionally, statistical models have been popularly adopted to estimate the expected number of crashes based on traffic volume (e.g., average daily traffic), geometry, and traffic control features [3-16]. Non-parametric modeling approaches such as Artificial Neural Network (ANN) [17], Support Vector Machines (SVM) [18], and Radial Basis Function (RBF) [19] have also been used to explain the relationship between traffic crashes and potential factors due to their advantages for mapping causal models where the relationship between input and output is non-linear, ambiguous, and/or unknown [20-23].

Despite all the research efforts on safety modeling, accurate predictions of traffic crashes and crash rates are still challenging due to the infrequent nature of crashes. In other words, traffic crashes are too rare to be used as an indicator of the traffic safety assessment for the traffic operational strategies. On the contrary, traffic conflicts (i.e., near-crashes) are more frequent than crashes, and can be readily observed in the traffic simulation models as well as in the real field. Therefore, the traffic conflict technique, which estimates traffic safety based on surrogate safety measures, has been highlighted as a useful tool that shows the likelihood of a traffic crash in a given area. In addition, as the traffic conflict technique study requires a sizeable observation to obtain vehicle trajectories, the microscopic traffic simulation models have been commonly used to generate vehicle trajectories. The data extraction capability of the microscopic traffic simulation models has provided many advantages in the development of new surrogate safety measures [24-28], the safety impact assessment of traffic alternatives [29-33], and the validation of traffic conflict [34-37].

Yet the representation of crash probability using the surrogate safety measures continues to be disputed as the surrogate measures depend heavily on how realistic the vehicle trajectory extracted from the microscopic traffic simulation model is, especially in untried conditions. Existing microscopic traffic simulation models such as VISSIM [38], AIMSUN [39], and PARAMICS [40] are limited in modeling lateral vehicle movements while those movements such as lane change and lane departure are commonly observed on roadways, more frequently in merging/diverging sections. VISSIM 5.40 [38], the newest version of VISSIM; and one of the widely used microscopic traffic simulation models in the transportation engineering field, complemente the lateral behavior and enables vehicles to adjust their own lateral position within a lane. However, each vehicle travels in its initially assigned lateral position unless additional maneuvers such as a lane change are required; this happens even at a curved section, where the vehicle maneuvering is affected by a centrifugal force. In addition, during a lane-change, a vehicle transitions linearly from the current lane to the adjacent lane regardless of the vehicle's kinematic characteristics including speed and acceleration/deceleration rates. Figure 1 shows an example plot of a vehicle lane change trajectory obtained from the latest VISSIM version 5.40 and the Next Generation Simulation (NGSIM) data. As the figure indicates, a vehicle changes the lane along a straight line in VISSIM while the lane change vehicle trajectories collected for the NGSIM project show a curved shape as opposed to a straight line. Therefore, the vehicle's lateral movements in the traffic microscopic simulation models do not show realistic vehicle trajectories.

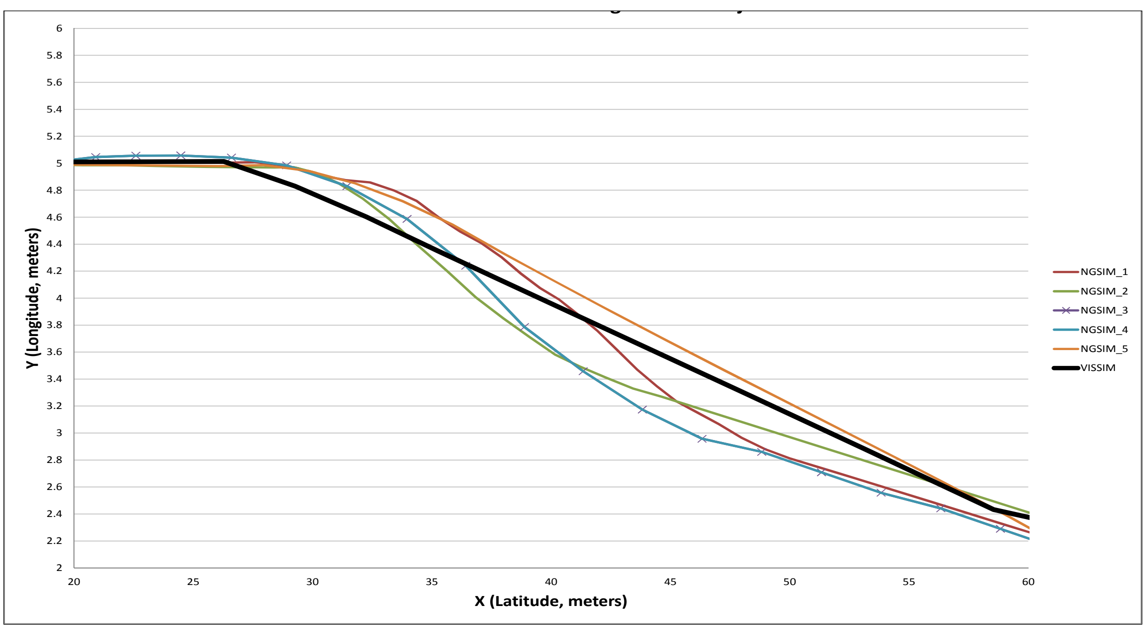


Figure 1. Lane change trajectory comparison with VISSIM 5.40 and NGSIM

The unrealistic vehicle trajectories can generate skewed surrogate safety measures used to identify traffic conflicts. Unrealistic results also undermine the credibility of the traffic conflicts-based safety estimation. Therefore, there is a need to develop a more advanced traffic simulation environment that can generate realistic vehicle trajectories for more effective traffic safety assessment studies.

In addition, despite the wide use of traffic conflicts as a traffic safety estimator, the relationship between the number of conflicts and the frequency of crashes needs further research. In other words, traffic crashes and conflicts seem to be related, but their direct relationship is difficult to determine. Some previous studies [25, 34, 41-44] have concluded that traffic conflicts are a significant factor representing the probability of traffic crashes. Other studies [45-48] have indicated that traffic crashes and conflicts could be determined by location, time, and human factors as well as traffic conflicts affected by traffic and geometric characteristics. Therefore, in order to ensure the potential of this integrated simulation environment as a crash prediction tool, it should be investigated to determine whether a significant correlation exists between the number of conflicts estimated from the developed simulation environment and actual traffic crashes collected within the same network.

In the past a few decades, many safety applications have been studied and developed by taking advantage of the Global Positioning System (GPS) [49] and the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technology. In Particular, in the United States, since the Connected Vehicles research program [50] was initiated, various studies have been conducted to develop safety applications as well as to investigate and improve its performance regarding several state-of-the-art safety systems, namely, the Cooperative Intersection Collision Avoidance System (CICAS) [51-53], the Forward Collision Warning system (FCW) [54-58], the Cooperative Adaptive Cruise Control (CACC) [59-61], and the lane change and lane departure warning system (LCW) [62, 63].

However, existing safety performance assessment studies have been conducted based simply on the assumption of a perfect vehicle positioning data and communication success, although it is unlikely in reality due to the imperfect nature of radio signals and the surrounding obstructions (e.g., buildings and mountains). Since GPS was introduced, more advanced positioning systems such as a Differential Global Positioning System (DGPS) [64] and Wide-Area DGPS (WADGPS) [65] were subsequently developed. In addition, for the blackout of GPS, an Inertial Navigation Unit (INU) [66], which measures the position, orientation, and velocity of moving object by motion sensors (i.e., accelerometer) and rotation sensors (i.e., orthogonal gyroscopes), was recently introduced and used as a GPS supporting device. Despite the advances in positioning systems, positioning errors are still prevalent. The current gaps in the existing positioning system (i.e., 1.5 to 4 meters [65]) may not significantly affect the general traffic applications such as travel time study and route guidance system, but they can be crucial to the traffic safety and operations applications that require a lane-distinguished accuracy level. Even a relatively small error (e.g., a few meters in positioning error) can significantly affect vehicle warning systems such as CICAS, FCW, CACC, and LCW due to false alarms. In other words, given that the skewed surrogate values based on the positioning errors can increase the likelihood of false alarms, it could lead to not only dangerous conditions but also decreases in the driver's compliance rate in response to the warning messages. Obviously, this does not help traffic safety on US highways.

Likewise, given that the basic safety data including vehicle positioning would be transmitted to adjacent vehicles and/or infrastructures based on the Connected Vehicles (CV) technology environment [67], the quality of communication can be another factor that affects safety. In terms of vehicular communication, some studies [68-70] have investigated the performance of a vehicular wireless network such as Wireless Access in Vehicular Environments (WAVE)/Dedicated Short-Range Communications (DSRC) standard [71, 72], through field tests or under the communication simulator and traffic simulator-integrated environment. However, communication performance is generally affected by various external factors such as the distance between devices (i.e., transmitters and receivers), the amount of data transmitted, and the surrounding environment (e.g., buildings, tunnels, and any other physical obstacles) [69, 73, 74]. Such communication delays are crucial given that many recent vehicle safety applications have been implemented by utilizing the V2V/V2I communications. Therefore, potential communication delays and vehicle positioning errors need to be considered when a safety assessment is implemented with safety applications.

2. Research Goal and Objectives

The goal of this research is to enhance roadway traffic safety and make driving safer by providing a reliable traffic safety assessment framework for traffic safety engineers and researchers. This research aims to proactively estimate traffic safety using realistic vehicle trajectories under Global Positioning System (GPS)/Inertial Navigation Unit (INU) and Connected Vehicles technology environment.

With this goal in mind, the following objectives are addressed in this dissertation research:

1) Develop a vehicle dynamics model-integrated simulation environment to accommodate lateral vehicle movements that are not available in the existing traffic simulation models

2) Validate the performance of the vehicle dynamics model-integrated simulation environment by comparing the new traffic conflict estimation result with traffic crash data in a given area

3) Develop a new surrogate safety assessment framework incorporating traffic simulator, vehicle dynamis model, positioning accuracy levels, and communication delays and implement it with various driver warning scenarios

3. Dissertation Organization

The remaining chapters of this dissertation are organized as follows:

Chapter 2 presents a relevant literature review on the following major tasks: 1) traffic safety modeling studies, 2) surrogate safety studies, 3) validation efforts of traffic conflicts, 4) traffic safety warning systems studies, 5) GPS accuracy and V2V/V2I performance, 6) vehicle dynamics model, and 7) Surrogate Safety Assessment Model (SSAM).

Chapter 3 describes the overall research tasks carried out in this dissertation research. The tasks are described using a flow chart and its explanation.

Chapter 4 presents the vehicle dynamics model-integrated traffic simulation environment developed in this research. The integrated simulation environment is described with the vehicle trajectory extraction from the traffic simulator, the vehicle dynamics simulation, and the SSAM implementation.

Chapter 5 addresses the validation study of the traffic conflict estimation results obtained from the vehicle dynamics model-integrated traffic simulation environment. The traffic conflict estimation results are analyzed in terms of their correlation with the traffic crash data in a given area.

Chapter 6 presents a new safety assessment framework developed and implemented in this research. The safety assessment is conducted with various driver warning scenarios, vehicle positioning accuracy levels, and communication delays.

Chapter 7 summarizes the research efforts, key findings, conclusions, and recommendations for future research gleaned from this dissertation.

Chapter 2

LITERATURE REVIEW

1. Traffic Safety Modeling Studies

As traffic safety is a major concern for the general public as well as public agencies, considerable crash prediction research has been carried out. Road geometry (e.g., lane width and road curvature) and traffic characteristics (e.g., traffic volume and the percentage of heavy trucks) are closely related to the probability of traffic crashes; thus, statistical modeling has been widely used to account for the traffic crash occurrence. This section reviews research efforts focused on estimating traffic crashes based on statistical models and non-parametric models.

Safety Performance Function (SPF)

The Highway Safety Manual (HSM) [3]—the first national resource to provide new techniques and knowledge regarding traffic safety estimation—was published by the American Association of State Highway Transportation Officials in 2010. The core of HSM is predictive methodology, including safety performance functions (SPF), calibration factors, and crash modification factors (CMF), for the expected number of crashes for various facility types. SPFs are a form of a regression model that uses the expected number of crashes as a dependent variable and the traffic operation and roadway geometric characteristics as independent variables. Since SPFs and CMFs in HSM were developed based on specific state data, many studies have attempted to adjust the SPFs and CMFs or develop new statistical models for specific purposes.

Brimley et al. [4] recently calibrated the HSM SPF for rural two-lane two-way roadway segments and developed a new SPF for Utah through a negative binomial regression. Mehta and Lou [5] developed a new Utah state-specific SPFs for two-lane two-way rural roads and four-lane divided highways based on the HSM SPFs. Lord and Bonneson [6] developed a new SPF for rural one-lane and two-way frontage roads in Texas by estimating accident modification factors (AMF). Xie et al. [7] calibrated the HSM SPF for local Oregon facilities, focusing on three facility types: rural two-lane two-way roads, rural multilane roads, and urban and suburban arterial roads. In addition, researchers have made many efforts to adjust SPF for specific road characteristics or enhance the prediction performance of SPF, such as SPF for the Italian secondary road network [8], SPF for the Canadian roads [9], and the validation of SPF for rural intersection [10].

Statistical Modeling Approach

Various statistical models, such as the linear regression model, negative binomial regression model, and Poisson model, have been applied to account for the relationship between traffic crashes and the traffic and geometric characteristics. Polus and Cohen [11] proposed a non-canonical Poisson model to predict the number of crashes on rural highways. In developing the model, they collected data on highway types, populations, traffic conditions, geometric conditions, and the number of traffic crashes from 86 highway segments over a three-year period. Based on the significance test with various forms of the Poisson model corresponding to different combinations of the candidate variables, they developed a non-canonical Poisson model consisting of one constant and two independent variables (i.e., section length and ADT volume). Ma et al. [12] developed a statistical model that predicts traffic crash counts and the level of severity based on a multivariate Poisson-lognormal (MVPLN) specification and a Bayesian estimation technique. They collected the crash data sets used in their study from Washington state through the Highway Safety Information System (HSIS). They used a random sample of 60% of all rural two-lane road segments in the region, which included 16 fatal crashes, 50 disabling-injury crashes, 180 non-disabling-injury crashes, 175 possible-injury crashes, and 532 property-damage-only (PDO) incidents, to develop the MVPLN model. The study results indicated that the MVPLN's prediction accuracy ranged from 82.93% to 97.55% in all severity levels while the univariate Poisson and negative binomial (NB) models showed the prediction performance within the range from 69.96% to 94.09%. Therefore, this study concluded that the MVPLN model can be more useful for simultaneously estimating the traffic counts and the level of severity than the other regular forms of Poisson and NB models. The study results further indicated that the relationship between crashes and that the daily volume (AADT) is non-linear and varies by crash type and significantly differs from the relationship between crashes and segment length for all crash types. Qin et al. [13] used a zero-inflated-Poisson (ZIP) modeling to estimate the number of crashes as a function of the daily traffic volume, segment length, speed limit, and roadway width and explored the characteristics of the relationship between traffic crashes and each variable. The traffic crash data and physical characteristics data of the study segments were extracted from the Highway Safety Information System (HSIS). This study conducted three hypothesis tests based on the developed functions consisting of the traffic volume (i.e., AADT) variable and the segment length variable. The hypothesis tests extracted three meaningful results: 1) the relationship between the number of crashes and AADT is non-linear, 2) the number of crashes increases non-linearly with the road segment length, and 3) the non-linear relationships between AADT and crash count and those between segment length and crash count are not the same; rather the segment length has the least impact on the occurrence of traffic crashes. In addition, Khattak et al. [14] used a negative binomial (NB) modeling approach to estimate traffic safety on rural expressway intersections. Lord et al. [15] compared various modeling approaches including binomial, Poisson, Poisson-Gamma, zero-inflated Poisson, negative binomial models, and multinomial probability models in terms of estimating traffic safety. Kwoen and Kockelman [16] attempted to explain the relationship between the fatal crash rate and the speed limit changes using a negative binomial (NB) model.

Non-parametric Modeling Approach

A non-parametric approach has been used to explain the relationship between traffic crashes and potential factors, such as road geometry and traffic operation condition (e.g., traffic volume and speed limit). Non-parametric approaches include Artificial Neural

Network (ANN)[17], Support Vector Machines (SVM) [18], and Radial Basis Function (RBF) [19] and are especially advantageous for mapping causal models where the relationship between input and output is non-linear, ambiguous, and/or unknown. Therefore, several studies have taken advantage of these non-parametric modeling approaches. Chang [20] developed a negative binomial regression model and ANN to estimate the freeway crash frequencies and compared the prediction performance of the two approaches. This study used the 1997-1998 crash data of the National Freeway-1 in Taiwan as a dependent variable and the geometric characteristics (e.g., number of lanes and vertical alignment) and traffic characteristics (e.g., ADT per lane and the percentage of trucks) as input variables. The prediction accuracy of the binomial regression model was 58.3% while ANN showed a 61.4% of prediction accuracy. Therefore, this study proposed using the ANN approach to estimate freeway crash frequencies. Akgungor and Dogan [75] attemped to estimate the number of accidents, injuries, and fatalities in Ankara, Turkey, based on ANN and the Genetic Algorithm (GA). For the development of the ANN and GA models, the number of vehicles, fatalities, injuries, accidents, and population collected between 1986 and 2005 was selected as model parameters. ANN performaed better than the GA model given its lower mean absolute error (MAE) value in predicting the number of accidents, injuries, and fatalities. Abdel-Aty and Pande [22] applied a probabilistic neural network (PNN) to classify crash or non-crash. For the model parameters, historical crash (i.e., 377 crashes) and loop detector data (i.e., traffic volume, occupancy, and speed) collected from the Interstate-4 corridor in the Orlando metropolitan area were used. The results indicated that the PNN model developed in this study accounted for at least 70% of the crashes in the evaluation dataset. The model further demonstrated 62.1% accuracy in overall crash and non-crash identification. Abdelwahab and Abdel-Aty [23] evaluated the traffic safety impacts of toll plazas and the electronic toll collection (ETC) systems using two different approaches: the Multi-Layer Perceptron and Radial Basis Functions (RBF) ANN and the nested logit models. The 1999 and 2000 accident reports for the Central Florida expressway system were used to train the ANN models and develop the logit model. The input variables included the driver's characteristics (e.g., age and gender), vehicle's aspects (e.g., E-pass use, vehicle type, and speed), and toll plaza's characteristics (i.e., mainline and on/off ramp). The study results indicated that the logit model was best (i.e., 63.8% of prediction rate) for predicting the probabilities of accident location whereas the RBF ANN was best for analyzing driver injury severity (63.6% of prediction accuracy). In addition, this study indicated that E-Pass users and drivers stopped in E-Pass lanes or sitting in passenger cars have a higher chance of being injured when they are involved in crashes in a toll plaza.

Despite the extensive research efforts using statistical models and non-parametric approaches, some concerns about their effectiveness have emerged. One of the greatest concerns related to these statistical model-based studies is that they require a relatively long observation period to collect sufficient crash data because traffic crashes are rare events. In addition, these studies have been conducted based on AADT, speed, and road geometry, but they have failed to consider other factors that might influence traffic crashes, such as driver behaviors and vehicle interactions. In addition, unreported traffic crashes including very light crashes or near-crashes have not been considered in the statistical model-based studies using traffic crash data.

On the contrary, traffic conflicts (i.e., near-crashes) are more frequent than crashes and can even be readily observed in the traffic simulation models as well as in the real field. Traffic conflict-based safety studies have taken advantage of the data extraction capabilities of the microscopic traffic simulation models so that traffic safety can be proactively estimated. Based on these advantages, the traffic conflict-based safety research has been highlighted as a useful tool for showing the likelihood of a traffic crash in a given area.

2. Surrogate Safety Studies

Traffic safety is considered challenging to analyze because of its inherent rarity. Among many undertakings to estimate the traffic safety, few studies have been conducted to develop surrogate measures that represent traffic crashes. These studies generally require a large amount of data containing individual vehicle’s trajectories (e.g., x/y/z coordinates, speed, and acceleration/deceleration rates), which has been accomplished by using advanced traffic simulation tools. The output from these traffic simulation models enables the computation of the surrogate safety measures based on crash-likely conflict analysis. This section summarizes selected research efforts on crash analyses based on surrogate safety measures.

Development of New Surrogate Safety Measures

Minderhould and Bovy [26] introduced two new surrogate safety indicators—namely, time exposed time to collision (TET) and time integrated time to collision (TIT)—based on extensions of the time to collision (TTC) measure. The TET measure refers to the amount of time exposure to safety-critical situations. In other words, TET is a summation of all moments in which the TTC value falls below the threshold value. Meanwhile, TIT uses the integral of the TTC measure and takes into account the severity of different TTC values. In contrast to the TTC measure, these two new surrogate safety measures consider the full course of vehicles over space and time in contrast to TTC, measured at a cross-section. According to Minderhould and Bovy, these new measures can be used for assessing the safety impacts of driver support systems such as Autonomous Intelligent Cruise Control (AICC).

Vogel [27] compared two surrogate safety indicators, namely, headway and TTC, in terms of their usefulness in assessing traffic safety of various traffic situations. The comparison was conducted based on a six-day field-collected traffic flow measures at a four-way junction, with stop signs on the minor road. The comparison results showed that headway and TTC are independent of each other for following vehicles. Vogel further found that a shorter headway can produce small TTC value, but it does not always mean actual danger. Rather, a smaller TTC represents actual danger because traffic crashes can occur based on relative speed and distance. Therefore, Vogel recommended that TTC is more appropriate for indicating dangerous situations while headway can be used to check whether a vehicle drives too closely behind another vehicle.

Morita et al. [28] used an inverse time-to-collision (iTTC), defined as the relative speed difference between two vehicles divided by the relative distance these vehicles, in determining when to apply the brakes. Considering that emerging Intelligent Transportation Systems (ITS) technologies can boost the advances of Adaptive Cruise Control (ACC), the iTTC measure was used to determine the best timing to prevent a rear-end crash. In order to ensure the performance of iTTC in determining the brake timing, a field test was conducted with the leading and following vehicles. Brake timing derived from the iTTC values was also compared to the brake timing decided by drivers. For the selection of the best measure, various surrogate indicators (e.g., relative speed, time headway, and inverse time headway) were compared to the iTTC measure to determine the brake timing. The study concluded that iTTC was best approach for identifying appropriate braking timing.

Ozbay et al. [24] proposed new simulation-based surrogate safety measures that were validated using direct comparison with real accident data from the New Jersey Turnpike over a ten-year period, starting in 1996. In this paper, the authors proposed two surrogate safety measures: 1) a modified time-to-collision (MTTC), derived from TTC but additionally considering the relative speed and acceleration rates between leading and following vehicles; and 2) a crash index (CI), developed to incorporate a “crash severity” factor for the MTTC. A larger MTTC means less probability of a crash and vice versa, while a zero CI value indicates a perfectly safe condition. The study showed that the simulated MTTC and CI values are important for estimating potential traffic conflicts because the correlation values between the actual accident data and the simulated MTTC and CI are found to be 0.92 and 0.91, respectively.

Following the previously discussed research, Yang and Ozbay [25] proposed a new methodology for estimating rear-end conflicts on highway merge sections, using the MTTC value. This research consisted of two major parts; the first part created a highway merge section using the Next Generation Simulation (NGSIM) model and estimated the merging probability of a vehicle whereas the other part evaluated the likelihood of rear-end traffic crashes based on the MTTC values within the merging vehicles. The author demonstrated the performance of MTTC on the safety estimation for the merging vehicles by case study, and it was concluded that the MTTC can be used to estimate potential conflicts on the highway merge sections.

Use of Traffic Conflicts for Traffic Safety Estimation

Lee et al. [29] examined the safety and the environmental impacts of the Coopertative Vehicle Intersection Control (CVIC). The CVIC algorithm was developed by Lee and Park [76] in order for vehicles to pass urban intersections without a stop-and-go caused by traffic signals. Their paper focused only on the safety and sustainability impacts of the CVIC algorithm when applied to a corridor consisting of 4 traffic signal intersections with 9 traffic congested volume cases. The authors used VISSIM, one of the microscopic traffic simulation models compatible with the Surrogate Safety Assessment Model (SSAM), to generate vehicle trajectories. Based on the output of the VISSIM simulation, the SSAM software was applied to evaluate the effect of CVIC in the safety aspect. The authors concluded that the CVIC system would reduce the number of rear-end crash events by 30% to 87%.

Archer and Young [30] evaluated different signal treatments (i.e., amber time extension, dilemma zone green extension, and all-red extension) at signalized intersections in order to estimate safety. In their research, VISSIM was used to extract vehicle trajectories, and the number of red light violations and the post-encroachment time (PET) were used as surrogate safety measures. Meanwhile, Nezamuddin et al. [31] applied VISSM to model the active traffic management (ATM) strategies such as variable speed limit (VSL) and peak-period shoulder use, and evaluated the safety benefits of these strategies using SSAM. Likewise, Habtemichael and Santos [32] took advantage of the VISSIM and SSAM to quantify the impact (i.e., crash risk) of aggressive driving on motorway safety. The authors evaluated the quantitative safety impact of the driver compliance to VSL through VISSIM and SSAM in the other study [77]. In Ishak et al. [33], VISSIM was also used to simulate the joint and conventional lane merge configurations for freeway work zones; uncomfortable deceleration and speed variance were used as a surrogate safety measure. Stevanovic et al. [78] used SSAM and the estimated traffic conflicts in optimizing traffic signal timings with regard to the safety benefits.

Based on the review of previous traffic conflict-based studies, it can be concluded that the microscopic traffic simulation models are commonly used to extract vehicle trajectories and serve as the basis for surrogate safety measures. Therefore, the estimation of surrogate safety measures relies entirely on the realistic vehicle behavior modeling capability of the microscopic traffic simulation models. This clearly indicates that efforts to make vehicle trajectories more realistic are required in the traffic conflict technique research.

3. Validation Efforts of Traffic Conflicts

Recently, some research efforts have been made to calibrate or validate the microscopic traffic simulation models by comparing them to field-collected data. Caliendo and Guida [34] tried to prove the potential of microscopic traffic simulation models for assessing traffic safety at urban unsignalized intersections by comparing traffic crashes and traffic conflicts estimated from the AIMSUN traffic simulation software. They developed three different regression models, traffic volume-based model, traffic conflict-based model, and traffic volume and conflict-based model, using five-year crash data, the number of conflicts estimated from the simulation runs, and peak hour volumes on major/minor roads. They used SSAM to estimate the number of traffic conflicts with the default setting of threshold values (i.e., 0< TTC<=1.5 s and 0<PET<=5.0 s). The results indicated that the traffic conflicts-based model provided the best performance in terms of the goodness-of-fit test (i.e., 0.967 R-squared value and the p-value of conflict variable less than 0.05) over the traffic volume-based models.

Cunto and Sacomanno [35] developed a systematic procedure for calibrating a microscopic simulation model and validated the model based on a deceleration rate to avoid the crash (DRAC) and a crash potential index (CPI). This study focused on rear-end crashes at a signalized four-legged intersection; the NGSIM real-time vehicle trajectory data were used as a representative of the signalized intersection. The study also suggested four steps for calibrating the microscopic traffic simulation (e.g., VISSIM) as follows: 1) heuristic selection of initial model inputs; 2) statistical screening using Plackett-Burnman with foldover factorial design; 3) development of linear expressions relating significant model inputs to safety performance; and 4) application of a genetic algorithm to obtain the best estimate model parameters. The simulated CPI per vehicle and number of vehicles in conflict were then compared to the observed values obtained from the NGSIM data to validate the model. This study indicated that the two measures—that is, one from the simulation and the other from the NGSIM data—matched within the 95% confidence interval. Therefore, the authors concluded that the calibrated traffic simulation model reflected the realistic safety performance measures as collected in the field.

Guido et al. [36] investigated six car-following models in terms of the models' accuracy and reproducibility of the field traffic condition. The six models are: 1) General Motor 3, 2) Van Aerde, 3) Fritzsche, 4) Wiedemann, 5) Gipps, and 6) Fresim/INTRAS. These six models were implemented by TRITONE, a microscopic simulation model, and the simulation results were compared to the field-collected vehicle trajectory data based on a deceleration rate to avoid the crash (DRAC) and TTC. The authors concluded that psychophysical models (i.e., Wiedemann and Fritzsche models) were best at mimicking the field condition in terms of TTC while the Van Aerde model was best in terms of the DRAC values.

Huang et. al [37] validated the simulated traffic conflict data obtained from the VISSIM simulation model and SSAM implementation by comparing field-collected traffic conflict data. To calibrate the VISSIM model, the researchers carried out several tasks: 1) 80 hours of traffic data were recorded using four video cameras at 10 signalized intersections; 2) traffic conflicts were identified and classified into three types (i.e., rear-end, lane change, and crossing conflicts); 3) the VISSIM network was constructed using an aerial photo and specific geometric information; and 4) the VISSIM model was calibrated in two stages: one stage to use the headway, traffic volume, and speed information collected from the field and the other stage to compare the simulated traffic conflicts to the field-collected traffic conflicts. Finally, the authors developed a linear regression model and the Spearman rank correlation coefficient to identify the relationship between the simulated and the field-collected traffic conflicts. As a result, the R-squared value for the total conflict model was 0.783, 0.831 for the rear-end conflicts, 0.573 for the crossing conflicts, and 0.188 for the lane-change conflicts. Based on the data, the authors concluded that the two-stage calibration procedure developed in this study has a reasonable potential to be used in practice for the traffic safety assessment in relatively simple driving environments, such as freeway mainlines, where the majority of traffic conflicts are rear-end conflicts.

In light of this thorough review of previous traffic conflict validation studies, it can be concluded that not many research efforts have been made given the difficulties inherent in directly linking traffic conflicts and traffic crashes. However, validating whether or not the traffic conflict estimation results reflect traffic safety in a given area is essential for ensuring that the traffic conflict technique-based research gains credibility. Such validation is particularly crucial if a new surrogate safety measure is to be developed or a new traffic simulation technique as the basis of estimating traffic conflicts is to be introduced.

4. Traffic Safety Warning Systems Studies

In the past few decades, many efforts have been made to develop vehicle safety applications by taking advantage of and evaluating GPS and the V2V/V2I communications technology. For example, recently, cooperative safety applications such as the Cooperative Adaptive Cruise Control (CACC), Cooperative Collision Warning System (CCWS), and Cooperative Intersection Warning System (CIWS) have been developed and studied by many researchers. Some remarkable research efforts related to the GPS and V2V/V2I-based cooperative safety applications are presented in the following subsections.

Cooperative Adaptive Cruise Control (CACC)

Ploeg et al. [59] tested the performance of the Cooperative Adaptive Cruise Control (CACC) in terms of the velocity response by comparing it to the Adaptive Cruise Control (ACC). They conducted the experiment using a test fleet of six vehicles; each vehicle was assumed to be equipped with a WiFi device operating according to the IEEE 802.11a standard in ad-hoc mode, GPS receiver, and the Human-Machine Interface (HMI) consisting of levers and a display. The authors concluded that CACC can be a better solution than ACC in terms of the roadway throughputs because the CACC velocities of six vehicles were more stable than the ACC velocities.

Bu et al. [60] developed a prototype of CACC based on the V2V communication and GPS device and tested the performance using two vehicles. Their study also presented the performance of CACC by comparing to ACC. The results showed that the enhanced performance of the CACC-equipped vehicle operated at time gaps between 0.6 and 1.1 seconds compared to a range of 1.1 to 2.2 seconds with the ACC control. Since the vehicle operating time gap of CACC was shorter than that of ACC, the authors concluded that CACC is more promising to enable significant increases in highway capacity.

Cooperative Collision Warning System (CCWS)

Tan and Huang [54] designed the system architecture of the Cooperative Collision Warning System (CCWS) and explored possible technical issues. Their study compared the vehicle trajectory obtained from a differential GPS and the conflict detection results to the ground-truth vehicle trajectory and its conflict detection results. Using multiple charts showing the difference between the DGPS-collected vehicle trajectory and the ground-truth trajectory and their conflict estimation results, the authros concluded that the positioning accuracy degraded as the duration of the DGPS blockage increased. In addition, they mentioned that the inaccuracy of the positioning system can lead to false alarms due to inaccurate conflict estimation.

Misener and Sengupta [55] evaluated the performance of three Cooperative Collision Warning safety applications: 1) a forward collision warning assistant, 2) an intersection assistant, and 3) a blind-spot and lane-change situational awareness assistant. They conducted a field operational test in the PATH Richmond Field Station (RFS) facility, using five equipped vehicles. The major findings of this study included the following: 1) multiple vehicle sensors such as forward-looking radar and side-looking radar were effective for operating CCW, 2) IEEE 802.11 communications technology was adequate for a CCW system, and 3) fusing GPS with steering angle, wheel speed, and yaw rate sensors met the positioning requirement of CCW. However, the authors also identified some limitations in operating CCW—namely, 1) the communication system needs to be extended to cover enough vehicles and 2) the warning system needs to operate with a digital map to detect even further vehicles.

Dogan et al. [51] evaluated the performance of an intersection collision warning system in terms of the communication success rate using a Vehicle Traffic Simulator (VTS) and a Wireless Simulator (WS). The authors assumed that each vehicle was equipped with a GPS receiver, digital map, and communication device. Using these devices, a driver was informed a collision warning when a vehicle was approaching or crossing an intersection. The study result showed that packet losses are mostly due to physical layer errors under realistic traffic conditions and multiple retransmissions of short packets with a low data rate can improve the communication performance of the intersection collision warning system.

Driving Simulator-based Traffic Safety Studies

Driving simulators have also been used to identify drivers' driving behaviors and evaluate the performance of warning systems. Tijerina et al. [79] evaluated the effects of an adaptive warning system on a surprise event using a driving simulator. In their experiment, forty volunteers drove the driving simulator; their responses were compared when an adaptive LDW was adopted and a non-adaptive LDW was adopted or vice versa. The results indicated that even in the adaptive LDW, thirteen subjects (34%) experienced delayed activation of the LDW warnings or no warnings were provided. Therefore, the authors concluded that the performance of adaptive LDW depended on various factors, such as system hardware, algorithms, and algorithm parameters as well as the system principles (i.e., adaptive and non-adaptive).

Kircher and Thorslund [80] evaluated the effects of road surface appearance and low friction warning system on drivers' behavior. To identify drivers' behaviors during the warnings, 75 participants drove in a high-fidelity driving simulator that included visible/invisible low friction road surfaces (e.g., ice and slippery conditions). The authors concluded that 1) the low friction driver warnings (e.g., speed recommendation) led to the reductions of speed and 2) this warning system was especially useful in situations in which the driver cannot see the road conditions.

Curry et al. [81] investigated the driver recall performance for a forward collision warning (FCW) alert. They used the Ford Motor Company driving simulator "VIRTTEX" with 120 test participants. Immediately after the crash-likely event, participants were asked if they had received any warning and, if so, what they recalled about the warning message. The data showed that 26% of participants did not remember receiving a warning at all and only 58% of participants remembered in detail the information they received from the warning system.

Lenne et al. [82] investigated the effects of an advance warning device (AWD) given the situation that drivers interact with emergency vehicles (EVs). The experiment used an advanced driving simulator in a range of circumstances in which EV crashes and near-misses occur. Each event consisted of the combination of traffic scenarios (i.e., adjacent lane, turning across, and car following) and warning conditions (i.e., control, standard, and advance). the driving behaviors of the 22 participants were recorded. The data indicated that the AWD reduced mean speed and led to an earlier lane change so that vehicles can clearly avoid a conflict with EVs.

The studies summarized in this section mainly focused on the performance of vehicle safety applications. These proposed and studied safety systems are based on vehicle positioning and V2V/V2I communication technologies. However, none of these studies investigated how the positioning accuracy levels corresponding to the vehicle positioning system technologies affect the performance of safety applications. In addition, only a few studies considered the potential communication delays despite the fact that communication performance can negatively affect the performance of safety applications by delaying driver warnings. Thus, this thoughtful literature review on the safety application studies has proven the need to consider potential positioning errors and communication delays when traffic safety is estimated using vehicle safety applications.

5. GPS Accuracy and V2V/V2I Performance Studies

Since the Global Positioning System (GPS) was introduced during the 1980s by the U.S. military, it has been popularly used to collect and analyze vehicle activity in terms of the time and location in the transportation engineering field. In addition, some studies examined the accuracy level of GPS and the V2V/V2I communication performance to check whether or not they provide a reasonable performance in the transportation engineering applications.

For example, Yunchun and Farrell [83] evaluated the performance of a triple redundancy navigation system incorporating magnetometer, inertial navigation system (INS), ad differential Global Positioning System (DGPS). The field experiments were conducted in the University of California at Riverside CE-CERT facility in Riverside, CA, based on four scenarios: GPS/magnetometer-aided INS, GPS-only-aided INS, magnetometer-only-aided INS, and switching randomly between GPS and magnetometer aiding INS. The standard deviation accuracies of the devices used in this study were 2.8 cm in positioning, 0.8 cm/s in velocity, 2.2 cm/s^2 in acceleration, 0.03°/s in pitch, 0.18° in roll, and 0.1° /s in yaw.The study results were indicated by the lateral trajectories of vehicles; all device combination scenarios (i.e., triple redundance navigation system) provided a reasonable positioning accuracy in the lateral vehicle control

Clanton et al. [84] demonstrated the ability to use low-cost GPS/INS for lane tracking. The authors suggested to use the GPS/INU in conjunction with a vision-based lane departure warning (LDW) system and a high-accuracy map because a typical GPS has approximately seven meters of positioning error which cannot be used for the lane tracking. The study results indicated that the maximum horizontal positioning error were approximately five meters when a GPS only be used; the combination of GPS, INS, and a vision system (i.e., camera measurement) provided a reasonably enough accuracy for performing LDW.

Ogle et al. [85] investigated the accuracy of GPS in terms of the effects on horizontal location accuracy, speed, and acceleration/deceleration rates. The military removed the degrading of the positioning accuracy of GPS signals (i.e., selective availability) for commercial use in 2000. Ogle et al. validated the data obtained from GPS to the data from a distance-measuring instrument. The results showed that, although non-corrected (i.e., with selective availability) data can be used to obtain data with 10 meters of error, both the corrected and the non-corrected data are still problematic, especially in urban canyons and under heavy tree canopies.

Herrera et al. [86] evaluated the accuracy of speed data obtained from GPS-enabled mobile phone data. In their study, they deployed 100 vehicles equipped with GPS-enabled mobile phones in Union City, California; they collected vehicle trajectories and derived speed measurements compared to the data from loop detectors. The analysis indicated that a 2% to 3% penetration rate of mobile phones in the driver population could extract accurate measurements of the velocity of traffic flow.

McCormack and Hallenbeck [87] also evaluated the accuracy of both GPS technology and the commercial vehicle information system, including an electronic truck transponder. They collected data on distance and time using both technologies and then compared the calculated speed data. Both technologies were shown to be useful in monitoring truck movements, but this information is credited to having a sufficient number of equipped trucks. Zhao et al. [88] similarly investigated the accuracy of GPS spot speeds in terms of the use for estimating truck travel speed. Their study aggregated the collected GPS spot speed data to generate space mean speed and compared the data to the data obtained from loop detectors. The authors concluded that the aggregated GPS spot speed data generally matched the loop detectors' speed data and represented travel conditions over time and space.

The previously discussed studies examined the impacts of GPS errors on general traffic applications. Although the previous studies concluded that the positioning error level identified did not significantly affect the traffic operations applications, the errors can be more significant in the traffic safety application. A few studies (Yunchun and Farrell [83] and Clanton et al. [84]) pointed out that a typical GPS is not enough to perform vehicle safety application; suggested the combined forms of GPS, INS, and a vision system. However, none of these studies thoroughly reviewed various types of positioning system and investigated how the accuracy levels affect the performance of safety applications. This dissertation research will consider various types of positioning technologies corresponding to different accuracy levels to simulate its effects on the safety applications.

The Connected Vehicle (CV) program was initiated in 1999, and the CV technology was expected to produce many more benefits than existing ITS services by taking advantage of V2V/V2I/I2V wireless communications. However, the communication performance and its impacts on the CV applications are still in dispute due to a variety of factors, such as the separation distance between transceivers, the number of vehicles within a communication range, and physical obstacles (e.g., buildings and barriers), which can affect communication performance. In order to examine CV communication performance, some research efforts have sought to integrate communication simulators and traffic simulators or conduct field tests.

Kandarpa [68] conducted a proof-of-concept (POC) test on Vehicle Infrastructure Integration (VII) communication performance. The key feature of this study was that the test was conducted in an actual field (i.e., Novi, Michigan) with the VII standards-incorporated software and hardware whereas previous studies were completed under simulation environments. Regarding DSRC communication performance, Kandarpa's study revealed that both the height of the antenna and the geometrical topologies affected the communication performance in terms of packet error rate (PER), but the effects of vehicle speeds were not significant. In addition, the multi-path fading in radio propagations caused temporary communication dropouts.

Lee [69] examined the CV communication delays for both the control and service channel operations regarding WAVE/DSRC communication standards. To simulate the CV communication performance, a modified NCTUns communication network simulator [89] was developed and adopted by interfacing with the VISSIM traffic network. This study found: 1) despite insignificant packet transmission delays for both V2V/V2I/I2V messages, the delays occurred with 5% packet drop rates at most, 2) the observed maximum delay of the V2I communications was larger than those of the I2V communications, and 3) relatively long delays were frequently observed in the V2I communications. The study further revealed that the delays would increase as the number of On-Board-Units (OBUs), the distance between transceivers, and the sizes of packets received at the Road-Side-Units (RSUs) increase.

Miroslavov and Veeraraghavan [70] evaluated the performance of WAVE/DSRC Connected Vehicle (CV) communication on the Probe Data Service (PDS), defined for collecting in-vehicle sensor data snapshots and subsequently transmitting those data from OBE to RSE. As in the previously discussed study, their study took advantage of a VISSIM and NCTUns-integrated simulation environment to simulate PDS communication performance. Their study showed that the communication losses would frequently occur as the distance between OBUs and RSUs increase. In addition, a Vehicular Datagram Transport Layer Security (VDTLS), initially developed to secure the transfer of PDS messages between OBUs and RSUs, unexpectedly provided a high success rate of message deliveries with a high time-out interval while it generated a trade-off of longer delays between snapshot generation and transmission.

As indicated in previous studies, communication performance remains an important factor that needs to be considered when evaluating CV-based traffic applications. From this point of view, this dissertation research will examine the communication delays based on multiple traffic scenarios, including the number of transceivers and the distance between OBUs and RSUs. Ultimately, the communication performance simulation results will be used to identify the communication delay levels that need to be considered for safety estimation studies.

6. Vehicle Dynamics Model – CarSim

In the transportation engineering domain, there is no relevant simulation model that can examine the vehicle dynamics such as pitch, yaw, roll, and etc. In order to obtain vehicle's realistic trajectory, CarSim [90], which is a widely used and extensively validated commercial vehicle dynamics simulation, was used. Since CarSim was developed in 1998 by Mechanical Simulation Corporation, it has been validated by many automotive manufacturers, research labs, and universities in terms of its capabilities to simulate the vehicle’s performance. Although CarSim was developed focusing on a vehicle’s performance itself in response to driver controls such as steering, throttle, and braking, its math model was expected to produce realistic vehicle trajectories in a given traffic setting (speed, acceleration, and deceleration rate) and road geometry. In particular, it is expected that CarSim is capable of generating realistic in-lane lateral movement and lane change trajectories, something that existing traffic simulation models are lacking.

The vehicle's position in CarSim is defined by a station (that is, the distance along a reference line) and its lateral offset from the station. These can also be converted to a global X/Y position. CarSim uses vehicle data (e.g. inertia, spring rates) and driver input (e.g. closed-loop target speed or open-loop throttle) to calculate the multibody dynamics of the system using numerical integration.

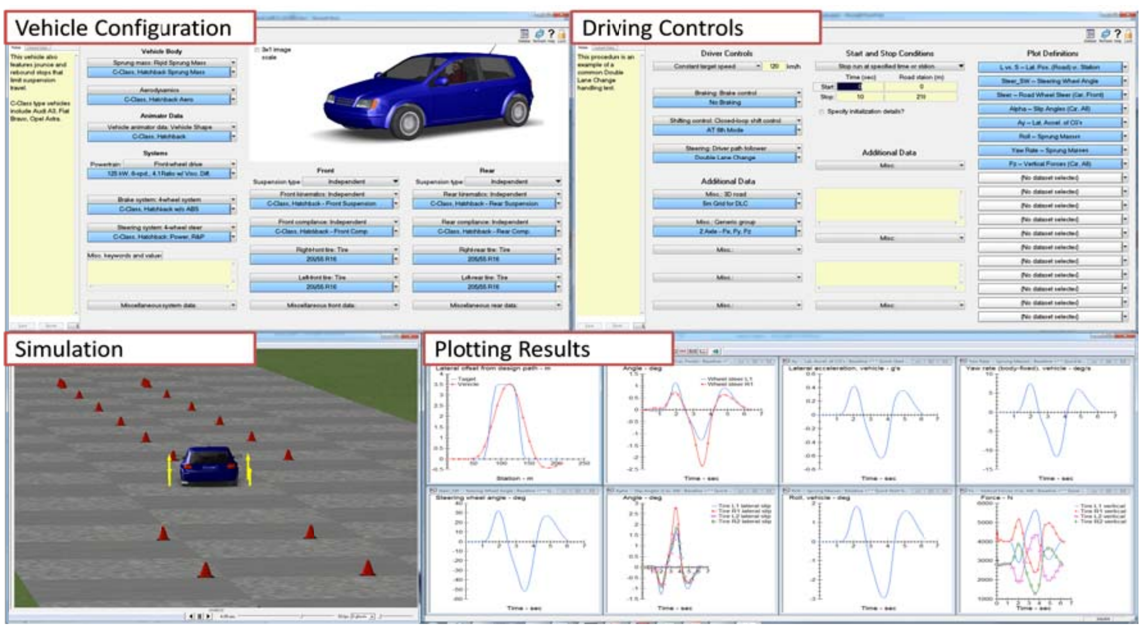


Figure 2. CarSim Control Modules

In the effort to consider vehicle dynamics in the transportation engineering field, only a few studies have been made. Donoughe et al. [91] developed a hardware-in-the-loop (HiL) system for testing in-truck safety technology such as an electronic stability system. The HiL system developed in this study consists of the TruckSim [92] module to simulate the vehicle dynamics (e.g., wheel lift and rollover) of trucks and the HiL client program to communicate between the TruckSim and the HiL server. This study validated the developed TruckSim-based HiL system with multiple scenarios consisting of various speeds, rollover, and wheel lift cases. In relation to this study, Park et al. [93] evaluated the safety benefits of electronic stability control (ESC) systems for tractor-semitrailers using the HiL simulation. Using the TruckSim-based HiL system, this study estimated the number of rollover and loss of control (LOC) crashes that may potentially benefit from the ESC and conducted a benefit-cost analysis.

Although a few research efforts have been made to reflect vehicle dynamics, it was limitedly applied to specific vehicle types (i.e., truck and trailer) and its in-vehicle safety applications with a few evaluation cases. Also, there were no cases that the vehicle dynamics model was fully integrated with the microscopic traffic simulation models in the purpose of traffic operations or traffic safety studies. However, based on the vehicle dynamics model's capabilities in simulating vehicle's realistic maneuvers and its uses in evaluating vehicle's safety systems, it is expected that the vehicle dynamics model can give many advantages to the traffic operations and safety studies by integrating with the microscopic traffic simulation model.

7. Surrogate Safety Assessment Model (SSAM)

The difficulty of the data extraction and observation have been problematic in the traffic conflict technique studies. However, since the advent of the microscopic traffic simulation models, a lot of SSAM-based studies have been done on the basis of the data extraction capability of the simulation models. Gettman and Head [94] proposed surrogate safety measures that can be obtained from the traffic simulation models through investigating the simulation models in terms of its capability of data extraction. Following that study, they developed a Safety Surrogate Assessment Model (SSAM) software [95] in order to automate the process of conflict analysis. SSAM was designed to automatically calculate the following surrogate safety measures regarding the vehicle pairs that projected to conflict by their trajectories.

- Time-to-collision (T.T.C.)
- Post-encroachment time (P.E.T.)
- MaxS (maximum speed)
- DeltaS (difference in vehicle speeds)
- DR (initial deceleration rate of the second vehicle)
- MaxD (maximum deceleration of the second vehicle)
- Conflict type (angle)
- MaxDeltaV (maximum DeltaV)
- FirstDeltaV (change of conflict velocity)

As a first step, SSAM selects vehicle pairs that are projected to conflict each other, by analyzing their trajectories (e.g., x/y/z coordinates, speed, acceleration rate, deceleration rate, etc.). Then, the surrogate safety measures are calculated for each vehicle pair, and SSAM identifies a conflict if both the TTC and the PET of the vehicle pair are found to be within their threshold values (i.e., 1.5 seconds of TTC and 5.0 seconds of PET in default settings, but adjustable). In addition, it defines conflict types based on projected conflict angle. For example, if the conflict angle of one vehicle pair is less than 30 degrees, SSAM defines it as a rear-end crash (these values are also adjustable). Note that the occurrence of a conflict in SSAM does not mean that a crash would necessarily occur, just that it is a dangerous situation and a crash may occur if drivers to not take evasive action.

In addition, SSAM is compatible with following commercial microscopic traffic simulation models: AIMSUN, PARAMICS, TEXAS, and VISSIM. Thus, the vehicle trajectories obtained from the above simulation models can be used directly to calculate the surrogate safety measures by SSAM.

Ever since SSAM was developed, it has been a standard practice to post-process the data obtained from the microscopic traffic simulation models and make it useful for the surrogate safety measures. SSAM has been widely used to estimate the safety impacts (i.e., the number of conflicts) of various traffic alternatives such as: active traffic management (ATM) strategies [31], Cooperative Vehicle Intersection Control (CVIC) [29], dual right-turn lanes [96], intersection design [97], auxiliary through lane in the freeway merging area [98], and roundabouts [99].

8. Summary

The literature review examined some of the important research in traffic safety modeling, surrogate safety estimation, validation efforts of traffic conflicts, vehicle safety applications, GPS and V2V/V2I performance studies, vehicle dynamics model, and surrogate safety assessment model. This literature review demonstrated the need of this dissertation research in the following aspects:

1) the need of a reliable traffic simulation environment for traffic safety to be proactively estimated with realistic vehicle trajectories;
2) the need of a validated traffic simulation environment that can be used as a safety estimator reflecting the probability of traffic crashes;
3) the need of an enhanced surrogate safety assessment framework that can reflect the potential possibility of the degradation of vehicle positioning and communication systems on the vehicle safety applications.

The following chapter presents an overall study design of this dissertation research with flowcharts and descriptions.

Chapter 3

OVERALL STUDY DESIGN

This chapter presents the research design and the tasks conducted in this dissertation research. Flow charts (Figures 3 and 4) depict the research methodology for each task.

As a first research task, a vehicle dynamics model (i.e., CarSim) is integrated with the microscopic traffic simulation (i.e., VISSIM) in order to generate more realistic vehicle trajectories. The lane change vehicle trajectories are fed into CarSim and simulated by the CarSim's vehicle dynamics model. These CarSim-simulated vehicle trajectories are incorporated with the other VISSIM vehicle trajectories (i.e., straight ahead VISSIM trajectories which were not simulated by CarSim), and a new set of vehicle trajectories is used to estimate the number of traffic conflicts by SSAM. [100]

For the integration of VISSIM, CarSim, and SSAM, and for automating the process, an interface program is developed, based on the Visual C# Integrated Development Environment (IDE). Since heterogeneous simulation models (i.e., VISSIM and CarSim) are proposed for integration, the interface program is essential in the integration of the two simulation models and in reformatting the input/output data structure. In addition, VISSIM is compatible with SSAM and can generate the required input SSAM files, but

CarSim cannot. Consequently, an interface module connecting VISSIM, CarSim, and SSAM is developed and used to produce a new traffic conflict estimation result.

Considering that more realistic vehicle trajectories are used to estimate traffic conflicts, the proposed VISSIM-CarSim integrated approach and its conflict estimation result might represent the surrogate safety better than the VISSIM-only approach. However, it still needs to prove whether or not this new result can better represent the probability of traffic crashes. With this in mind, the two conflict estimation results, one from the proposed approach (i.e., VISSIM-CarSim) and the other from the existing approach (i.e., VISSIM-only), are compared to the traffic crash data in terms of their correlations. Consequently, this validation research task will answer the following questions.

1) Is there a significant correlation between traffic crashes and conflicts so that traffic conflicts can be used as a traffic safety indicator?
2) Is the proposed simulation approach (i.e., VISSIM-CarSim) better than the existing approach (i.e., VISSIM) in terms of the representativeness of the surrogate safety?

Figure 3 shows the flow of these research tasks.

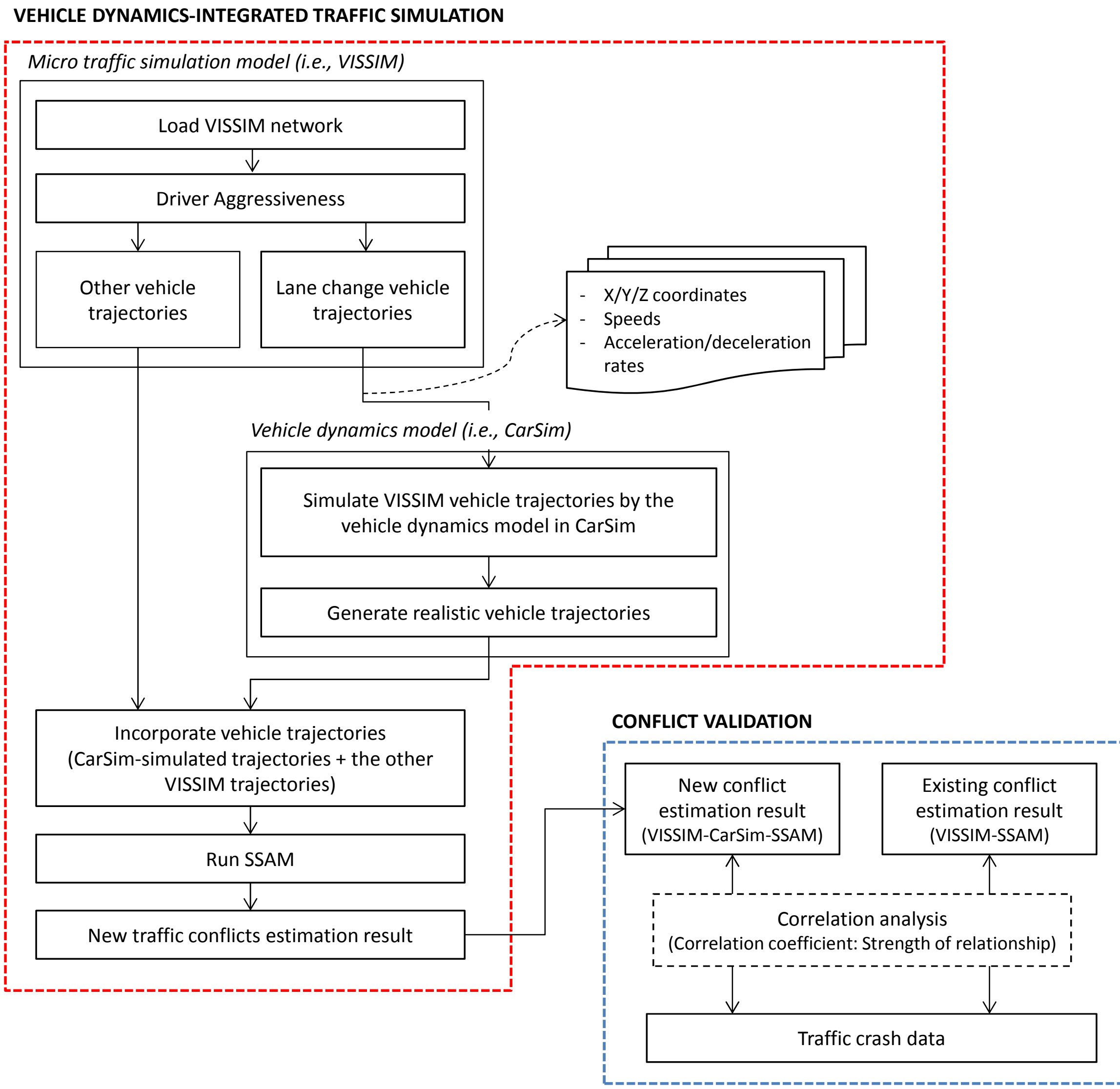


Figure 3. Overall Study Flow (Ch.4 and Ch.5)

While the previous research tasks focus on the post-processing of vehicle trajectories to generate more effective surrogate safety measures, the third research task contributes to the development of a new safety assessment framework. Considering that the traffic safety applications are being developed and deployed by taking advantage of the vehicle positioning system and communication system, the proposed safety assessment framework is implemented with driver warning scenarios, the positioning accuracy levels and communication delays scenarios. Not only the safety impact, but also the mobility and environment impacts are examined. Figure 4 shows the compositions and process of the integrated traffic safety assessment framework proposed in this dissertation research.

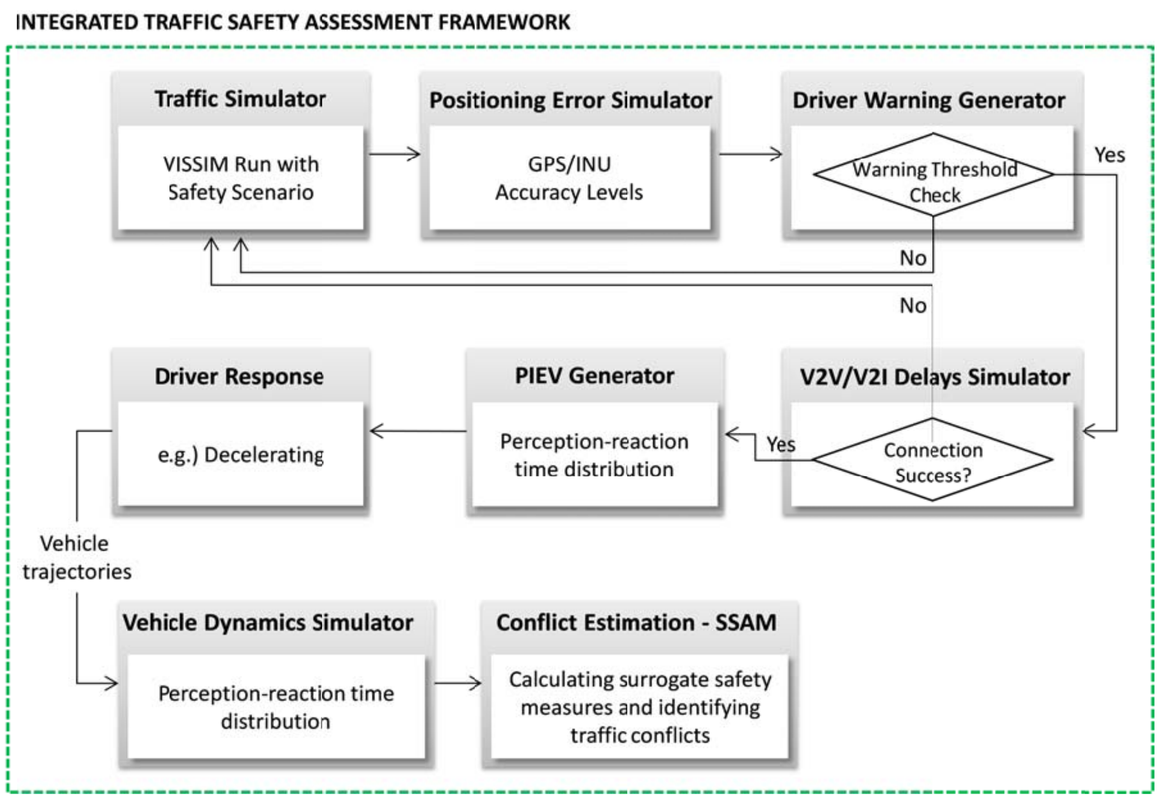


Figure 4. Overall Study Flow (Ch.6)

The following section describes the development of the VISSIM-CarSim integrated traffic simulation environment. Chapter 5 presents a validation study of the effectiveness of the vehicle dynamics model-integrated traffic simulation environment for assessing traffic safety. In Chapter 6, the safety/mobility/environmental impacts are assessed using the proposed traffic safety assessment framework.

Chapter 4

DEVELOPMENT OF VEHICLE DYNAMICS-INTEGRATED TRAFFIC SIMULATION

This chapter integrates the vehicle dynamics model into the microscopic traffic simulation model to accommodate the vehicles' lateral movements, which the off-the-shelf driver model of the microscopic traffic simulation model does not reflect well. On one hand, the microscopic traffic simulation models have been used to model possible traffic scenarios in the network, but they do not well reflect the lateral movements of individual vehicles. On the other hand, the vehicle dynamics model has an extensive capability of modeling a vehicle's dynamics such as pitch, yaw, and roll based on vehicle maneuvers, geometric conditions, and vehicle mechanical characteristics, but it does not create various traffic situations. Therefore, this chapter addresses the integration of the two heterogeneous simulation models and a new traffic conflict estimation result through the integrated simulation environment.

1. Vehicle Trajectory Extraction from the Microscopic Traffic Simulator

Many traffic conflict-based studies have taken advantage of the data extraction capabilities of the microscopic traffic simulation models. In this study, VISSIM 5.40 [101], the latest VISSIM, was selected because it is one of the most widely used traffic simulation models in the transportation operation research area and due to the author's hands-on experience with it.

VISSIM lacks the ability to model realistic vehicles' movements, especially lateral movements. In this research, only lane change vehicle trajectories in VISSIM were selected and extracted to be simulated by the vehicle dynamics model (i.e., CarSim) because VISSIM has a reasonably good capability to simulate vehicle movements such as decelerating/accelerating and stop-and-go.

VISSIM includes two types of lane change behavior: a 'free lane change,' and a 'necessary lane change.' The 'free lane change' (Figure 5-up) takes place when a subject vehicle changes its lane to reach a higher speed or to have a longer gap distance to a leading vehicle. The 'necessary lane change' (Figure 5-down) occurs when a subject vehicle changes the lane for route choice such as entering or existing a freeway or turning at an intersection. VISSIM has an indicator of the lane changes, so it can be easily captured from the VISSIM trajectory record file.

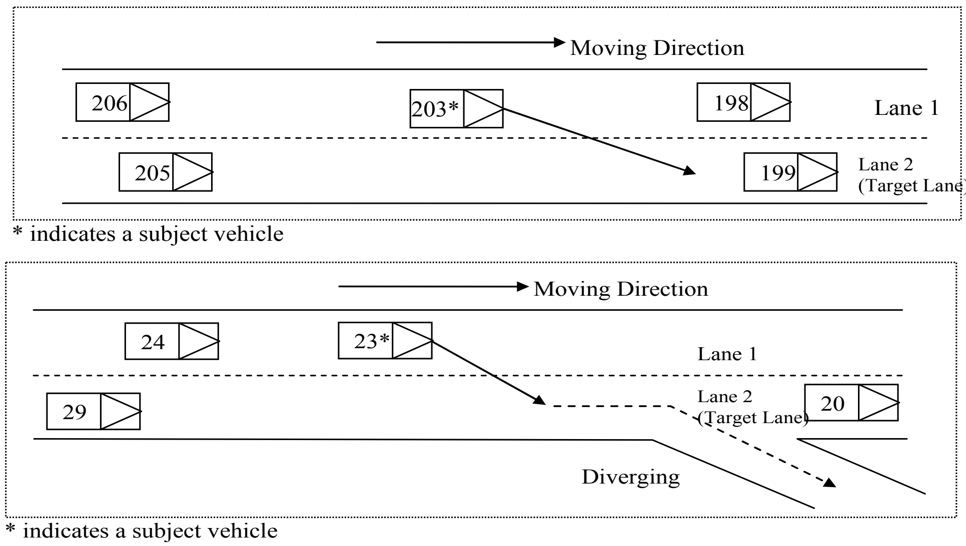


Figure 5. VISSIM lane change diagrams (up-free) (down-necessary)

Lane change trajectories are processed based on the following steps:

1) Using a lane change indicator, identify the lane change vehicles.
2) Search for the adjacent four vehicles, i.e. the leading and following vehicles in the initial and final lane.
3) Extract the trajectories (e.g., X and Y coordinates, speed, and acceleration rate) of five vehicles (i.e., one lane change vehicle + adjacent four vehicles).
4) The lane change vehicle's trajectory is simulated by CarSim. The straight line VISSIM lane changed is smoothed using a third order polynomial, and this is used as a target trajectory by the closed-loop CarSim driver model.
5) The vehicle dynamics-simulated vehicle trajectory is combined with the other trajectories (i.e., adjacent four vehicles) to calculate surrogate safety measures.

2. Driver Aggressiveness

Every driver has different driving characteristics in terms of driver aggressiveness. Some drivers change lanes quickly and aggressively and other some drivers do not. However, the off-the-shelf driver model of VISSIM does not support driver aggressiveness; all the lane changes occur at approximately three seconds. In order to simulate more realistic lane change driving behaviors in VISSIM, the lane change vehicle trajectories from two corridors (i.e., I-80 and US-101), collected for the Next Generation Simulation (NGSIM) project [4], were investigated as a function of the movement threshold (i.e., ΔLat/ΔLong). This movement threshold is defined as a ratio of the change in the subject vehicle's lateral position over the change in longitudinal position. Figure 6 shows the aggregated lane change duration distributions for I-80 (Figure 6 up) and US-101 (Figure 6 down), derived from the movement threshold values and vehicle speeds.

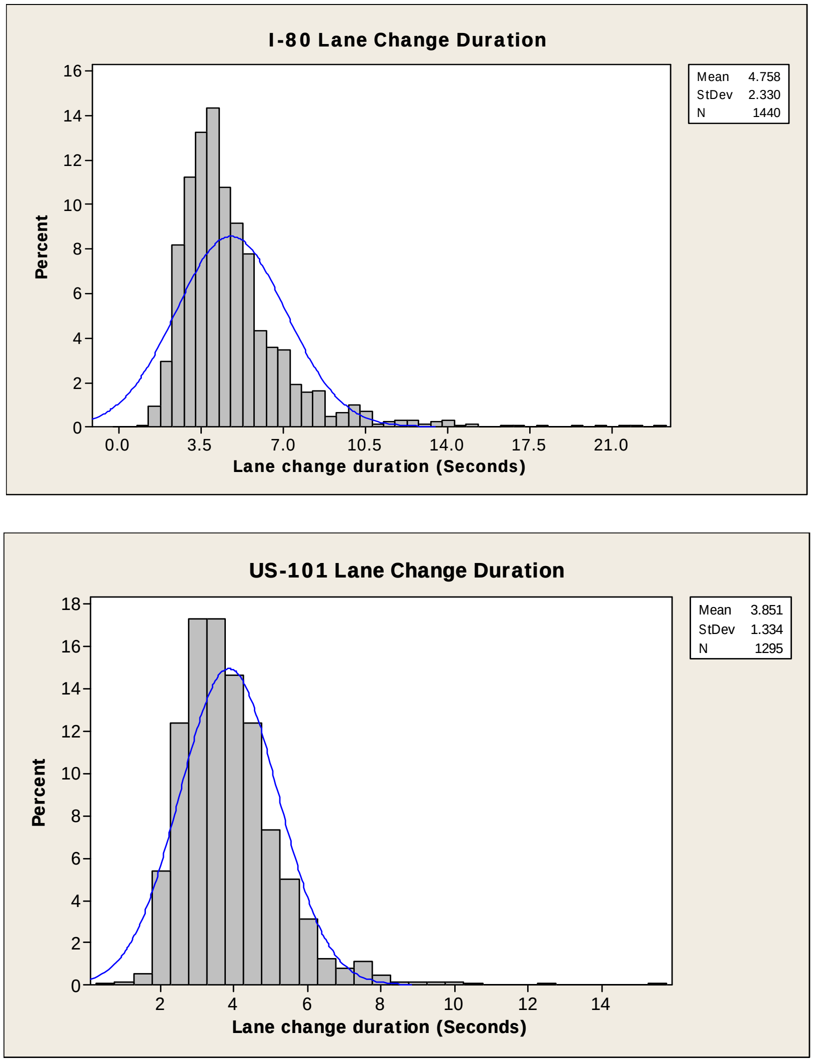


Figure 6. Distributions of the lane change duration (up – I80), (down – US-101)

These lane change duration distributions were used to generate various lane change durations in VISSIM through an external DriverModel.dll, a VISSIM's API module. This external driver model replaces the VISSIM's internal lane change logic so that a vehicle can change its lane by the specified lane change movement. As a result, the VISSIM lane changes controlled by the external DriverModel.dll reflected more realistic lane change durations ranging between 1.5 and 8.0 seconds as shown in Figure 7, while the original VISSIM lane changes occurred at approximately three seconds.

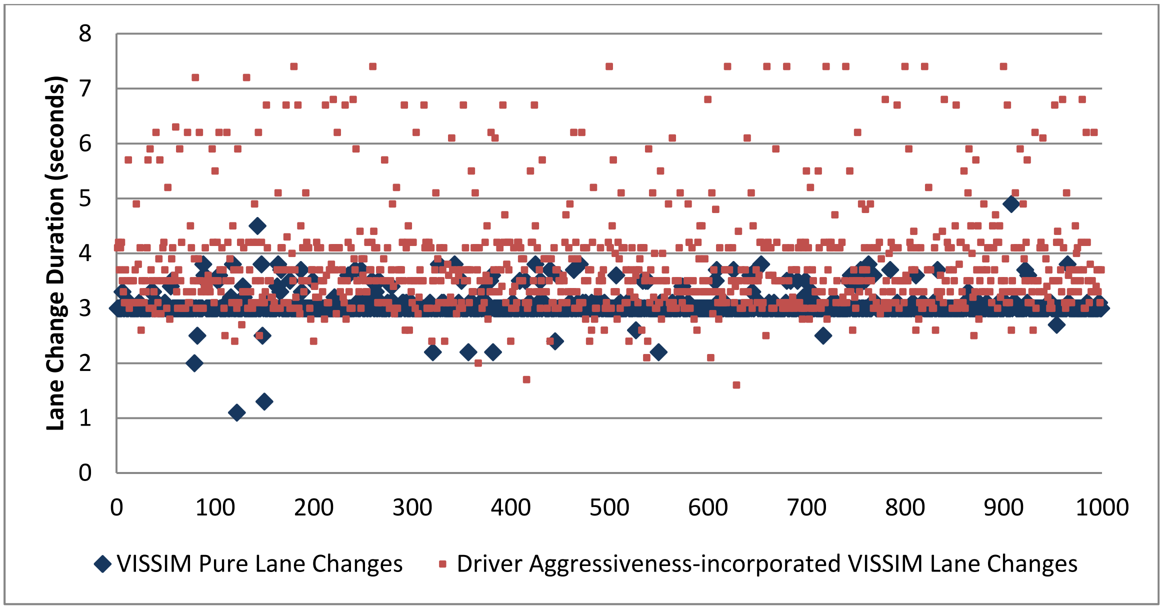


Figure 7. Lane change aggressiveness-incorporated VISSIM trajectories

3. Vehicle Dynamics Integration

The CarSim closed-loop driver model requires two pieces of information which are the form of text files (called 'parsfiles') to simulate vehicle dynamics. One is a reference vehicle trajectory, and the other is a speed-time history that will be used to decide the appropriate throttle and braking pressure.

The VISSIM x and y coordinates were used as a reference trajectory in CarSim. The VISSIM trajectory nominally consists of three straight lines: the path in the initial lane, the path in the final lane, and the straight line connecting the two. In order to create a more realistic vehicle path profile, the vehicle trajectory was re-produced by a third-order polynomial. This polynomial-incorporated vehicle trajectory was used a reference line in CarSim.

The vehicle path is defined by a station that is the distance along a reference line, and a vehicle follows the stations consisting of a unique set of x and y coordinates at each station. The actual path and the lateral position of the vehicles are calculated at every station to advance to the next station in consideration of vehicle dynamics (i.e., yaw, pitch, and roll).

Likewise, the vehicle's speed is recorded at every time step in VISSIM and this speed profile was exported directly to CarSim. Using the reference trajectory and speed-time profile, CarSim simulated the vehicle’s lane change trajectory and generated the vehicle dynamics-incorporate trajectory. Figure 8 shows the trajectories for lane change simulated in CarSim. The colored lines represent duration of 1, 3, and 5 seconds. For all cases, the CarSim trajectory showed a curved shape while the VISSIM trajectory showed a straight line. The difference was more significant at the starting and ending points of lane change. Since all trajectories were generated with the same speed but with different durations, each CarSim trajectory was influenced by vehicle dynamics in a different manner and therefore looked slightly different from each other. The results showed that the difference between the VISSIM and CarSim trajectories increased as the lane change duration decreased. This implies that the vehicle dynamics' influence over VISSIM had increased with driver aggressiveness.

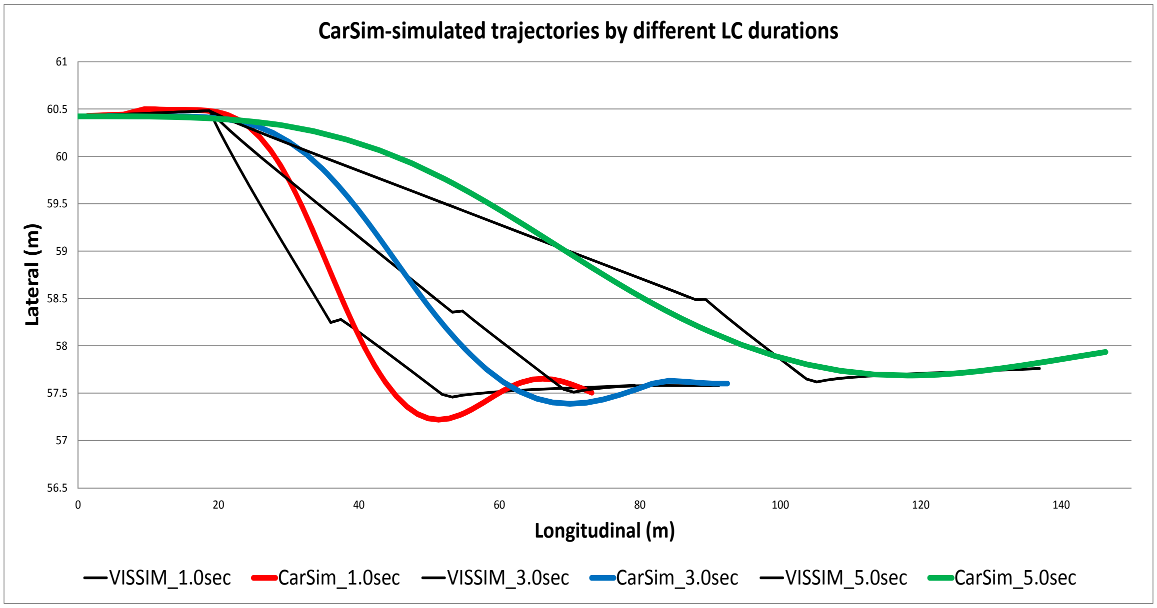


Figure 8. CarSim-simulated trajectories by different driver aggressiveness

4. Conflict Thresholds

SSAM was used to estimate traffic conflicts based on the vehicle trajectories which were generated by the vehicle dynamics-integrated simulation environment. SSAM identifies a conflict if time-to-collision (TTC) and post-encroachment time (PET) are found to be below specific threshold values. Note that the default settings of the threshold values are TTC less than or equal to 1.5 seconds and PET less than or equal to 5.0 seconds. In this study, a TTC value of less than or equal to 2.5 seconds and deceleration rate difference (DRD) greater than or equal to 4.5 m/s^2 were proposed to identify the traffic conflicts according to the previous study [102] which suggested these threshold values to reduce the probability of false warnings. Accordingly, the source code of SSAM was modified to incorporate these new threshold values since the off-the-shelf of SSAM does not provide the DRD measure. Moreover, the conflicts estimated from 'TTC = 0' cases were excluded from this analysis because actual crashes (i.e., TTC=0) cannot be realized in the existing traffic simulation models. SSAM classifies conflict types (i.e., rear-end, lane change, and crossing) on the basis of the conflict angle between conflicting vehicles. Specifically, the conflict types are classified as follows: 1) a rear-end conflict if $|\text{conflict angle}| < 30°$, 2) a crossing conflict if $|\text{conflict angle}| > 85°$, and 3) the others are lane change conflicts.

5. Experiment Test-bed

Two freeway corridors (i.e., Interstate 495 and State Road 267) in the Tysons Corner area in Fairfax, Virginia, were selected as shown in Figure 9 and were used to estimate the number of traffic conflicts. Interstate 495 is approximately 2.7 miles long and the State Road 267 is about 3.3 miles long. This network was constructed based on the P.M. peak traffic volume dataset obtained from the Virginia Department of Transportation (VDOT) Northern Virginia District [103].

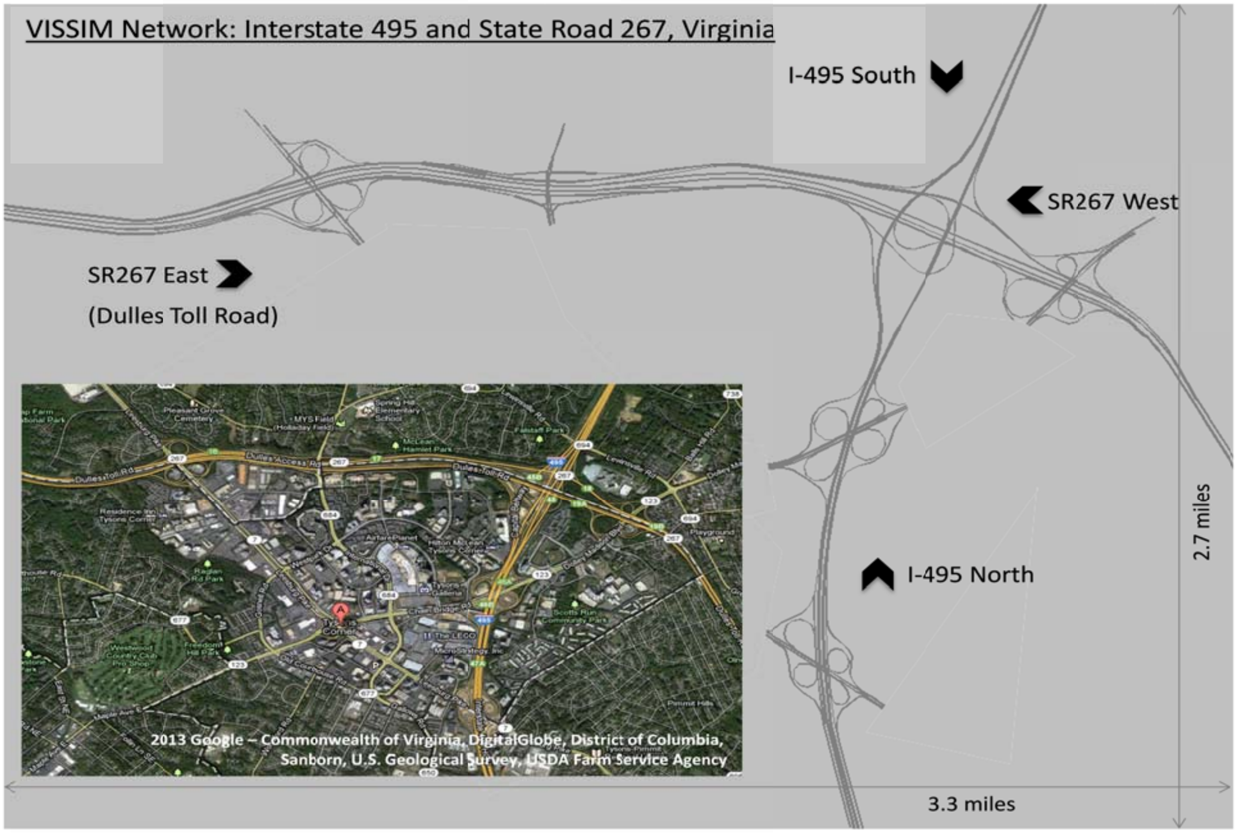


Figure 9. VISSIM test-bed network – I-495 and SR-27, Fairfax, Virginia

6. Conflict Estimation Results

Using the C#-based automated interface, nine replications of simulation runs were conducted with a 10-minute (i.e., from 1800-second to 2400-second) simulation period after a 30-minute warm-up. Noted that the nine replication runs constitute a statistically significant sample size at the 95% confidence level.

Table 1. Simulation settings for conflicts estimation

	Settings
Simulation Period (seconds)	600 (i.e., 1800-2400)
Resolution (seconds)	0.1
Number of replications	9
Warm-up period (seconds)	1800
Average Number of vehicles	4534
Average VMT	18,259

The results show that the VISSIM-CarSim integrated simulation estimated 398 traffic conflicts which is 9.5% fewer conflicts compared to the 440 conflicts extracted from the VISSIM-only simulation. A t-test result (i.e., p-value 0.008) indicated that the results of the VISSIM-only approach and those of the proposed VISSIM-CarSim integrated approach are statistically different. Table 2 shows the conflict estimation results obtained from both approaches.

Table 2. Conflict Estimation Results

	VISSIM Only	VISSIM-CarSim Integrated
Average Number of Conflicts	440	398
Standard Deviation	20.9	26.5
Percent Changed	-	(-) 9.5%
t-test (p-value)	0.008 (reject H0)	

Although the proposed VISSIM-CarSim integrated approach estimated a smaller number of traffic conflicts, it does not mean that the number of traffic conflicts from the proposed approach will always be smaller than those from the existing VISSIM-only approach. Rather, the result can differ by location, time, and the number of aggressive drivers, as the lane change durations are different depending on these factors. In this experiment, the number of lane change vehicles that were less aggressive (i.e., longer lane change duration) than the original lane change vehicles in VISSIM exceeded the number of vehicles that were more aggressive (i.e., shorter lane change duration). The lane change durations collected from the NGSIM data ranged from 1.5 to 8.0 seconds while the original VISSIM lane changes happened at approximately three seconds. In conclusion, according to the lane change duration distribution corresponding to the characteristics of vehicles, the conflict estimation result obtained from the proposed VISSIM-CarSim integrated approach can differ from those in the VISSIM-only approach.

In summary, a field-collected lane change duration distribution was reflected, and the lane change aggressiveness-incorporated vehicle trajectories were simulated by the vehicle dynamics model that have been extensively validated in testing vehicle's movements. In light of these facts, the proposed VISSIM-CarSim integrated approach could generate more realistic vehicle trajectories even including drivers' aggressiveness. Accordingly, the proposed VISSIM-CarSim integrated approach would be more promising to represent the probability of traffic crashes.

Chapter 5

VALIDATION OF TRAFFIC CONFLICTS AS A SAFETY ESTIMATOR

This chapter presents the validation efforts of the effectiveness of the proposed vehicle dynamics model-integrated traffic safety simulation environment. This newly developed traffic safety simulation environment has a potential to calculate surrogate safety metrics. This is because the traffic conflict estimation was conducted using more realistic vehicle trajectories which have incorporated the field-collected lane change duration distribution (i.e., driver aggressiveness) and were simulated by the vehicle dynamics model (i.e., CarSim). However, the relationship between a new traffic conflict estimation result obtained from the proposed traffic safety simulation environment and actual crashes still needs to be validated to ensure that this traffic conflict estimation result effectively can be used as a traffic safety estimator.

With this in mind, in this chapter, the results of the proposed VISSIM-CarSim integrated approach and from the existing VISSIM-only approach (i.e., no driver aggressiveness and the CarSim simulation), were analyzed to estimate their correlation with the actual traffic crashes. These correlations were then used to assess and compare the effectiveness of these two approaches for assessing traffic safety. This correlation analysis was based on the number of traffic crashes and traffic conflicts from I-495 and SR-267 during the evening rush hour from 5 P.M. to 6 P.M.

1. Origin-Destination (OD) Estimation

Traffic crashes and traffic conflicts must be compared on the same basis of traffic demand. To determine whether or not the links in the VISSIM Tysons Corner network truly represent field-collected traffic demand, the field-collected traffic count and the simulated traffic volume were compared. In order to compare the simulated traffic demand with the field-collected traffic demand by links, initially, the network (i.e., Interstate 495 and State Road 267) was separated, and 28 links consisting of 12 sections in I-495 and 16 sections in SR-267 were identified, as shown in Figure 10. Note that the links selected include north and southbound and east and westbound directional links and were separated by considering the link characteristics such as main line and merging/weaving. A unique ID was assigned to each link in order to distinguish the links. For example, each link ID consists of 'road-direction-number' and 'S-E-01' indicates the first link of the east bound at SR-267.

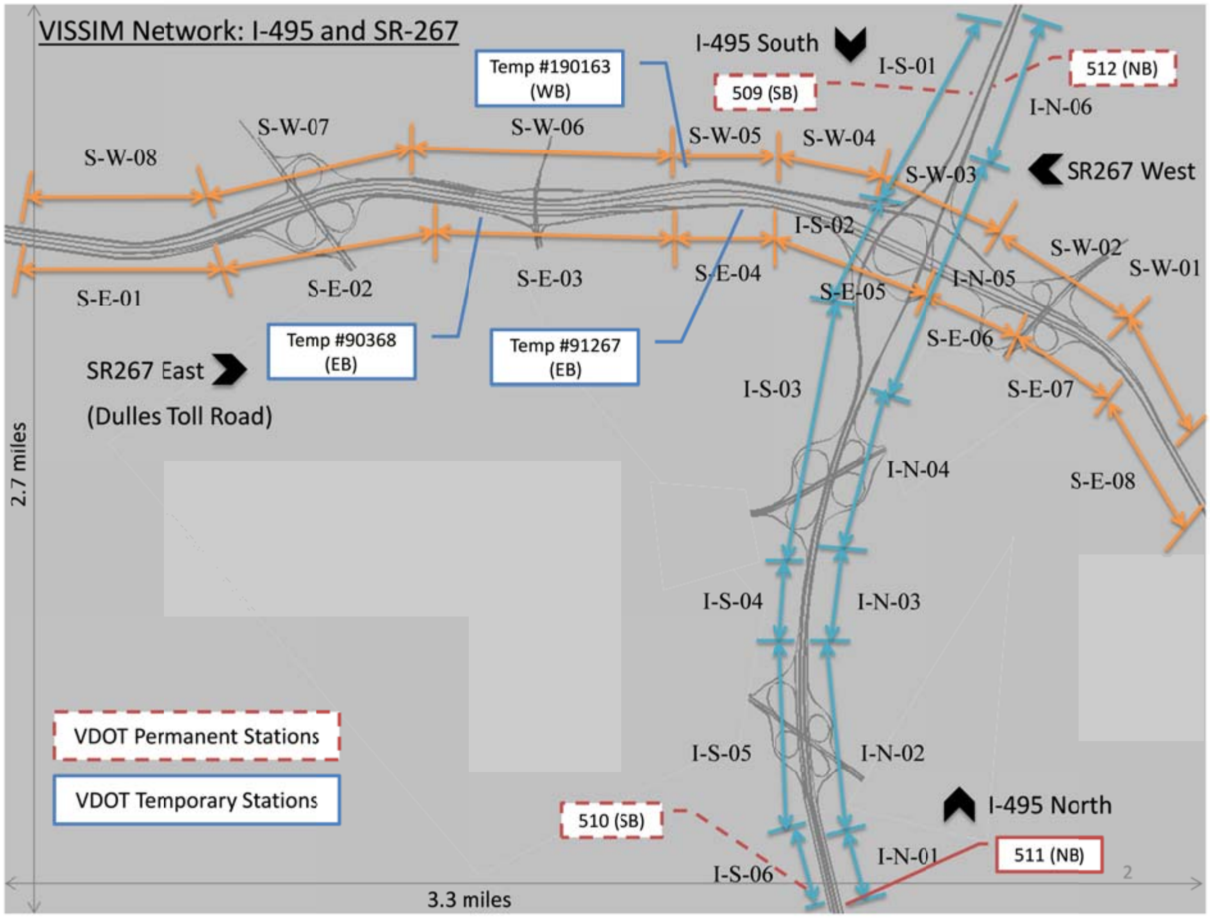


Figure 10. Link separations and VDOT traffic count stations

For each link, a peak hour volume (PHV) was measured by links using Annual Average Daily Traffic (AADT) data with the proportion of PHV out of 24 hours. The 24-hour traffic count data were extracted and analyzed to obtain the proportion of PHV by road sections. In the study area, the Virginia Department of Transportation operates four permanent stations in I-495 and three temporary stations in SR-267. The permanent station traffic counts are being managed by VDOT through the Archived Data Management System (ADMS) so that the traffic count data can be extracted by date, time, and station ID. The station numbers and the dates which were used to extracte the traffic counts are as follows:

- I-495
  - Collected from the VDOT's permanent traffic count stations: Station #509 to #512
  - Used 65 weekdays of 24-hour traffic count data from August to November in 2012
- SR-267
  - Collected from the VDOT's temporary traffic count stations: Station #90368, #91267, and #190163
  - Used 4 weekdays of 24-hour traffic count data in 2012 (11/7 to 11/8 and 11/14 to 11/15)

Finally, the proportions of PHV for I-495 north and south, and SR-267 east and west were obtained from 24-hour traffic count data. As shown in Table 3, 0.082 for I-495 eastbound, 0.057 for I-495 westbound, 0.057 for SR-267 eastbound, and 0.080 for SR-267 westbound were turned out. PHVs for all link sections were computed by multiplying the proportion to AADT.

While the measured PHVs were decided using AADT and the proportion of PHV, the simulated PHV for each link was directly extracted from the simulation outputs. Nine replications of simulation run were conducted and the number of replications constitutes a statistically significant sample size at the 95% confidence level. The initial simulation result indicated that the simulated link traffic volumes (i.e., red-colored) measured based on the initial Origin-Destination (OD) table showed a fairly large difference compared to the field-collected traffic counts, as shown in Figure 11. Therefore, the OD estimation process was conducted by adjusting directional traffic volume at each on/exit ramps while no other adjustment of parameters (e.g., car-following and lane change parameters) was performed.

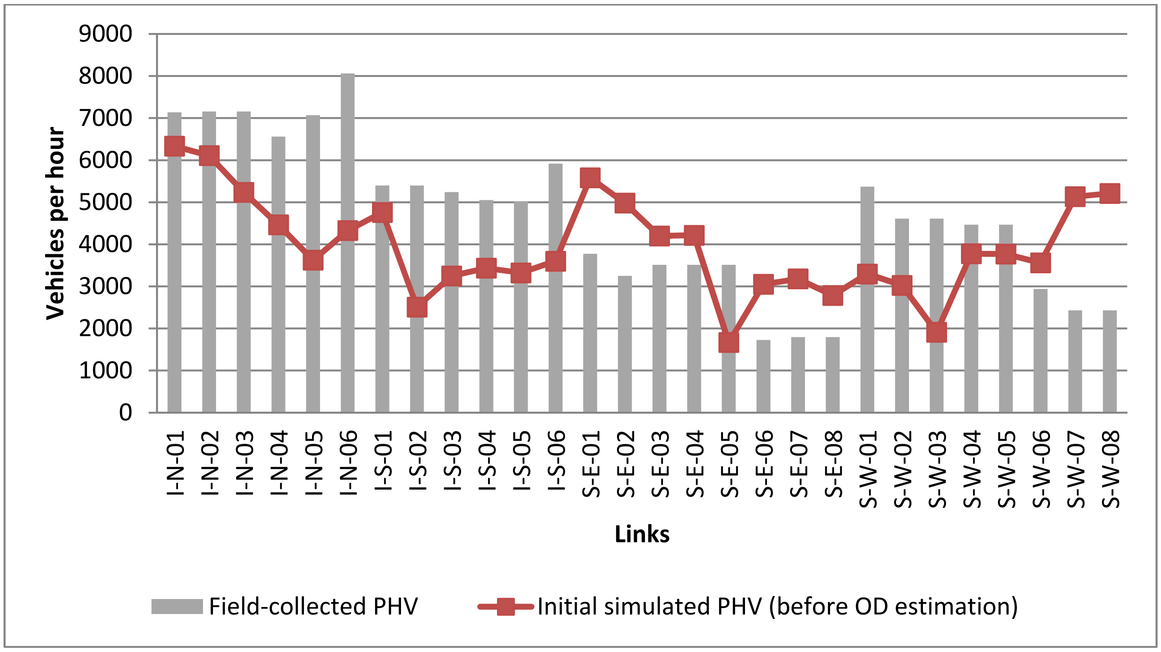


Figure 11. Comparison of measured and simulated peak hour volume

After OD estimation, the measured PHV and the simulated PHV were compared and the difference was measured by the GEH statistics. The simulated PHVs can be accepted to be used for the traffic engineering study when the GEH values are less than 5.0 in 85% of data points [104].

$$\mathrm{GEH} = \sqrt{\frac{2(\mathrm{M}-\mathrm{C})^2}{\mathrm{M}+\mathrm{C}}} \qquad \text{(Eq. 1)}$$

Where, M = simulated hourly traffic volume,

C = hourly traffic volume measured from the field-collected AADT data.

Consequently, the conformity between the simulated PHVs and the PHVs measured from the field-collected data were demonstrated since the GEH value was smaller than 5.0 in all the links. Table 3 shows both the final simulated PHVs and the PHVs measured from the field-collected data and their differences in term of the absolute percentage and the GEH values. Therefore, this VISSIM Tysons Corner network was verified to estimate traffic conflicts which will be compared with traffic crashes observed in this network.

Table 3. Simulated peak hour volume and GEH statistics (after OD estimation)

#	Sections	Links	AADT	% of PHV	Measured PHV	Simulated PHV	% Difference	GEH statistic
1	I-495 (NB)	I-N-01	87051	0.082	7138	7058	-1.12%	0.95
2		I-N-02	87299		7159	7231	1.01%	0.85
3		I-N-03	87299		7159	6779	-5.30%	4.55
4		I-N-04	80004		6560	6581	0.32%	0.26
5		I-N-05	86236		7071	7013	-0.83%	0.7
6		I-N-06	98319		8062	7887	-2.17%	1.96
7	I-495 (SB)	I-S-01	94699	0.057	5398	5770	6.89%	4.98
8		I-S-02	94699		5398	5403	0.10%	0.07
9		I-S-03	91939		5241	5382	2.70%	1.94
10		I-S-04	88659		5054	5145	1.81%	1.28
11		I-S-05	88140		5024	5138	2.27%	1.6
12		I-S-06	103831		5918	6072	2.60%	1.98
13	SR-267 (EB)	S-E-01	66230	0.057	3775	3812	0.98%	0.6
14		S-E-02	57061		3252	3438	5.70%	3.21
15		S-E-03	61667		3515	3632	3.33%	1.96
16		S-E-04	61667		3515	3604	2.53%	1.49
17		S-E-05	61667		3515	3478	-1.05%	0.63
18		S-E-06	30274		1726	1809	4.83%	1.98
19		S-E-07	31482		1794	1943	8.28%	3.44
20		S-E-08	31482		1794	1992	11.01%	4.54
21	SR-267 (WB)	S-W-01	67161	0.080	5373	5021	-6.55%	4.88
22		S-W-02	57663		4613	4518	-2.06%	1.41
23		S-W-03	57663		4613	4657	0.95%	0.65
24		S-W-04	55832		4467	4224	-5.43%	3.68
25		S-W-05	55832		4467	4173	-6.57%	4.47
26		S-W-06	36744		2940	2829	-3.76%	2.06
27		S-W-07	30362		2429	2463	1.40%	0.69
28		S-W-08	30362		2429	2490	2.51%	1.23

2. Crash Data Description

The crash data collected during the past 3 years (i.e., 2006 through 2008) were used for this correlation analysis. Note that the crash data were extracted from the Virginia Traffic Management System which is managed by the Virginia Department of Transportation (VDOT). The following data reduction was conducted in order to obtain the appropriate crash data for this research.

1) Three years of crash data were aggregated because traffic crashes take place infrequently and too few crashes can be observed within a specific time period. In other words, aggregating crash data was essential to obtain enough crash data for analysis.
2) Only traffic crashes occurring during evening rush hour, 5 P.M. to 6 P.M. were collected since the VISSIM Tysons Corner network was constructed with the evening peak hour volume.
3) The number of total crashes included both property-damage only crashes and injury/fatal crashes. The current traffic conflict estimation framework cannot take into account the severity of the crashes. Although lower TTC and PET values constitute a higher probability of crashes, it cannot be directly linked to the severity of traffic crashes. Therefore, this study did not distinguish the severity of traffic crashes.
4) Only the rear-end and angle crash types were considered while the other types were excluded. According to the crash data collected by VDOT, it contains 16

types of traffic crashes[1]. Some crash types result from human error while the traffic conflict analysis can account for the conflicts derived from vehicle interactions. In addition, the traffic crashes occurred at opposite direction such as head-on and sideswipe; pedestrian- and bicyclist-related crashes are unlikely in the freeway sections in which the roads are separated by physical barriers.

According to the data reduction strategies, the crash data were extracted as shown in Table 4.

[1] Collision types defined in the VDOT crash record: rear end, angle, head on, sideswipe (same direction), sideswipe (opposite direction), fixed object in road, train, non-collision, fixed object (off road), deer, other animal, pedestrian, bicyclist, motorcyclist, backed into, other.

Table 4. Crash data by links

#	Sections	Links	Crashes	Conflicts (VISSIM)	Conflicts (VISSIM-CarSim)
1	I-495 (NB)	I-N-01	2	0	0
2		I-N-02	4	2	8
3		I-N-03	3	2	4
4		I-N-04	4	6	10
5		I-N-05	11	58	40
6		I-N-06	3	23	7
7	I-495 (SB)	I-S-01	2	0	2
8		I-S-02	8	69	23
9		I-S-03	1	1	2
10		I-S-04	5	3	4
11		I-S-05	1	0	3
12		I-S-06	3	0	0
13	SR-267 (EB)	S-E-01	0	0	0
14		S-E-02	4	2	2
15		S-E-03	3	1	3
16		S-E-04	1	1	4
17		S-E-05	9	12	8
18		S-E-06	3	0	1
19		S-E-07	4	3	3
20		S-E-08	1	2	2
21	SR-267 (WB)	S-W-01	2	18	4
22		S-W-02	6	1	1
23		S-W-03	6	5	6
24		S-W-04	0	8	4
25		S-W-05	2	18	9
26		S-W-06	0	7	3
27		S-W-07	0	5	1
28		S-W-08	0	0	0

3. Conflict Estimation

In this section, the number of conflicts obtained from the VISSIM-only approach and the proposed VISSIM-CarSim integrated approach were estimated and compared to the number of traffic crashes. Nine replications of VISSIM runs were conducted and the trajectory outputs (.trj) were processed through SSAM in order to estimate the number of conflicts. Note that traffic conflicts were counted during 600 seconds of simulation time period after a 30-minute warm-up period. The nine replication runs constitute a statistically significant sample size at the 95% confidence level. Finally, the number of traffic conflicts was estimated by the following criteria.

1) Two vehicles that had a TTC less than 2.5-second and DRD greater than 4.5 m/s2 were identified as a traffic conflict.
2) The conflicts having a TTC = 0 were excluded from the analysis because the traffic simulation models cannot reflect actual crashes.
3) Only rear-end and lane change conflicts were counted since this validation study was conducted on the basis of freeway corridors.

To estimate the number of conflicts through the VISSIM-CarSim integrated model, additional data post-processing work was conducted to replace the VISSIM lane change trajectories by the CarSim-simulated lane change trajectories. These incorporated vehicle trajectories were converted into the input format of SSAM. Thus, a C#-based data post-processing program was developed and this program generated the CarSim trajectory-incorporated vehicle trajectory file which is an input of SSAM. Consequently, SSAM produced the number of conflicts based on the proposed conflict identification criteria.

Table 5 provides the number of traffic conflicts estimated by each link in I-495 and SR-267.

Table 5. Number of crashes and conflicts

#	Sections	Links	Crashes	Conflicts (VISSIM)	Conflicts (VISSIM-CarSim)
1	I-495 (NB)	I-N-01	2	0	0
2		I-N-02	4	2	8
3		I-N-03	3	2	4
4		I-N-04	4	6	10
5		I-N-05	11	58	40
6		I-N-06	3	23	7
7	I-495 (SB)	I-S-01	2	0	2
8		I-S-02	8	69	23
9		I-S-03	1	1	2
10		I-S-04	5	3	4
11		I-S-05	1	0	3
12		I-S-06	3	0	0
13	SR-267 (EB)	S-E-01	0	0	0
14		S-E-02	4	2	2
15		S-E-03	3	1	3
16		S-E-04	1	1	4
17		S-E-05	9	12	8
18		S-E-06	3	0	1
19		S-E-07	4	3	3
20		S-E-08	1	2	2
21	SR-267 (WB)	S-W-01	2	18	4
22		S-W-02	6	1	1
23		S-W-03	6	5	6
24		S-W-04	0	8	4
25		S-W-05	2	18	9
26		S-W-06	0	7	3
27		S-W-07	0	5	1
28		S-W-08	0	0	0

4. Correlation Analysis Results

One objective of this correlation analysis was to identify whether the traffic conflicts and traffic crashes are related; the other objective was to check the ability of the VISSIM-CarSim integrated simulation environment to estimate traffic conflicts. Specifically, the correlation coefficient corresponding to the strength of the relationship between two variables correlation will identify how strongly the traffic conflicts and traffic crashes are correlated and which approach between the existing VISSIM-only method and the VISSIM-CarSim integrated method better represents the probability of traffic crashes. For the correlation analysis, SPSS Statistics version 20.0 was used to analyze the data and generate a Pearson Product Moment Correlation (PPMC) coefficient (γ) and p-value [105]. Equations 2 and 3 show the formula of correlation coefficient and p-value, respectively. Note that a p-value less than 0.05 means that there is a statistically significant correlation between the traffic conflicts and traffic crashes at the 95% confidence level. In addition, a cross-validation approach [106, 107] was used to estimate confidence intervals of the correlation coefficients. For each approach, a correlation coefficient calculation was repeated 28 times by selecting 27 data points out of 28 data points to split the data set by sliding the window.

$$\gamma = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \qquad \text{(Eq. 2)}$$

where, γ = Pearson correlation coefficient

n = number of samples

x = value of group 1

y = value of group 2

$$t = \frac{\gamma}{\sqrt{\frac{1-\gamma^2}{n-2}}} \qquad \text{(Eq. 3)}$$

where, t= t-statistic

γ = Pearson correlation coefficient

n = Number of samples

Table 6 shows the correlation coefficients and p-values between traffic crashes and the conflicts obtained from the VISSIM-only approach and between traffic crashes and the traffic conflicts obtained from the VISSIM-CarSim integrated approach.

Table 6. Results of Pearson correlation analysis

			Conflicts (VISSIM only)	Conflicts (VISSIM-CarSim)
Crashes	γ-value		0.61	0.72
	p-value		2.69E-04 (reject Ho)	6.66E-06 (reject Ho)
	Cross-validation results	Standard deviation	0.038	0.032
		95% confidence interval [lower, upper]	[0.60, 0.62]	[0.71, 0.73]

Traffic conflicts obtained from the VISSIM-CarSim integrated approach and traffic crashes had a 0.72 correlation strength with the confidence interval between 0.71 and 0.73 while the VISSIM only traffic conflicts showed a 0.61 correlation strength with the confidence interval between 0.60 and 0.62. In both cases p-value was less than 0.05

indicating that there is a statistically significant correlation between traffic conflicts and traffic crashes in either approach. Based on the Pearson correlation coefficients, the VISSIM-CarSim integrated approach more effectively represents the traffic crashes than the existing VISSIM only approach. In addition, the cross-validation results demonstrated the validity of the obtained correlation coefficients because the confidence intervals and the standard deviation values in both cases were fairly small.

Chapter 6

DEVELOPMENT OF A SAFETY SURROGATE ASSESSMENT FRAMEWORK INCORPORATING V2V/V2I AND GPS/INU

This chapter addresses the development of an advanced traffic safety assessment framework that considers the impacts of vehicle positioning errors and communication delays when the safety estimation is conducted. The performance of the vehicle safety applications such as driver warning systems is shown to be affected by the positioning accuracy of GPS and the communication delays between vehicle-to-vehicle and vehicle-to-infrastructure. Specifically, vehicle positioning errors can generate a false alarm while the safety applications generally require the lane-distinguished level of positioning accuracy. The communication delays can delay the issuance of driver warning. Obviously, these two aspects merit consideration when the safety estimation is conducted. However, previous network-wide traffic safety studies have not explored the potential degradation of vehicle safety applications. This chapter therefore presents the development of the GPS/INU positioning error simulator and the V2V/V2I communication connection probability model and the implementation of these error and delays simulators with driver warning scenarios.

1. Safety Assessment Implementation Scenarios

In order to test the impacts of the GPS/INU positioning errors and V2V/V2I communication delays with driver warning scenarios, critical traffic situations were established. This is because the driver warning systems are developed to mitigate the impact of traffic crashes and conflicts in critical traffic situations. The following section describes the critical traffic simulations selected for this experiment and the implementation strategies of driver warnings

1.1. Critical Traffic Situations and Simulation Implementations

Based on the General Estimates System (GES) and the Fatality Analysis Reporting System (FARS), four types of crashes accounted for 85% of all crashes in 2009. The four crash types were run-off-road (23%), rear-end (28%), lane change (9%), and crossing path (25%). These four crash types also account for 75% of all road fatalities: run-off-road (41%), rear-end (5%), lane change (4%), and crossing path (14%) [108].

Although it cannot be simply linked between a specific traffic crash type and its cause, it is reasonable to believe that specific traffic conflict type or traffic situations can significantly affect the occurrence of a specific type of traffic crash. For example, rear-end traffic crashes are caused by relative difference in speed and the crossing path generally occur at a signalized intersection. With this in mind, this research considers the four types of critical traffic situations: lane change, sudden stop, red-light running at a signalized intersection, and road departure. Each critical traffic situation and its implementation in the simulation are described.

1.1.1. Lane Change

Lane change is one of the most common vehicle maneuvers on roadways, and occurs more frequently in merging/diverging sections. In VISSIM, lane changes last for about three seconds and consist of the free and necessary lane changes. The lane change indicator takes three possible values for no lane change (“-“),a lane change to the left (“<”), and a lane change to the right (“>”). Using these indicators, the lane change vehicles are easily detected during the simulation.

1.1.2. Sudden Stop

Sudden stopping is observed when a following vehicle is “forced” to brake, when the leading vehicle unexpectedly decelerates at a higher rate than the following vehicle or when the leading vehicle comes to a complete stop, and the following vehicle does not receive any prior warning. Although the deceleration rate depends on the driver characteristics and the vehicle's mechanical performance, drivers generate maximum decelerations from 6.9 to 9.1 m/s^2 [109]. Based on this reference, the lower bound of the maximum deceleration rate was used to select the suddenly stopping vehicles. Using this lower bound, the vehicles decelerating at or over 6.9 m/s^2 of deceleration rate were considered to be sudden stop vehicles.

1.1.3. Red-light Running at Signalized Intersection

Most of the crossing crashes occur at intersections, where the red-light running is the most serious cause of the crossing crashes [110, 111]. Therefore, the number of red-light running vehicles was used as a surrogate safety measure for the signalized intersection scenario. In order to capture the red-light running vehicles in VISSIM, detectors were installed beyond the stop bars as shown in Figure 12. Each detector was connected with each traffic signal head by sharing the same identical number. Therefore, the vehicles that passed through the detector at the onset of red were identified as red-light runners.

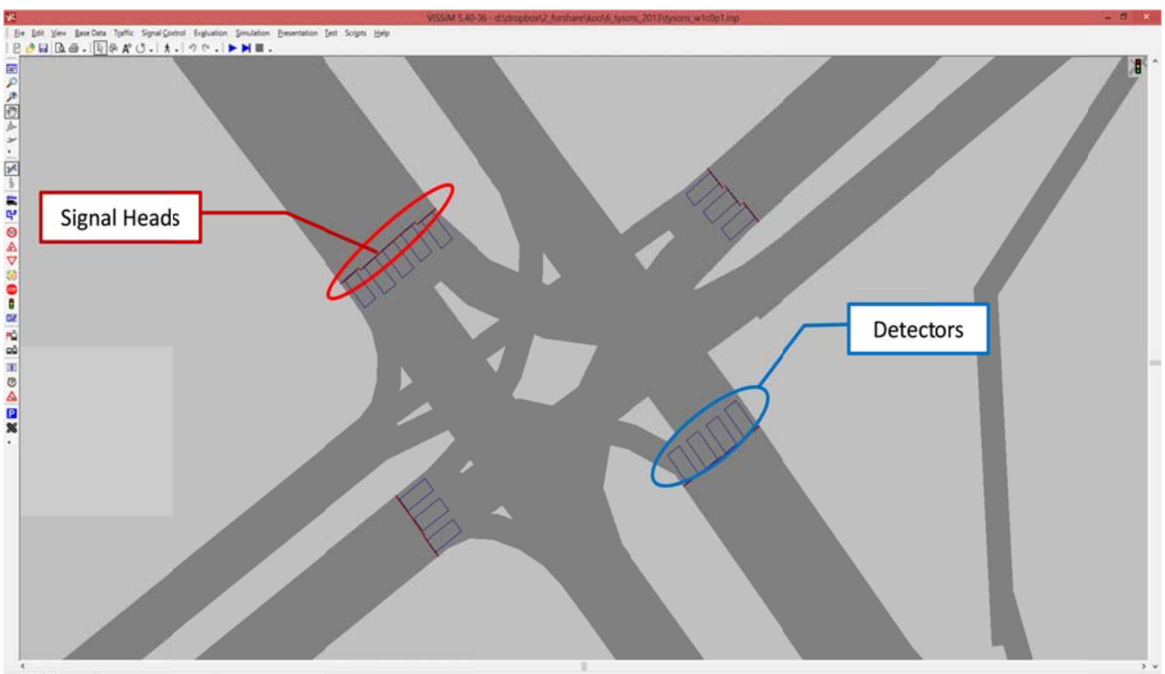


Figure 12. VISSIM red-light running detectors

1.1.4. Road Departure

Road departure takes place when a driver does not recognize the path of his vehicle or cannot control his vehicle's maneuvers and his vehicle runs off the road. As previously stated, road departure crashes are the most dangerous. This crash type could be extremely serious, when vehicles roll over or run into stationary objects such as trees or buildings. Because of the severity of road departure crashes, automobile companies have conducted many studies for developing effective warning systems to prevent these types of crashes.

VISSIM, however, cannot handle vehicles running off the road because VISSIM handles only the vehicles within a lane or link. In order to model the road departure scenarios using VISSIM, an external DriverModel.dll was developed and implemented, replacing VISSIM's internal driver model and allowing vehicles to travel off a road.

Road departure crashes are rare events that occur at the rate of 0.55 crashes per 100 million vehicle-miles traveled (VMT), according to the General Estimate System (GES) crash statistics in 2009 [112]. Therefore, it is a challenge for a road departure to take place during a single simulation. For instance, according to this crash rate, approximately 0.00053 crashes would be considered for the road departures during a one-hour simulation period (i.e., 95,928 vehicle-miles-traveled during one hour in the VISSIM Tysons Corner network). For the safety estimation, however, multiple cases of the road departure scenario must occur.

Road departure is a function of factors including roadway geometry, vehicle approaching speed, vehicle dynamics, lane changing maneuvers, driver inattention (e.g. drowsiness). In order to emulate the road departure scenario, one or more factors may force a vehicle to leave the road. Since VISSIM does not allow vehicles to depart from a road, VISSIM was used to develop a methodology to allow vehicles to depart from a road. This was accomplished through the use of 25 randomly selected vehicles with various speeds, acceleration, and deceleration rates operating in the Tysons Corner, Fairfax, Virginia network. The 25 vehicles were utilized since 25 'fixed-object-off road' crashes actually occurred in 2010 in the Tysons Corner area of Virginia. The 25 randomly selected vehicles were ordered to run off the road and the trajectories obtained for these vehicles were used to evaluate safety using driver warnings. Shoulder width was set as eight feet according to the American Association of State Highway and Transportation Officials' (AASHTO) recommendation [113].

1.2. Safety Assessment Scenarios

The following components are developed and integrated into the microscopic traffic simulation model and implemented with driver warning scenarios in this chapter.

1) Integrated traffic safety simulation environment (i.e., VISSIM-CarSim).
2) V2V/V2I communication delays simulator.
3) GPS/INU positioning errors simulator.

For testing each of these modules and for estimating how the V2V/V2I delays and GPS/INU positioning errors affect the driver warnings and responses, and ultimately traffic safety, the following four traffic safety assessment scenarios were established:

1) Base scenario – no driver warning and errors
2) Driver warnings without errors – ideal case

3) Driver warnings with V2V/V2I communication delays

4) Driver warnings with GPS/INU errors and V2V/V2I communication delays

Figure 13 shows a conceptual diagram of the four scenarios established for the safety assessment.

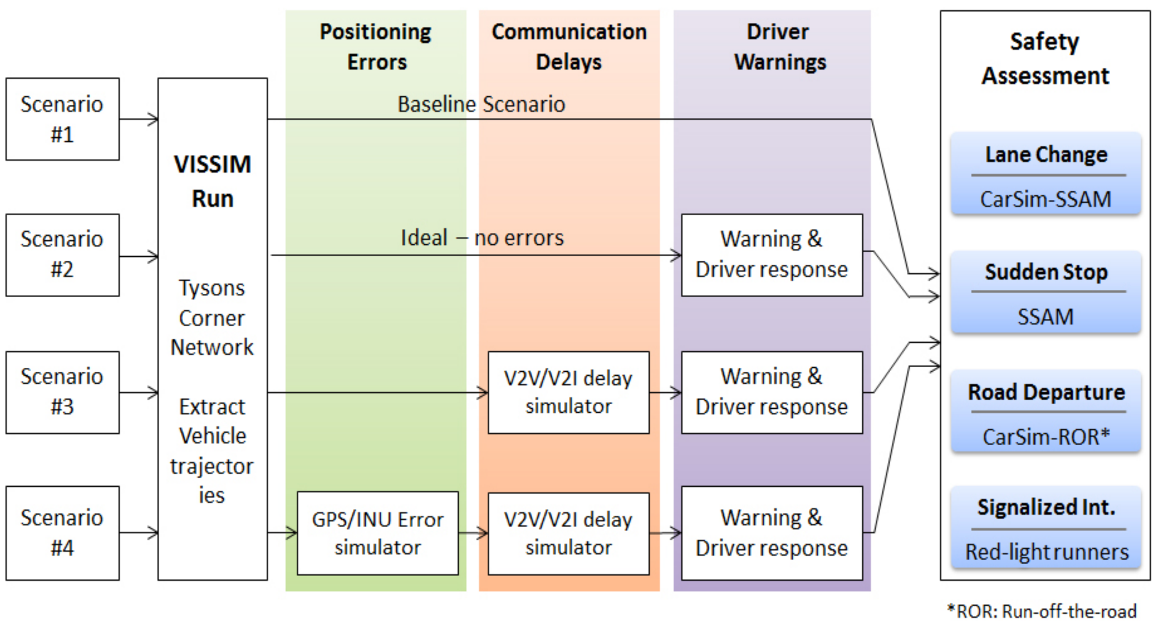


Figure 13. Conceptual diagram of the safety evaluation scenarios

The first scenario is a baseline scenario, reflecting the condition when no driver warnings are issued. In the second scenario, driver warnings are issued without any communication delays or positioning errors. This scenario reflects an ideal case when the driver warnings are issued on time without communication delays, and using errorless vehicle positions.

Assuming the drivers respond to the warnings with appropriate actions (e.g., braking), this scenario was considered as the safest.

In the third scenario, the communication delays were taken into account for issuing driver warnings. This scenario implies that the real-world communication delays result in delayed or missed driver warnings. In the last scenario, both the GPS/INU positioning errors and the V2V/V2I communication delays were considered for issuing driver warnings. Note that the GPS/INU positioning errors are expected to have a negative effect on detecting warning thresholds, and it could lead to false alarms due to vehicle location detection errors.

1.3. Driver Warnings

For the implementation of driver warnings and the investigation of their effects to the network-wide traffic safety, driver warning strategies for all conflict triggering scenarios were established. The rear-end crash warnings were adopted for the lane change and the sudden stop cases. The road departure warnings and the red-light running warnings were adopted for the road departures and the red-light runnings at signalized intersections. Table 7 summarizes the driver warning scenarios corresponding to the traffic conflict triggering situations.

Table 7. Driver warning scenarios

Traffic conflict triggers		Driver warnings
Lane change	→	Rear-end crash warning
Sudden stop	→	Rear-end crash warning
Road departure	→	Road departure warning
Red-light running at signalized intersections	→	Red-light running warning (Dilemma zone warning)

Warnings are triggered by a surrogate measure and its threshold value. The vehicle that needs to be warned responds through deceleration or steering maneuvers. A steering maneuver is considered in the road departure case and a deceleration maneuver is applied in response to the rear-end crash and red-light running warnings. Once a driver warning has been issued, the driver responds after the perception-reaction time (PIEV) has passed. Many previous studies have suggested various (PIEV) values. For this investigation we adopted a mean value of 1.0 second for PIEV in accordance with a more recent study as reported in [114]. Based on this study, a perception-reaction time was computed through a stochastic distribution, using a mean value of 1.00 s, a standard deviation of 0.37 seconds, a 15th percentile of 0.68 seconds, and a 85th percentile of 1.33 seconds.

1.3.1. Rear-end Crash Warning - Lane Change and Sudden Stop Cases

Since lane change and sudden stop conflicts are distinguished by different conflict angles in the direction of travel, the rear-end type warnings were adopted for both conflict types. A Time-To-Collision (TTC) of less than 2.5 seconds and a Deceleration-Rate-Difference over 4.5 m/s^2 were adopted for the rear-end warning threshold values [102]. Equations 4 and 5 were used for the computation of the TTC and DRD thresholds.

- Time-to-Collision (TTC):

$$\mathrm{TTC} = \frac{x_1 - x_2 - l_1}{v_2 - v_1}, \ \text{if } v_2 > v_1 \qquad \text{(Eq.3)}$$

where, x1, x2: positions of vehicles 1 and 2 in meters;
v1, v2: speeds of vehicles 1 and 2 in meters/second;
l1 : length of vehicle 1 in meters.

- Deceleration-rate-difference (DRD):

$$\mathrm{DRD} = d_2 - d_1, \ \text{if } d_2 > d_1 \qquad \text{(Eq.4)}$$

where d_1, d_2 are the deceleration rates of vehicles 1 and 2 in m/s^2.

The rationale for using the TTC and DRD values is that the probability of a crash increases, when the following vehicle travels at a higher speed than the leading vehicle and the following vehicle does not decelerate in correspondence to the leading vehicle's deceleration. Therefore, the TTC threshold is calculated only when the speed of the following vehicle (v2) exceeds the speed of the leading vehicle (v1). The DRD threshold value is also computed when the deceleration rate of a following vehicle (d2) exceeds the deceleration rate of the leading vehicle (d1). Finally, a driver warning was issued, when a pair of vehicles meets these two criteria. Note that driver warnings were generated based on the VISSIM trajectories.

1.3.2. Red-light Running Warning - Signalized Intersection Case

For the red light running warnings, the concept of the 'dilemma zone' was adopted [115]. The 'dilemma zone' is based on the difference between the distance at which the nearest vehicle can come to a complete stop (Xc) and the distance from the stop line to the farthest vehicle that can cross an intersection at the onset of yellow (Xs). This concept was used to identify the area for generating warnings. The length of dilemma zone is calculated as follows:

$$\mathrm{Xs} - \mathrm{Xc} = \mathrm{V}(\mathrm{tr} - \mathrm{YT} + \mathrm{V}/2\mathrm{a}) \qquad \text{(Eq.5)}$$

where,

Xs = minimum distance (meters) to safely stop at the intersection, calculated through the Equation with $\mathrm{Xs} = \mathrm{V}(\mathrm{tr} + \mathrm{V}/2\mathrm{a})$ which is equal to the stopping sight distance;

Xc = maximum distance (meters) to safely cross the intersection, calculated through the Equation $\mathrm{Xc} = \mathrm{V} * \mathrm{YT} - (\mathrm{W} + \mathrm{L})$; V is vehicle speed limit (m/s);

tr = reaction time (assumed 1 sec);

a = deceleration rate (m/s^2);

YT = yellow change interval, in seconds;

W = intersection width (meters);

L = vehicle length (meters).

1.3.3. Road Departure Warning – Road Departure Case

For the road departure warning criteria, time-to-line crossing (TLC) was used. TLC is the amount of time a driver has until the vehicle reaches any of the lane boundaries. Godthelp et al. [116] introduced the concept of TLC as a safe margin for the road departure warning, and Winsum et al. [117] suggested a simpler way to approximate the TLC . Previous studies [118, 119] have recommended using 1.0 second of TLC to issue the road departure warnings, assuming that perception-reaction time is usually less than 1.0 second for drivers. Therefore, when a vehicle has less than 1.0 second of TLC to reach the road-departure criteria, the road-departure warnings are generated.

- Time-to-line-crossing (TLC)

$$\mathrm{TLC} = \frac{y}{y' - y''} \quad \text{(Eq.6)}$$

where

y = lateral distance between the front wheel and the lane boundary (m);

y' = lateral velocity (m/s);

y'' = rate of change of lateral velocity (m/s^2)

2. V2V/V2I Connection Probability Model

Many advanced vehicle safety systems have been studied and developed by taking advantage of the Connected Vehicles communication technology (i.e., Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I)). However, most studies have been conducted simply assuming a perfect communication connection while the communication performance is affected by external factors including the distance between road side units (RSUs) and in-vehicle on-board units (OBUs), the number of transceivers within the communication coverage, and the physical obstructions (e.g., trees and buildings). During the course of this dissertation research, V2V and V2I communication delay models have been developed, for the evaluation of the wireless communication impact on the traffic safety estimation. Therefore, in this section, the development of the V2V/V2I communication simulator is presented.

2.1. Simulation Test-bed

For testing the performance of V2V and V2I wireless communications by various traffic conditions, one signalized intersection, located in Leesburg Pike, was selected inside the VISSIM Tyson's Corner network. Figure 14 shows the VISSIM network created for the V2V and V2I communication simulations.

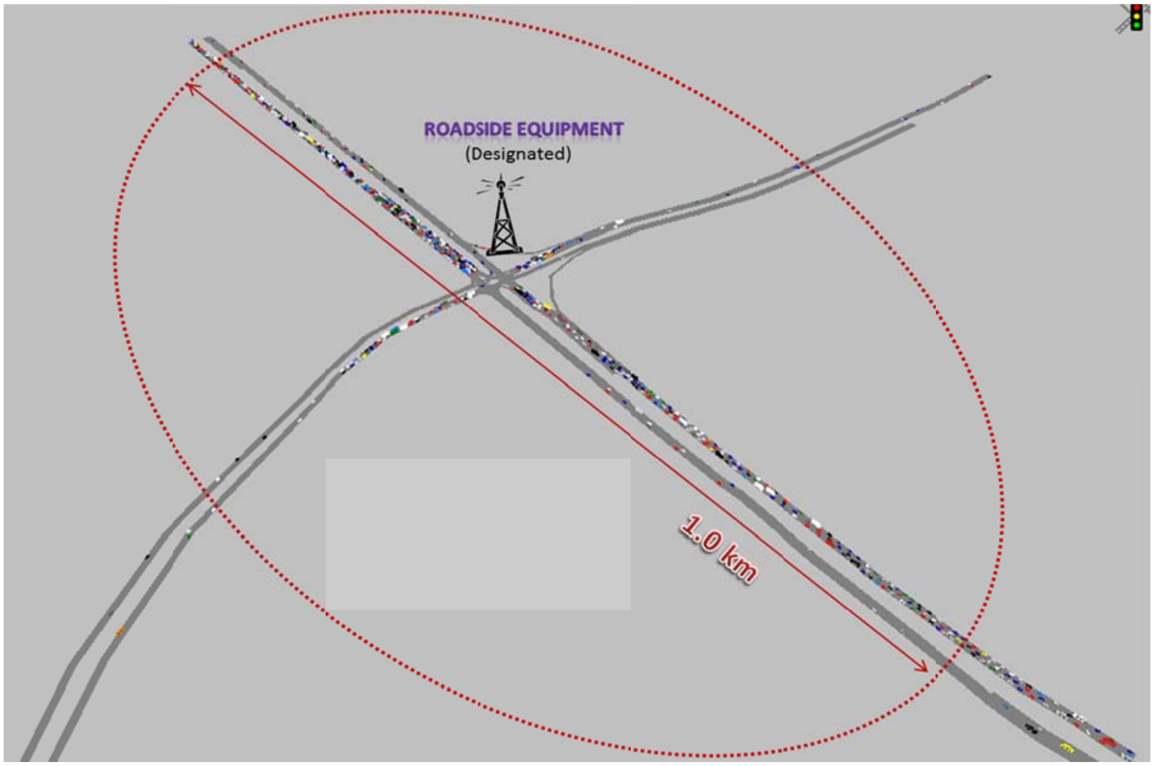


Figure 14. VISSIM V2V/V2I simulation network

For the simulation of the communication performance under a variety of traffic conditions, vehicle trajectories were recorded from the initial simulation time, when there is no traffic demand, to the time when queues are increased and the network is congested (i.e., peak-demand). Running VISSIM in the post-processing mode and using its output vehicle trajectory record (*.fzp) files, the vehicle trajectories were extracted and reformatted for the communication simulator. For the estimation of the V2V/V2I communication delays, the communication simulator uses the vehicle trajectories as a snapshot for each time step. For the traffic volume settings, the PM-peak traffic volume data were obtained from Fairfax County, Virginia.

Table 8. Traffic volume – P.M. peak demand

	EB	WB	SB	NB
Vehicles per Hour	821	2061	3764	4146

The vehicle trajectories, extracted at every time step, were recorded to a *.trj file. This is the input file to the communication simulator for importing each vehicle's location. As shown in Figure 15, each row of a *.trj file consists of vehicle's ID, x-coordinate, y-coordinate, and the speed.

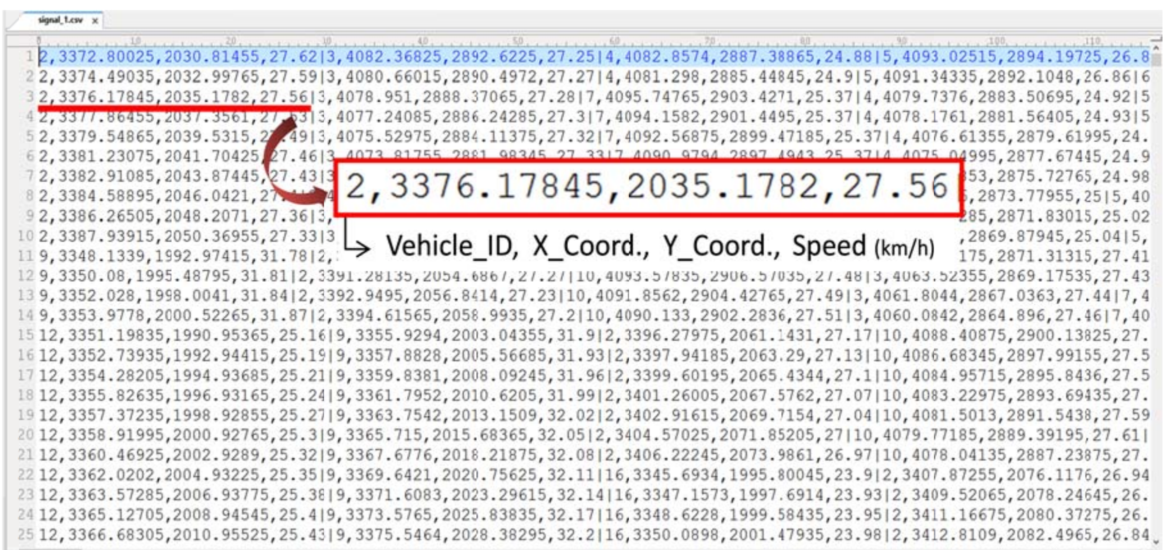


Figure 15. NCTUns vehicle trajectory input file (*.trj)

2.2. Communication Performance Simulation

For the V2V/V2I communication simulations, the NCTUns network simulator and emulator [89] was selected. The reason for this selection was because the models implemented in the NCTUns simulator adhere to the Connected Vehicles communication standards (i.e., IEEE 802.11p and IEEE 1609 family).

The NCTUns network traffic simulator and the VISSIM traffic simulator are not compatible for the following reasons: 1) NCTUns runs on Linux while VISSIM runs on Windows, 2) NCTUns and VISIM use different data formats, and 3) NCTUns runs under a pre-defined message dissemination schedule and a fixed number of vehicles. To compensate for the incompatibilities between NCTUns and VISSIM, a traffic simulator agent (TSA) program [120] was used. This TSA agent was developed at the Center for Transportation Studies (CTS) of the University of Virginia, and adopted for this dissertation to reconcile the incompatibilities between the NCTUns and VISSIM.

The following assumptions were made during the NCTUns simulation run;

1) V2V communications are used for lane change and sudden stop driver warnings.
2) V2I communications are used for signalized intersection and road departure driver warnings.
3) Use of Dedicated Short Range Communications (DSRC) – Control channel (CCH).
4) Each vehicle is equipped with an On-Board Equipment (OBE).
5) Road Side Equipment (RSEs) broadcast messages every 100-milliseconds through the CCH.

6) OBE communicates with RSE up to distances of 1Km.
7) The basic Safety Message (39-byte in the SAE J2735) was used for the safety applications.

The calibration of the NCTUns simulator to reflect the field conditions was accomplished through a calibrated parameter set, as shown in Table 9, developed at the Center for Transportation Studies of the University of Virginia [121].

Table 9. NCTUns simulation parameter set

Parameters	Level	Parameters	Level
Data Rate (Mbps)	27	Nakagami M1	1.85
Transmitter Power (dbm)	19	Nakagami M2	1.1
Large-scale Fading Model	Two-ray ground model (TGM)	Nakagami M3	0.7
Path Loss Exponent	2.2	Nakagami D1	59
System Loss	1.3	Nakagami D2	123
Small-scale Fading Model	Nakagami Fading Model		

2.3. Communication Success/Failure Modeling

In order to emulate the V2V or V2I communications, a communication connection logit probability model was developed to produce the communication success and failure rates as follows:

$$\text{Probability} = \frac{e^{\text{Utility}}}{1+e^{\text{Utility}}}, \qquad \text{Utility}_i = \alpha + \beta C_1 + \gamma C_2 \qquad \text{(Eq.7)}$$

where,

$\alpha, \beta,$ and γ = constant coefficients;

C_1 = total number of OBEs (i.e., total number of vehicles within the communication range);

C_2 = distance between transceivers (i.e., vehicles).

The logit utility functions for the V2V and V2I communications were computed on the basis of the NCTUns simulation results. Tables 10 and 11 show the logit coefficient values for V2V and V2I communications, respectively.

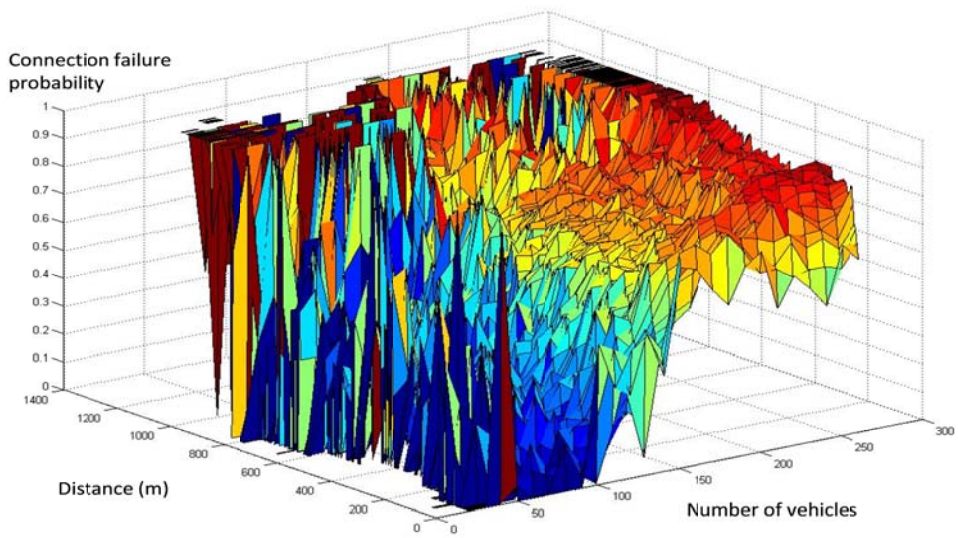
Table 10. Logit modeling results for V2V communications

Predictor	Coefficient	p-value
Constant (α)	1.65326	0
Vehicles (β)	-0.01396	0
Distance (γ)	-0.00014	0

Table 11. Logit modeling results for V2I communications

Predictor	Coefficient	P
Constant (α)	1.61021	0
Vehicles (β)	-0.00615	0
Distance (γ)	-0.00058	0

Figure 16 shows the probability of communication failures for the V2V (Figure 16-up) and V2I (Figure 16-down) communications as a function of the distance between vehicles and the number of vehicles in the network.



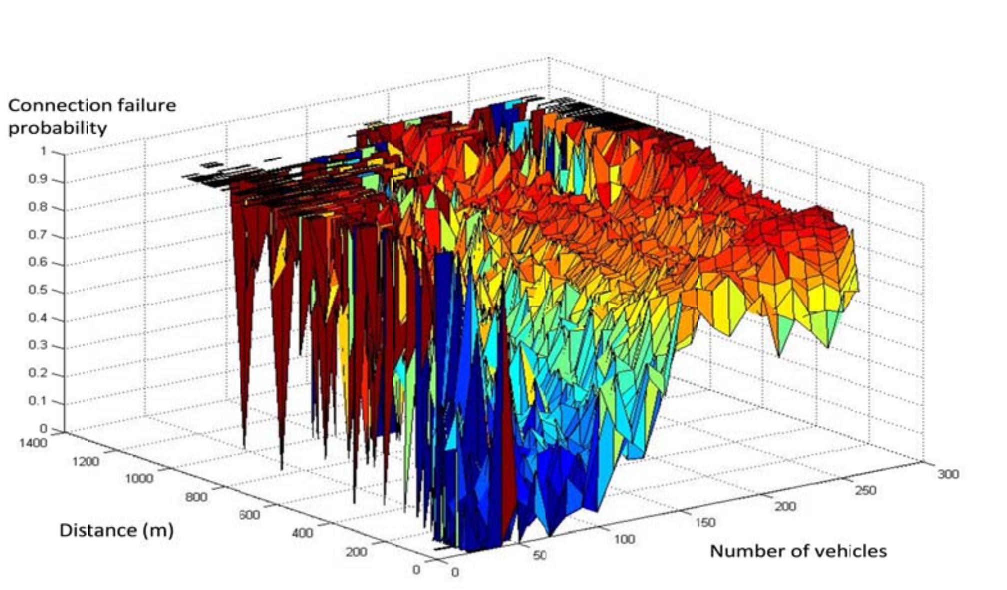


Figure 16. V2V/V2I connection failure probability plot (up-V2V) (down-V2I)

2.4. V2V/V2I Communication Delays with Driver Warnings

The logit models for the V2V/V2I communications were used to identify the existence of communication delays during the current time step. The driver warnings are delayed and not issued in the current step, when the connection probability indicates that communications failed. When the connection probability indicates communication success, the warnings are issued without any delays. For the final safety evaluation, this V2V/V2I communications simulator was integrated with the overall safety evaluation simulator.

3. GPS/INU Simulator

3.1. GPS Error Modeling

The GPS positioning errors depend on measurement and modeling errors. Both types of errors consist of internal receiver noise, residual satellite clock errors, ephemeris errors, ionospheric errors, tropospheric errors, and multipath errors [122]. All these errors are combined and expressed as the User Equivalent Range Error (UERE) which is the combined standard deviation of errors [123]. Table 12 shows the UERE values of different GPS devices employed for this experiment [122].

Table 12. User Equivalent Range Errors [122]

	Autonomous GPS	Local differential GPS	OmniStar-aided GPS	Real-Time Kinematic (RTK) GPS
UERE (meters)	7.1	0.45	0.060	0.029

In this research, these four GPS devices with different levels of accuracy were considered. As shown in Table 12, RTK GPS is the most accurate of the four alternative GPS devices, followed by OmniStar-aided GPS, Local Differential GPS, and Autonomous GPS.

Since the VISSIM Tysons Corner network is a horizontal network and does not reflect the elevations of the roads, height variation are not taken into account for the simulation of the GPS positions. Consequently, the GPS x, y positions are simulated using Equation 8 and 9 [122].

$$\mathrm{GPS}_{\mathrm{x,Simulated}} = \mathrm{x}_{\mathrm{true}} + \mathrm{N}(0, \sigma_{\mathrm{x}}) \qquad \text{(Eq.8)}$$

$$\mathrm{GPS}_{\mathrm{y,Simulated}} = \mathrm{y}_{\mathrm{true}} + \mathrm{N}(0, \sigma_{\mathrm{y}}) \qquad \text{(Eq.9)}$$

Where, xtrue, ytrue = ground-truth x, y coordinates

$\mathrm{N}(0, \sigma_{\mathrm{x}})$, $\mathrm{N}(0, \sigma_{\mathrm{y}})$= normally distributed variables with zero mean and $\sigma_{\mathrm{x}}, \sigma_{\mathrm{y}}$ standard deviations

The GPS satellite visibility map was constructed to consider the impact of the obstructions, mostly the buildings in the Tysons Corner network. The visibility map has been computed based on the actual building height obtained from the GIS and Mapping department of the Fairfax County, Virginia, at every pixel of actual size 0.3m*0.3m as shown in Figure 17 [122].

Figure 17. Tysons Coner building height map (pink-colored) [122]

3.2. INU Error Modeling

The INU sensor is used to support GPS positioning by estimating the vehicle positions when the satellite signals are obstructed and a sufficient number of satellites is not available to compute the vehicle positions. The INU sensor also enables vehicle orientation information to be generated at all times while GPS provides yaw information only when the vehicles are in motion. There are many types of INU sensors such as navigation-grade INU and tactical-grade INU. However, only high and low-accuracy Micro Electro-Mechanical Systems (MEMS) INU devices were used in this research.

The gyro measurements such as yaw and roll rates were simulated based on the front and rear vehicle coordinates obtained from VISSIM. Since the simulated network does not reflect elevations, the pitch rates are set to zero. In addition, the accelerometer measurement was simulated based on the vehicle Center of Gravity coordinates obtained from VISSIM. As a preliminary implementation, Table 13 shows the biases and the scale factors for the INU sensor types, simulated based on real-data [122].

Table 13. INU error characteristics [122]

INU Type		High Accuracy MEMS	Low Accuracy MEMS
Accelerometer	Bias (mg)	0.98	8.3
	Scale factor ($\mathbf{ppm}$)	300	10000
	Velocity random walk ($\frac{m/s}{\sqrt{s}}$)	1.50E-03	8.30E-04
Gyroscope	Bias ($\frac{\mathbf{deg}}{\mathbf{h}}$)	7	3506.5
	Scale factor ($\mathbf{ppm}$)	150	10000
	Angular random walk ($\frac{\mathbf{deg}}{\sqrt{\mathbf{h}}}$)	0.09	0.86

3.3. GPS/INU Scenarios

Eight combinations of GPS/INU devices consisting of four GPS devices and two INU devices were considered for this dissertation research.

1) Real-Time Kinematic (RTK) GPS and high-accuracy MEMS
2) Real-Time Kinematic (RTK) GPS and low-accuracy MEMS
3) OmniStar-aided GPS and high-accuracy MEMS
4) OmniStar-aided GPS and low-accuracy MEMS
5) Local Differential GPS and high-accuracy MEMS
6) Local Differential GPS and low-accuracy MEMS
7) Autonomous GPS and high-accuracy MEMS
8) Autonomous GPS and low-accuracy MEMS.

4. Experiment Settings

4.1. Driver Warning Simulation Architecture

The proposed safety assessment framework was designed based on the traffic simulator (i.e., VISSIM), and consists of two parts: the real-time simulation approach for the driver warnings and responses simulation based on the V2V/V2I communication delays and the GPS/INU positioning errors, and the vehicle trajectory post-processing approach for generating more realistic vehicle trajectories incorporating vehicle dynamics such as pitch, yaw, and roll. In the real-time simulation approach, three simulators were integrated into the driver warning module: the VISSIM microscopic simulator, the V2V/V2I communication delays simulator, and the GPS/INU simulator. The driver warnings and responses based on the communication delays and positioning errors were implemented by utilizing the VISSIM COM interface.

For the GPS/INU errors, eight levels of accuracy have been considered for generating surrogate safety measures using the horizontal x, and y coordinates. When the surrogate safety measures, generated from the GPS/INU erroneous x, y coordinates, cross the warning threshold values, the driver response module is activated after applying the communication and perception-reaction time (PIEV) delays. A driver deceleration rate of 3.5 m/ s^2 was assumed, in response to driver warnings. Previous investigations have used this deceleration rate for stopping vehicles [114]. Figure 18 shows the process of the driver warning simulation.

In addition, the vehicle trajectories generated from the real-time simulation approach were processed through the vehicle dynamics simulation (i.e., CarSim). This is because

CarSim is capable of generating realistic in-lane lateral movement and lane change trajectories, something that existing traffic simulation models are lacking. Thus, the VISSIM lane change vehicle trajectories were simulated by CarSim, and these CarSim-imulated vehicle trajectories were then incorporated with the other VISSIM vehicle trajectories. Finally, this incorporated vehicle trajectory set was used for estimating surrogate safety.

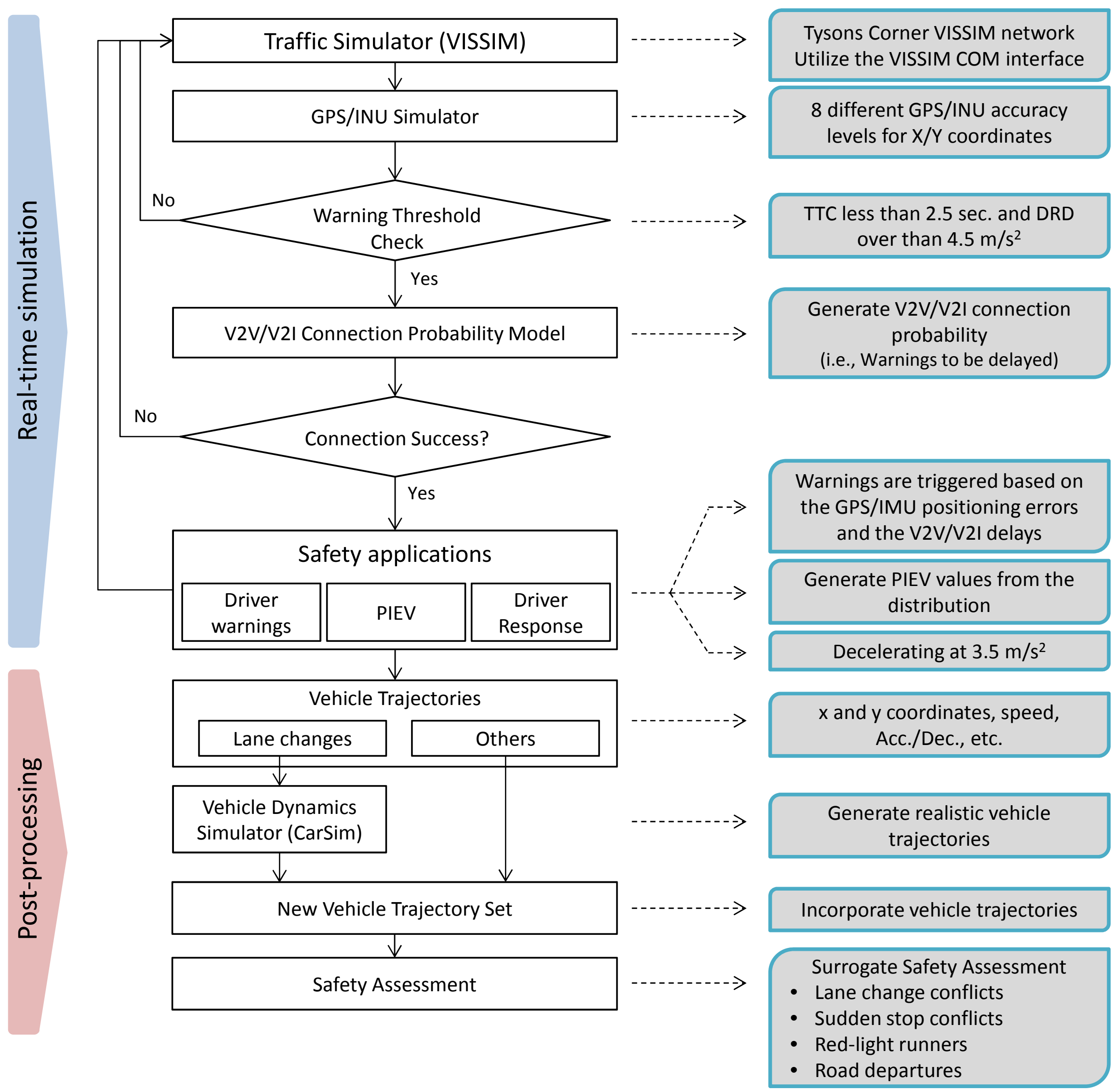


Figure 18. The process of driver warning simulation

4.2. Simulation Test-bed

The Tysons Corner area in Fairfax, Virginia, was selected as the transportation test-bed network because it includes freeways, arterials, signalized intersections, and also provides a wide network for a sizable variety of vehicle conflicts.

This network has a radial extension of approximately 1.5 miles, and consists of 2 freeway corridors, 5 major arterials, and 18 signalized intersections, as shown in Figure 19:

- Freeway sections (2): Interstate 495, Dulles Toll Road.
- Arterial sections (5): Leesburg Pike, International Drive, Chain Bridge Road, Gosnell Road, Dolly Madison Boulevard.
- Signalized intersections (18).

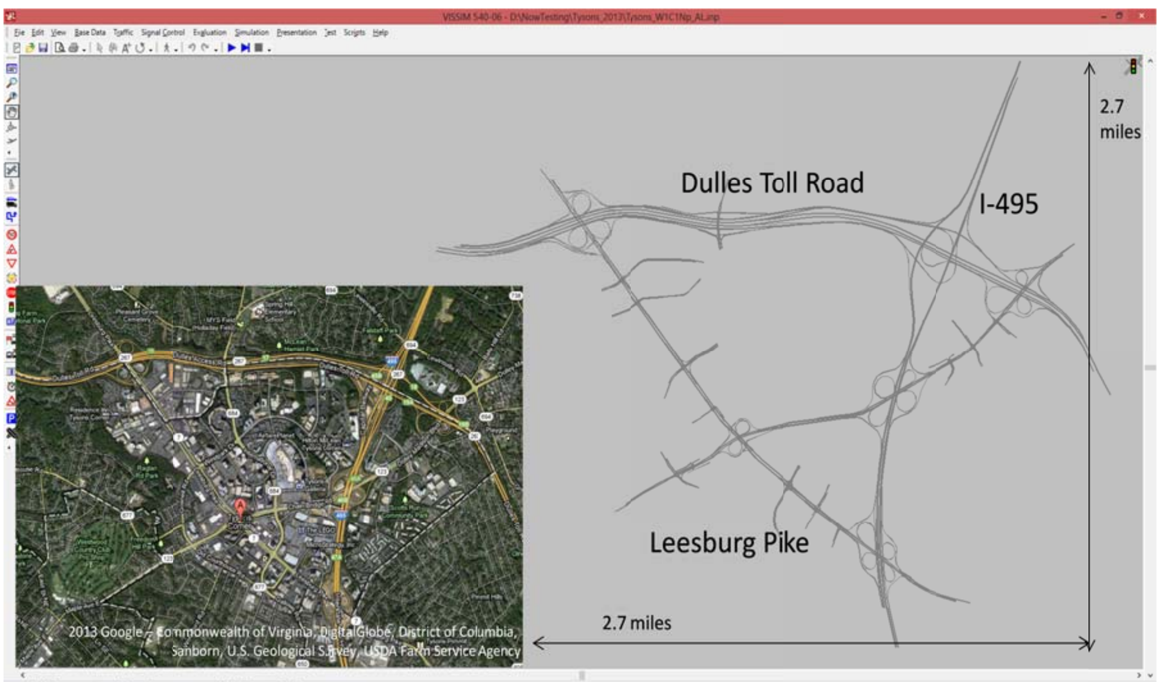


Figure 19. VISSIM test-bed network – Tysons Corner area, Fairfax, Virginia

Because of its complexity, the Tysons Corner network was expected to produce a variety of traffic conditions including lane changes, sudden stops, road departures, and red-light running at the signalized intersections. The P.M. peak traffic volume dataset was obtained from the Virginia Department of Transportation (VDOT) Northern Virginia District [103]. This data set was used to construct the VISSIM network, which was used for all tasks conducted in this project.

4.3. Simulation Settings

The driver warning simulations were conducted based on two traffic volume conditions: peak demand and non-peak demand. For this purpose, the initial 600 seconds of the Tysons Corner network simulation were devoted to the non-peak demand scenarios, and another 600 seconds between 1800 and 2400 seconds were devoted to the peak demand scenarios. The six replication runs constitute a statistically significant sample size at the 95% confidence level. Table 14 shows additional information for the simulation environment.

Table 14. Simulation settings

	Peak	Non-peak
Simulation Period (second)	600	600
Resolution (second)	0.1	0.1
Average Number of vehicles	10,232	7,708
Average VMT	18,022	16,054

4.4. Performance Measures

The proposed scenarios were evaluated with respect to safety, mobility, and environment. The VISSIM output is directly used to evaluate the mobility, and surrogate safety measures which are calculated using the VISSIM vehicle trajectories were used to evaluate safety. A VT-Micro model, a microscopic level model for estimating emissions and fuel consumption and subsequently assessing the environmental impact [124], was also used to evaluate the environment.

4.4.1. Safety

For the evaluation of the traffic safety for the lane change and sudden stop cases, a modified version of the SSAM software was used. This dissertation research adopted a time-to-collision value of less than 2.5 seconds and deceleration-rate-difference (DRD) greater than 4.5 m/s^2 to estimate traffic conflicts in overall sections. This is because the default threshold (i.e., TTC less than 1.5 seconds) is too short for a driver to respond before a crash. These TTC and DRD thresholds calculated in the modified SSAM program were used for the analysis of the lane change and sudden stop cases. In addition, the number of run-off-road cases and the number of red-light runners were used as surrogate safety measures for the road departure and signalized intersection cases respectively.

4.4.2. Mobility

The total delays in the network and the average speed per vehicle were used as the main mobility measures. These measures were computed from VISSIM's network performance output files (*.npe).

4.4.3. Energy and Environment

The main measures of performance estimated for the energy efficiency and air quality were the network-wide fuel consumption and CO_2 emissions. The estimates for fuel consumption and emissions were produced through the use of the VT-Micro model [124], which was developed from field experimental data and estimated emissions based on the individual vehicle's speed and acceleration/deceleration rates. The fuel consumption and CO_2 emissions were measured at every time step using vehicle's driving profile (i.e., speed and acceleration/deceleration rates) and aggregated for the entire simulation period.

5. Safety Assessment Results

5.1. Safety Impact

5.1.1. Base Scenario

In the base scenarios, the safety estimation was conducted without driver warnings, communication delays, and positioning errors. This scenario reflects a normal condition in which no safety application is considered. Table 15 presents the safety estimation result for the base scenario.

Table 15. Safety estimation results – Base scenario

Demand	Lane change	Sudden stop	Signalized intersection	Road departure
Peak	290	185	33	25
Non-peak	160	98	20	

1) Lane change: conflict duration (0.1 sec)
2) Sudden stop: conflict duration (0.1 sec)
3) Road departure: Number of run-off-road cases
4) Signalized intersection: Number of red-light runners

During the peak period, an average of 290 and 185 time steps of conflict duration were identified for lane changes and sudden stops respectively. During the same peak period 33 red-light runners were identified. During the non-peak period, an average of twenty red-light runners were identified. In addition, an average of 160 and 98 time steps of conflict durations were identified for the lane changes and sudden stops during the non-peak period, respectively. Finally, only 25 run-off-road cases were considered in the road departure case. Note that the road departure case was separately conducted regardless of demand scenarios because of the rarity of road departure crashes.

5.1.2. Driver Warnings without Errors

This scenario does not consider the communication delays and positioning errors, when driver warnings are triggered, which reflects an ideal condition. In every safety evaluation case, driver warnings reduced dangerous conditions from 28% to 35% compared to the base scenario. Figures 20 to 23 show the safety estimation results for each scenario.

1) Lane Change

During the peak period, 50 driver warnings reduced 30% of conflict durations from 290 to 203 time steps. During the non-peak period, 48 driver warnings reduced 31% of conflict durations from 160 to 110 time steps.

2) Sudden Stop

During the peak period, 29 driver warnings reduced 34% of conflict durations from 185 to 122 time steps. In addition, during the non-peak period, two driver warnings reduced 28% of conflict durations from 98 to 71 time steps.

3) Signalized Intersection

The number of red-light runners was used as a surrogate safety measure for the signalized intersection case. During the peak period, 342 vehicles received driver warnings and 10 vehicles avoided passing a red-light reducing the red-light runners by 30% from 33 to 23. In addition, during the non-peak period, 132 vehicles approaching the signalized intersections received driver warnings and seven vehicles avoided running a red-light, thereby reducing the red-light runners by 35% from 20 to 13.

4) Road Departure

While 25 run-off-road cases were considered, the road departure warnings removed all the run-off-road cases under no communication delays and positioning errors. Although a perception-reaction time is considered in the middle of driver warning and actual response, it is expected that the presence of shoulder lane provided enough space (i.e., 8 feet) for vehicles to recover their path. This implies that the road departure warnings are very effective for preventing road departure crashes, assuming that the warnings are issued on time and without any errors.

5.1.3. Driver warnings with V2V/V2I Communication Delays

In this scenario, the V2V/V2I communication delays were considered when driver warnings were triggered. The connection probability was calculated at every time step to identify communication connection success or failure. For instance, if the communication connection failed at a specific time step, driver warnings were delayed until the next time step when communication connection succeeds. For every safety evaluation case, the V2V/V2I communication delays degraded the effects of driver warnings on an average of 8% and 15%. Figures 20 to 23 show the safety estimation results for each scenario.

(1) Lane Change

The V2V/V2I communication delays degraded the effect of driver warnings by 8% of conflict durations (i.e., 22 time steps) during the peak period and 14% of conflict durations (i.e., 23 time steps) during the non-peak period.

(2) Sudden Stop

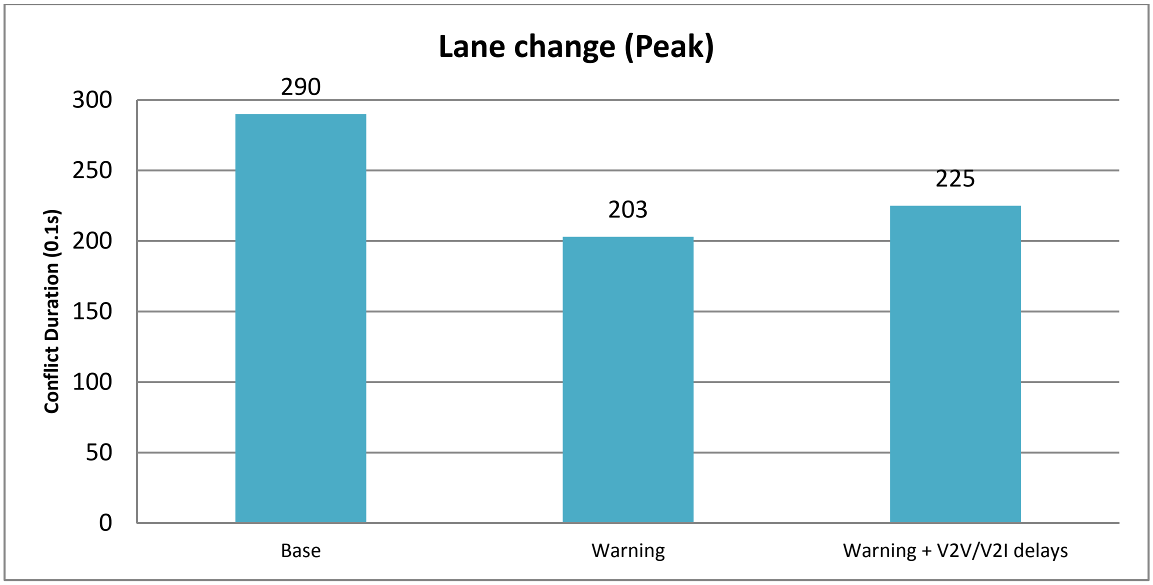
The V2V/V2I communication delays degraded the effect of driver warnings by about 10% of conflict durations (i.e., 19 time steps) during the peak period and 10% of conflict durations (i.e., 10 time steps) during the non-peak period.

(3) Signalized Intersection

Due to the V2V/V2I communication delays, the effect of the dilemma zone driver warnings was degraded, during the peak period, by 15% because of an increase by five red-light runners as compared to the no-communication delays case. During the non-peak period, the effect of dilemma zone driver warnings was degraded by 10%, due to an increase of two red-light runners as compared to the no-communication delays case.

(4) Road Departure

In the road departure scenario, the V2V/V2I communication delays did not affect the road departure warnings, since no run-off-road case was identified. Based on this result, it was concluded that a few time steps (0.1 second for one time step) of delays derived from the V2V/V2I communication errors did not have much impact on the road departure warnings. Note that the roadway sections used for the road departure scenario include a shoulder lane of eight feet wide.



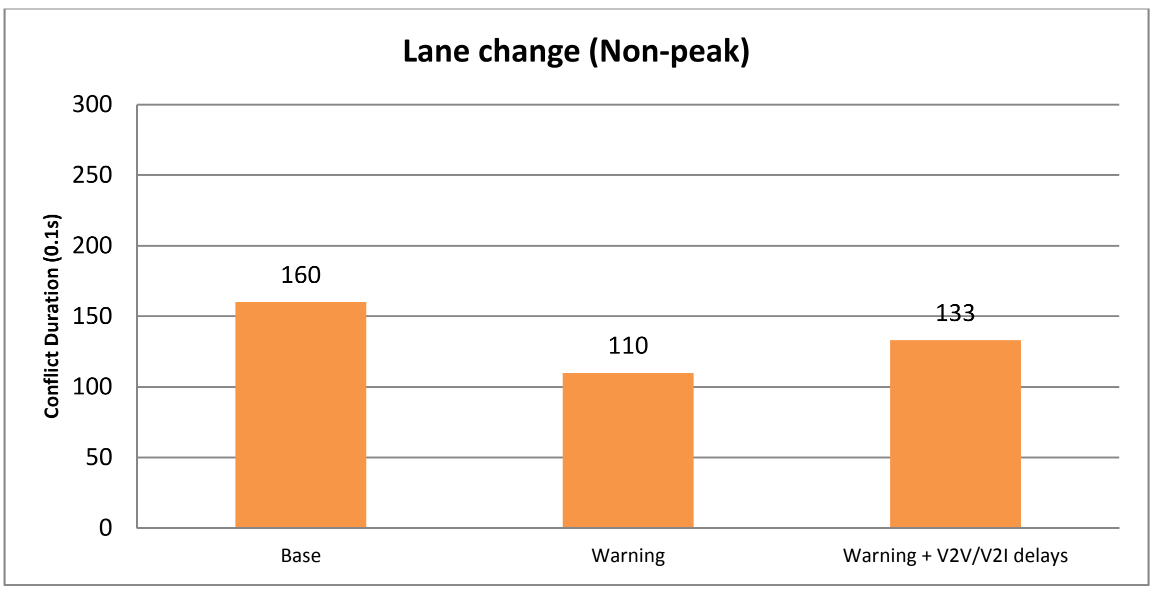
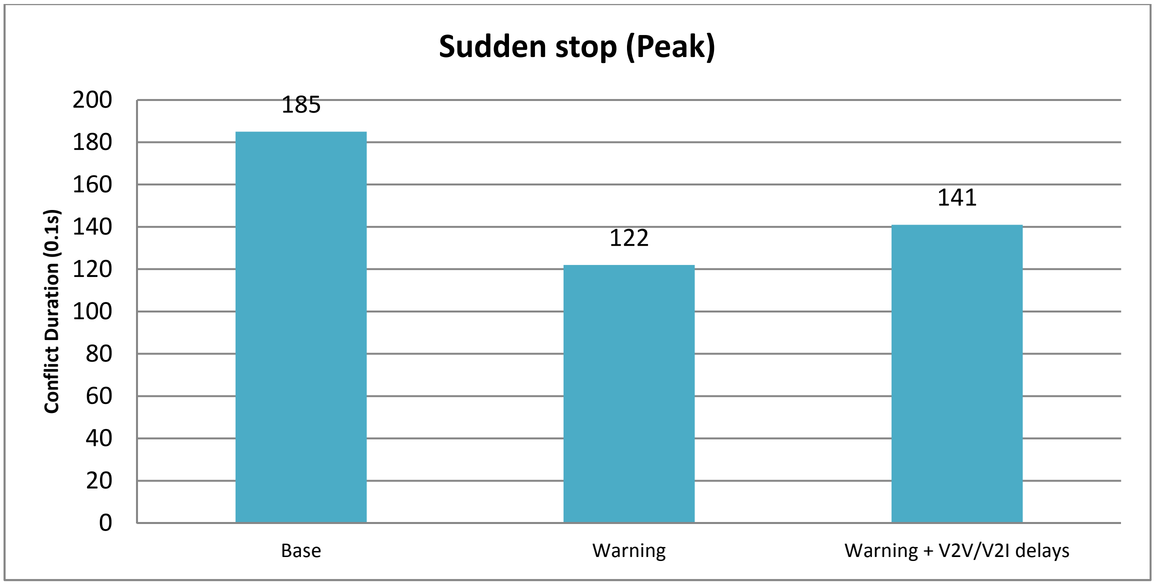


Figure 20. Safety estimation results – Lane change (up-Peak) (down-Non-peak)



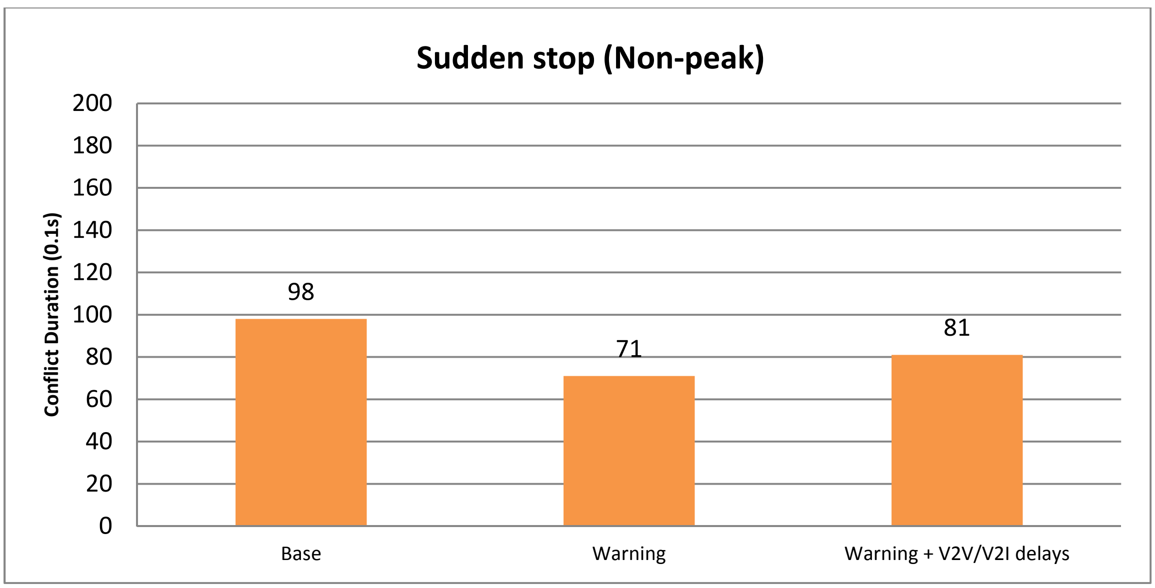


Figure 21. Safety estimation results – Sudden stop (up-Peak) (down-Non-peak)

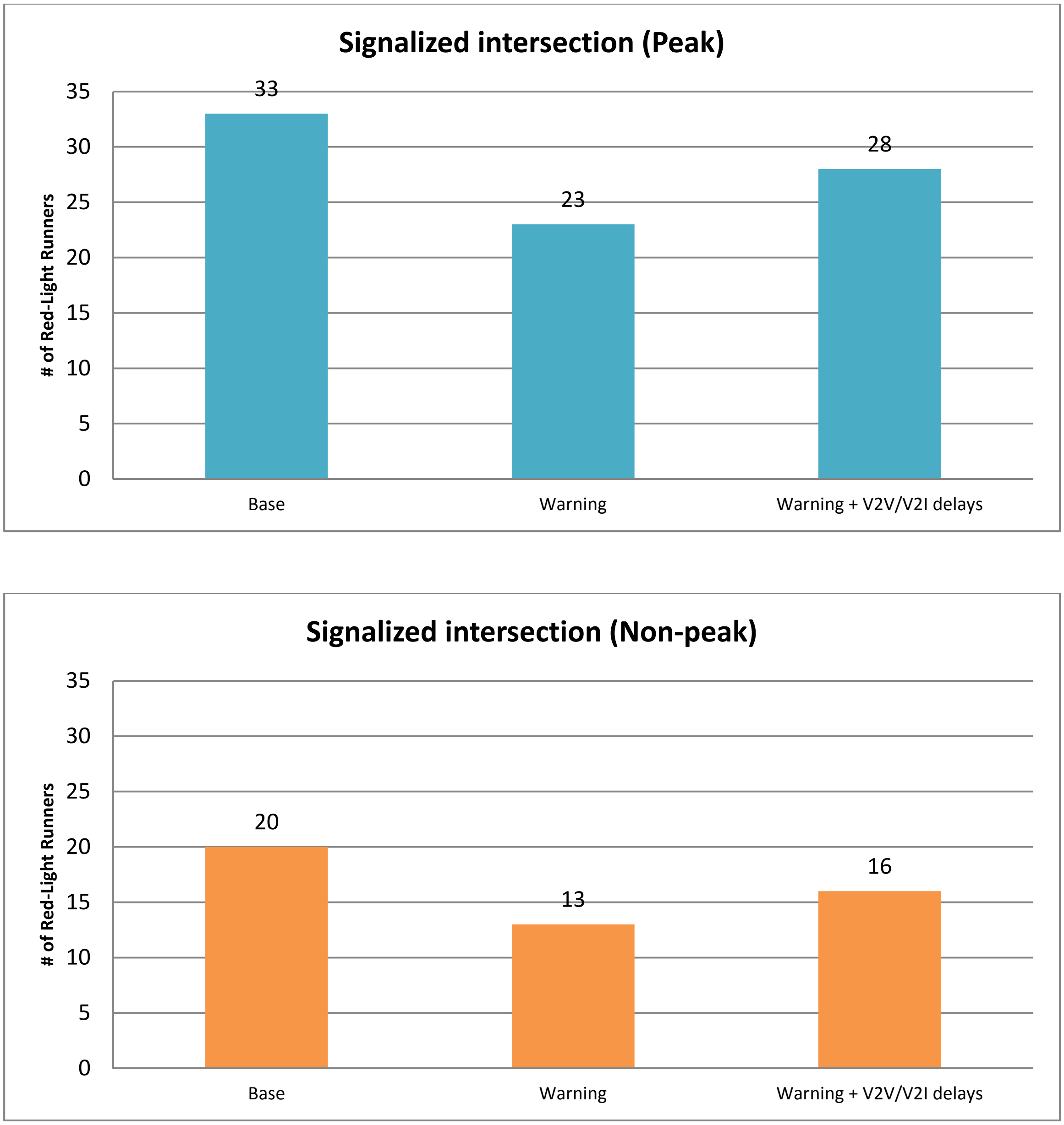


Figure 22. Safety estimation results – Signalized intersection (up-Peak) (down-Non-peak)

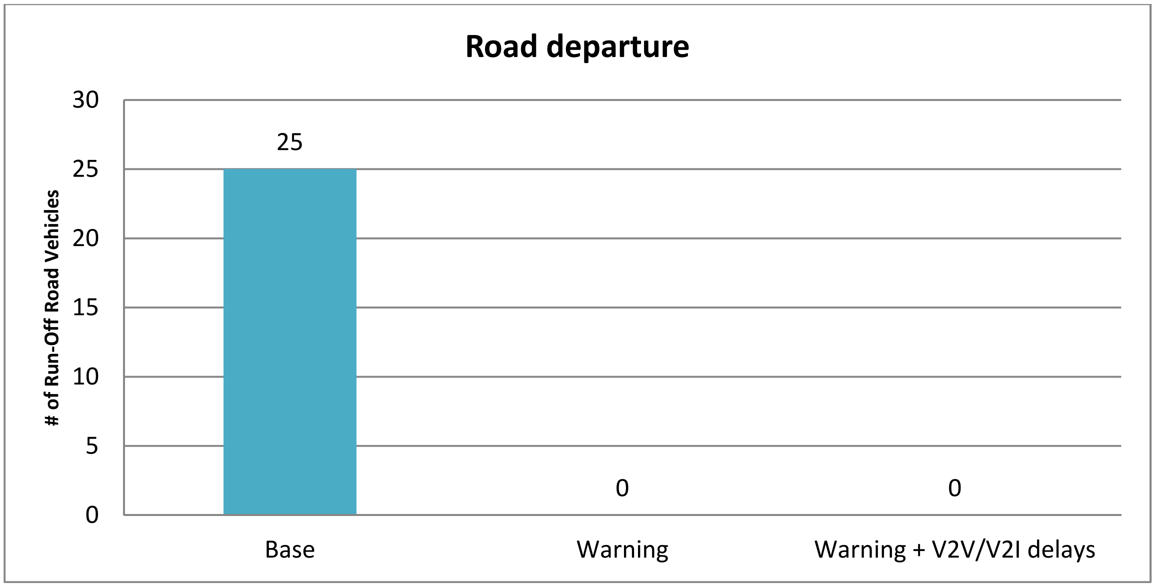


Figure 23. Safety estimation results – Road departure

5.1.4. Driver warnings with GPS/INU Errors and V2V/V2I Delays

In this scenario, both the GPS/INU positioning errors and the V2V/V2I communication delays were considered when driver warnings were triggered. The GPS/INU positioning errors result in both missing warnings and incorrect warnings. To estimate the effects of different accuracy levels of GPS/INUs on the safety estimation, eight combinations of GPS/INU devices were proposed as follows:

1) Real-Time Kinematic (RTK) GPS and high-accuracy MEMS
2) Real-Time Kinematic (RTK) GPS and low-accuracy MEMS
3) OmniStar-aided GPS and high-accuracy MEMS
4) OmniStar-aided GPS and low-accuracy MEMS
5) Local Differential GPS and high-accuracy MEMS
6) Local Differential GPS and low-accuracy MEMS
7) Autonomous GPS and high-accuracy MEMS
8) Autonomous GPS and low-accuracy MEMS.

For all simulation runs with the GPS/INU simulator, the following assumptions were made:

1) GPS multipath is present.
2) Satellite visibility map is considered.
3) V2V/V2I communication delays are considered for driver warnings.
4) Perception-reaction time is considered in the middle of driver warning with the actual driver response.

Note that the following abbreviated titles were used for the figures and tables listed in this section.

- **Base**: Base scenario – no warning case.
- **W-G**: Driver warnings based on ground truth – no communication delays and no positioning errors.
- **W-D:** Driver warnings with V2V/V2I communication delays.
- **W-D-RTK/High:** Driver warnings with V2V/V2I communication delays and RTK GPS and high-accuracy MEMS.
- **W-D-RTK/Low:** Driver warnings with V2V/V2I communication delays and RTK GPS and low-accuracy MEMS.
- **W-D-Omni/High:** Driver warnings with V2V/V2I communication delays and OmniStar-aided GPS and high-accuracy MEMS.
- **W-D-Omni/Low:** Driver warnings with V2V/V2I communication delays and OmniStar-aided GPS and low-accuracy MEMS.
- **W-D-DGPS/High**: Driver warnings with V2V/V2I communication delays and Differential GPS and high-accuracy MEMS.
- **W-D-DGPS/Low**: Driver warnings with V2V/V2I communication delays and Differential GPS and low-accuracy MEMS.
- **W-D-Auto/High**: Driver warnings with V2V/V2I communication delays and Autonomous GPS and high-accuracy MEMS.
- **W-D-Auto/Low**: Driver warnings with V2V/V2I communication delays and Autonomous GPS and low-accuracy MEMS.

(1) Lane Change Case during Peak Demand

During the period of peak demand, 239 time steps of conflict durations were identified in the base scenario, 159 time steps in the ground truth-based warning scenario, and 167 time steps in the V2V/V2I communication delays-added warning scenario. The driver warnings reduced 33.5% of dangerous situations, but the communication delays degraded the effectiveness of the driver warnings by 3.3%.

Regarding the GPS/INU scenarios, RTK GPS/INU scenarios showed the best performance with differences in the range of 5.4% and 7.5% as compared to the ground-truth scenario. The OmniStar-aided GPS/INUs, DGPS/INUs, and Autonomous GPS/INUs scenarios followed with differences in the range of 10.5% and 10.9%; 14.6% and 16.7%; and 38.5% and 35.1%, respectively. Especially, the duration of conflicts obtained from the Autonomous GPS scenarios with the two level INUs (i.e., high and low-accuracy MEMS) scenarios were even bigger than those of the base case (i.e., no warning case) which clearly indicates that the positioning accuracy of Autonomous GPS is not appropriate for issuing warnings.

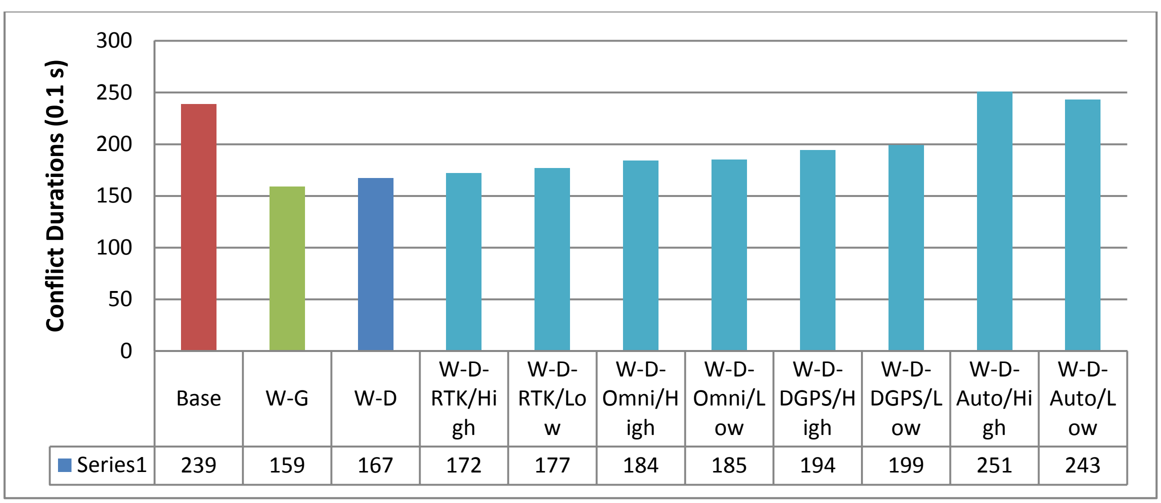


Figure 24. Safety evaluation result with GPS/INUs (Peak, Lane change)

(2) Sudden Stop Case during Peak Demand

During the period of peak demand, 154 time steps of conflict durations were identified in the base scenario, 113 time steps for the ground truth warning scenario, and 120 time steps for V2V/V2I communication delays-added warning scenario. The driver warnings reduced 26.6% of dangerous situations, but the communication delays degraded the effectiveness of the driver warnings by 4.5%.

Regarding the GPS/INU scenarios, RTK GPS/INUs showed the best performance by having the differences in the range of 9.7% and 11.0% as compared to the ground-truth scenario. The OmniStar-aided GPS/INUs, DGPS/INUs, and Autonomous GPS/INUs followed with the differences in the range of 13.6% and 14.9%; 9.1% and 16.2%; and 42.2% and 24.0%, respectively. Similar with the lane change cases, the duration of conflicts obtained from the Autonomous GPS/high-accuracy INU scenario was even larger than those of the base case (i.e., no warning case).

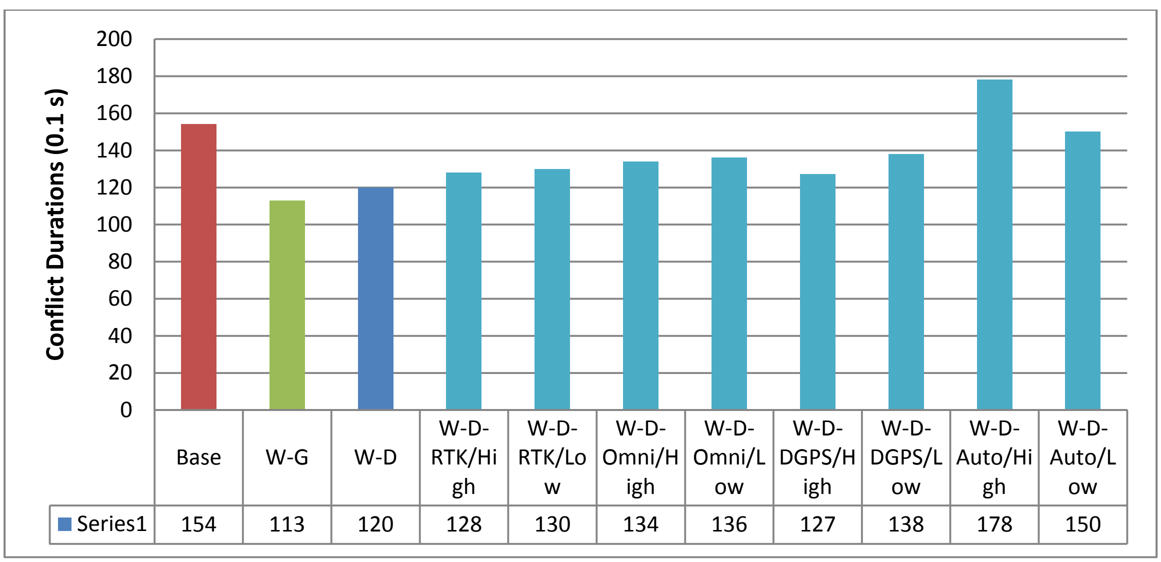


Figure 25. Safety evaluation result with GPS/INUs (Peak, Sudden Stop)

(3) Signalized Intersection Case during Peak Demand

During the period of peak demand, 38 red-light runnings took place in the base scenario, 24 in the ground truth-based warning scenario, and 26 in the V2V/V2I communication delays-added warning scenario. The driver warnings reduced 36.8% of red-light runners, but the communication delays degraded the effectiveness of the driver warnings by 5.3%.

Regarding the GPS/INU scenarios, RTK GPS/INUs showed the best performance by having the differences in the range of 7.9% and 18.4% as compared to the ground-truth scenario. The DGPS/INUs, OmniStar-aided GPS/INUs, and Autonomous GPS/INUs followed with the differences in the range of 15.8% and 13.2%; 15.8% and 18.4%; and 50.0% and 39.5%, respectively. Likewise, the Autonomous GPS/INU cases were even worse or the same compared to the base case (i.e., no warning case) in terms of the number of red-light runners.

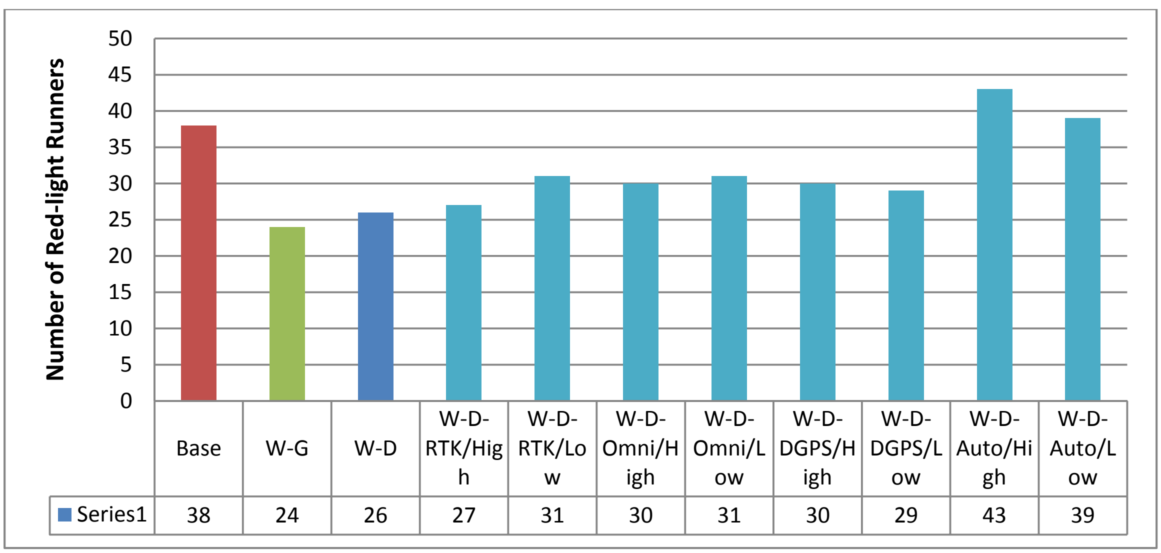


Figure 26. Safety evaluation result with GPS/INUs (Peak, Signalized Intersection)

(4) Lane Change Case during Non-peak Demand

During the period of non-peak demand, 159 time steps of conflict durations were identified in the base scenario, 115 time steps in the ground truth-based warning scenario, and 125 time steps in the V2V/V2I communication delays-added warning scenario. The driver warnings reduced 27.7% of dangerous situations, but the communication delays degraded the effectiveness of the driver warnings by 6.3%.

Regarding the GPS/INU scenarios, OmniStar-aided GPS/INUs showed a slightly better performance by having the differences in the range of 1.3% and 3.1% as compared to the ground-truth scenario. The RTK GPS/INUs, DGPS/INUs, and Autonomous GPS/INUs followed with the differences in the range of 1.9% and 8.8%; 5.7% and 14.5%; and 28.9% and 22.0%, respectively. Again, the duration of conflicts obtained from the Autonomous GPS/high-accuracy INU scenario was even bigger than those of the base case (i.e., no warning case).

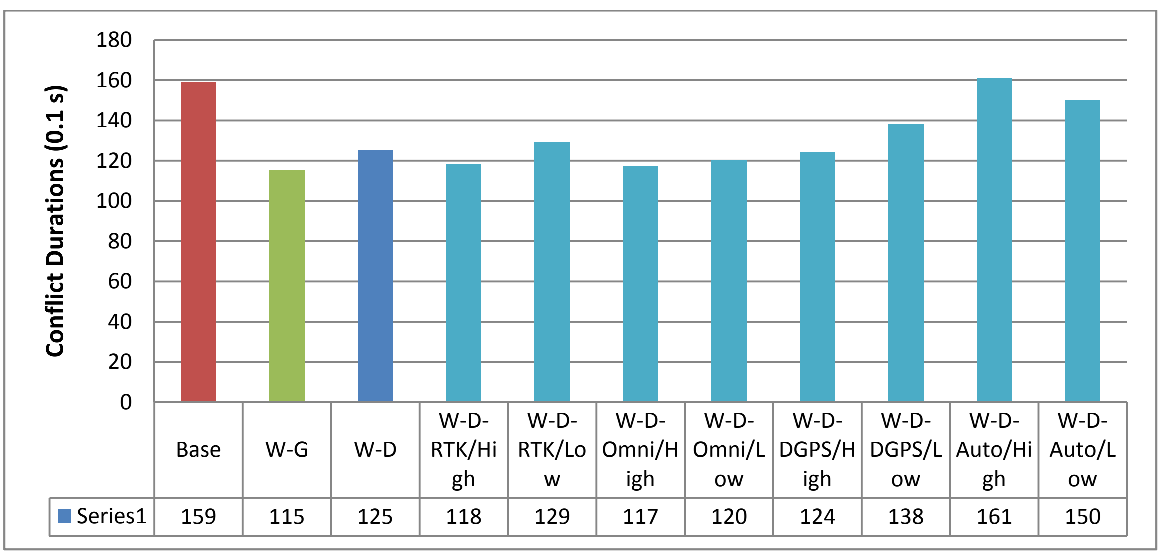


Figure 27. Safety evaluation result with GPS/INUs (Non-Peak, Lane Change)

(5) Sudden Stop Case during Non-peak Demand

During the period of non-peak demand, 91 time steps of conflict durations were identified in the base scenario, 55 time steps for the ground truth warning scenario, and 67 time steps for V2V/V2I communication delays-added warning scenario. The driver warnings reduced 39.6% of dangerous situations, but the communication delays degraded the effectiveness of the driver warnings by 13.2%.

Regarding the GPS/INU scenarios, RTK GPS/INUs showed the best performance by having the differences in the range of 8.8% and 7.7% as compared to the ground-truth scenario. The OmniStar-aided GPS/INUs, DGPS/INUs, and Autonomous GPS/INUs followed with the differences in the range of 12.1% and 9.9%; 18.7% and 12.1%; and 33.0% and 28.6%, respectively. In this case, all GPS/INU scenarios showed a better performance compared to the base scenario (i.e., no warning case). However, the effectiveness of driver warnings was worst when the driver warnings were issued based on the Autonomous GPS/INU devices.

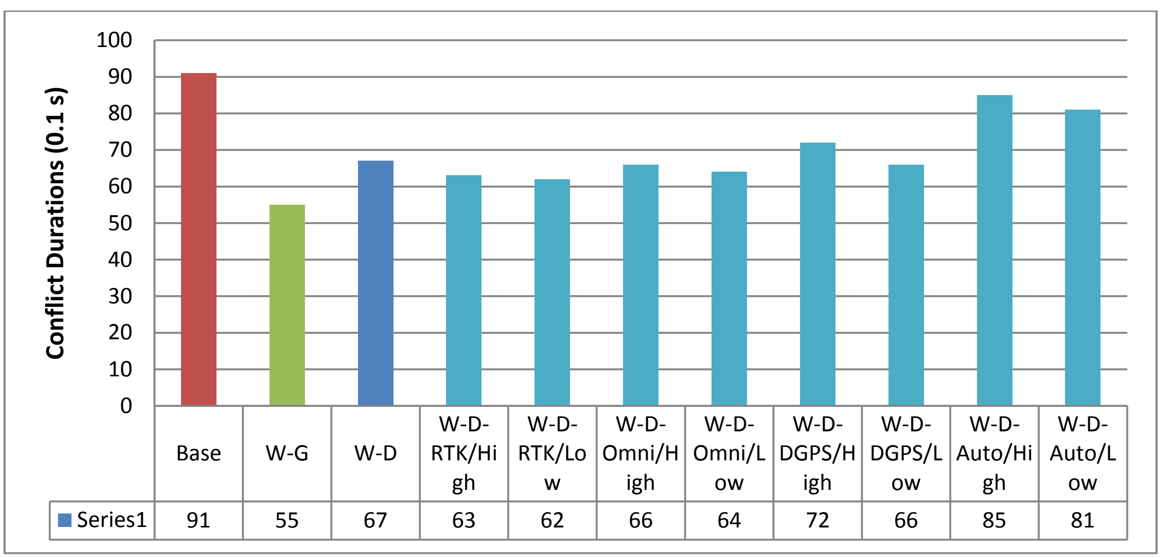
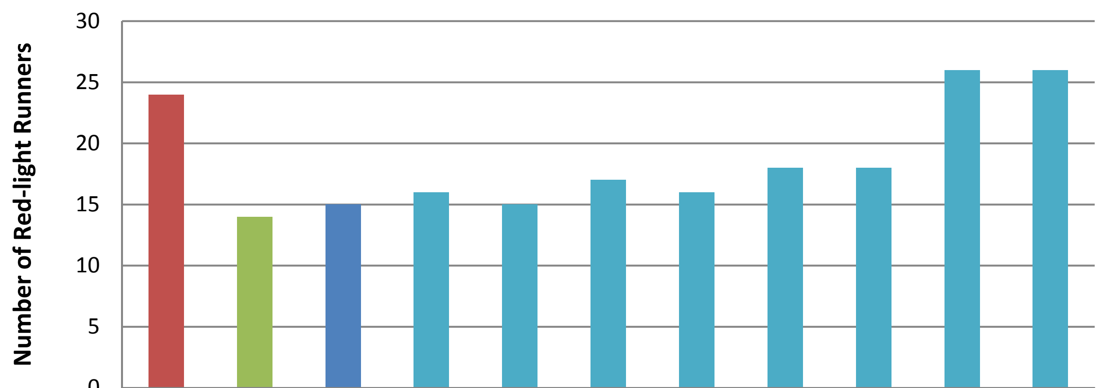


Figure 28. Safety evaluation result with GPS/INUs (Non-Peak, Sudden Stop)

(6) Signalized Intersection Case during Non-peak Demand

During the period of non-peak demand, 24 red-light runnings took place in the base scenario, 14 in the ground truth-based warning scenario, and 15 in the V2V/V2I communication delays-added warning scenario. The driver warnings reduced 41.7% of red-light runners, but the communication delays degraded the effectiveness of the driver warnings by 4.2%.

Regarding the GPS/INU scenarios, RTK GPS/INUs showed the best performance by having the differences in the range of 8.3% and 4.2% as compared to the ground-truth scenario. The OmniStar-aided GPS/INUs, DGPS/INUs, and Autonomous GPS/INUs followed with the differences in the range of 12.5% and 8.3%; 16.7% for both INU scenarios; and 50.0% for both INU scenarios, respectively. Similarly, the Autonomous GPS/INU cases were even worse or the same compared to the base case (i.e., no warning case) in terms of the number of red-light runners.



	Base	W-G	W-D	W-D-RTK/High	W-D-RTK/Low	W-D-Omni/High	W-D-Omni/Low	W-D-DGPS/High	W-D-DGPS/Low	W-D-Auto/High	W-D-Auto/Low
Series1	24	14	15	16	15	17	16	18	18	26	26

Figure 29. Safety evaluation result with GPS/INUs (Non-Peak, Signalized Intersection)

(7) Road Departure Case

While 25 run-off-road cases took place in the base scenario (i.e., no driver warnings), the road departure driver warnings reduced all the run-off-road cases in the both driver warning scenarios (i.e., 1) ground truth-based and 2) communication delays-added). However, the GPS/INU positioning errors had a large impact on the road departure driver warnings. Although there were no road departures identified in the RTK GPS and OmniStar-based driver warning scenarios, three to fourteen run-off-road vehicles were identified under the DGPS and Autonomous GPS-based driver warning scenarios, as shown in Figure 30. In particular, the Autonomous GPS/high-accuracy MEMS showed the worst performance among the other GPS/INU scenarios as sixteen run-off-road vehicles were identified.

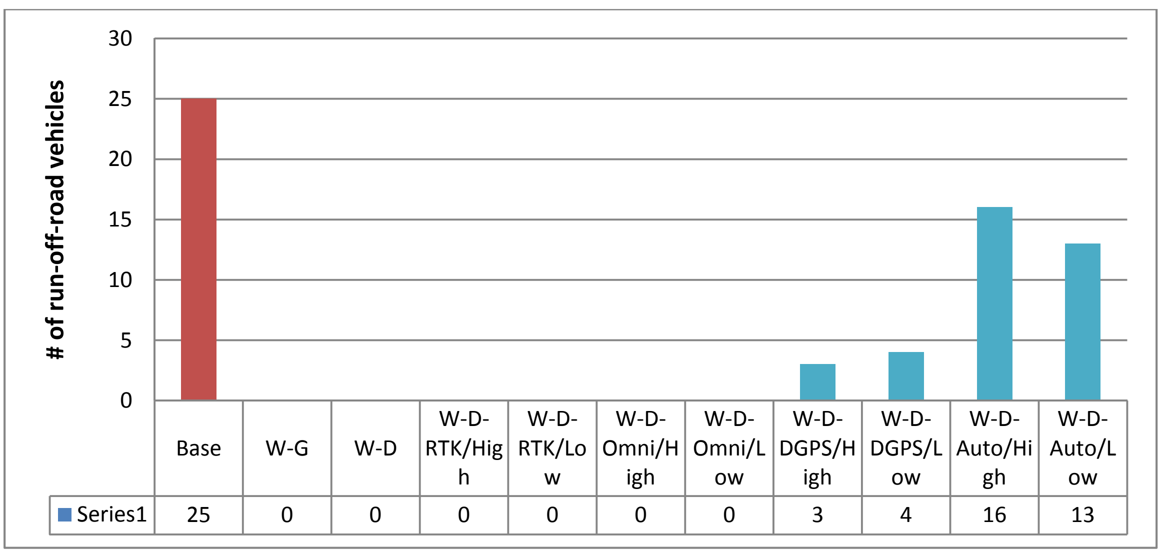


Figure 30. Safety evaluation result with GPS/INUs (Road Departure)

(8) Summary

Based on the comparison with the ground truth-based warning scenario (i.e., no positioning errors and communication delays), the RTK GPS/INUs (low-accuracy and high-accuracy) are the best combinations for vehicle safety applications, since these scenarios were the closest to the ground truth-based warning scenarios, as compared to the other GPS/INU device scenarios. As an example, in the lane change case during peak demand, while RTK GPS/INUs showed a maximum 8.8% of the difference as compared to the ground truth-based warning scenario, OmniStar-aided GPS/INUs, DGPS/INUs, and Autonomous GPS/INUs showed 10.9%, 16.7%, and 38.5% of differences, respectively.

Consequently, RTK GPS/INUs provides the most effective combination for issuing driver warnings with OmniStar-aided GPS/INUs following very closely. The DGPS/INUs performance for safety applications appears to provide some benefits. However, Autonomous GPS/INUs does not provide any benefits for all cases studied, except for the road departure case. Autonomous GPS/INUs showed the poorest performance. In most cases, the Autonomous GPS/INUs scenarios were worse than in the base case (i.e., no-driver warnings). These worst cases are highlighted in Table 16 and Table 17. Therefore, Autonomous GPS/INUs would not provide much benefit to the vehicle safety applications, except possibly for the road departure cases.

In most cases, the impact on the safety scenarios of high-accuracy MEMS and low-accuracy MEMS INUs, using the same GPS device, was not significantly different from the difference between GPS devices. This implies that the INU devices did not significantly affect the vehicle's safety applications. The effect of the accuracy level of the GPS devices had a more significant impact than those of the INU devices.

In conclusion, as the accuracy of a GPS/INU device increased, the difference with respect to the ground-truth scenario decreased either with or without the communication delays. This leads to two important findings: 1) the probability of false alarms would decrease as the high-accuracy positioning system is deployed in the vehicle safety applications, and 2) the traffic safety estimation result can vary according to the accuracy of the positioning systems.

Obviously, it is unlikely that the positioning devices deployed in the vehicles have flawless positioning accuracy. Moreover, the most commonly used positioning device on the vehicle safety applications is an Autonomous GPS while it showed the worst performance. This indicates a higher chance of false alarms according to the current positioning technology even though the state-of-the-art safety applications have been developed and deployed in the field. Therefore, the potential positioning errors need to be considered when the traffic safety is estimated under the advanced vehicle safety applications scenarios (e.g., Connected Vehicles applications)

Table 16. Safety Evaluation Results – Peak Demand

	Lane change		Sudden stop		Signalized Intersection	
	Conflict duration (0.1 s)	Percent changed	Conflict duration (0.1 s)	Percent changed	# of red-light runners	Percent changed
Base	239		154		38	
W-G	159	-33.5%	113	-26.6%	24	-36.8%
W-D	167	-30.1%	120	-22.1%	26	-31.6%
W-D-RTK/High	172	-28.0%	128	-16.9%	27	-28.9%
W-D-RTK/Low	177	-25.9%	130	-15.6%	31	-18.4%
W-D-Omni/High	184	-23.0%	134	-13.0%	30	-21.1%
W-D-Omni/Low	185	-22.6%	136	-11.7%	31	-18.4%
W-D-DGPS/High	194	-18.8%	127	-17.5%	30	-21.1%
W-D-DGPS/Low	199	-16.7%	138	-10.4%	29	-23.7%
W-D-Auto/High	251	5.0%	178	15.6%	43	13.2%
W-D-Auto/Low	243	1.7%	150	-2.6%	39	2.6%

*Shaded areas: worse than the base scenario (i.e., no driver warnings)

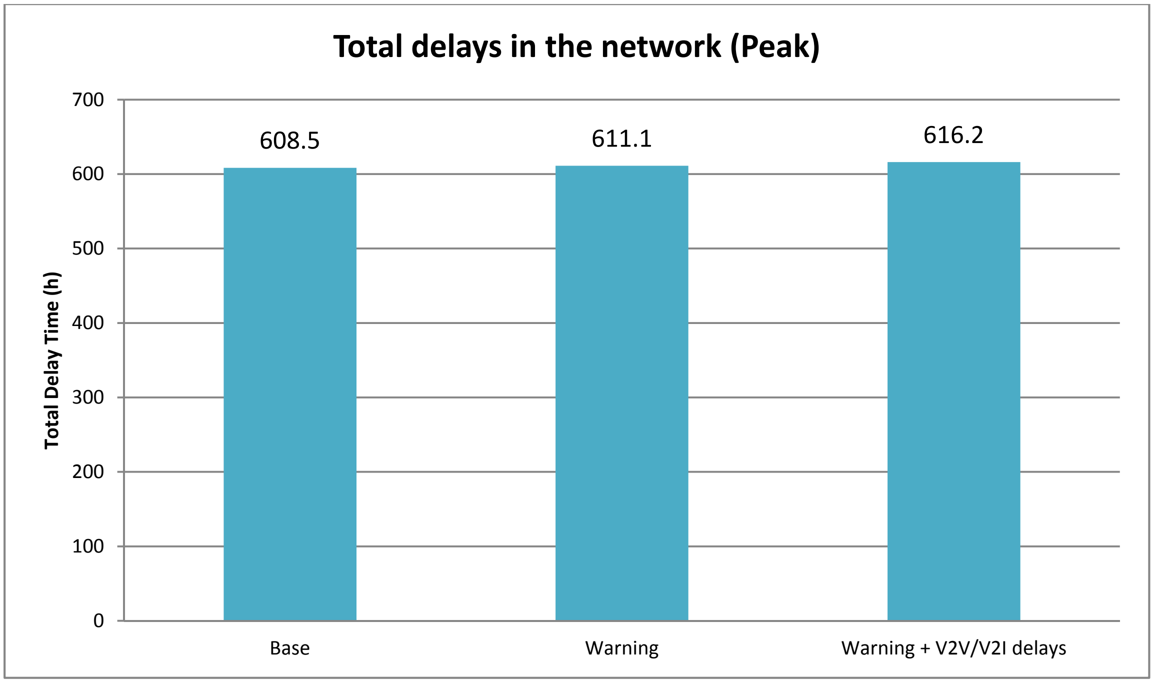
Table 17. Safety Evaluation Results – Non-peak Demand

	Lane change		Sudden stop		Signalized Intersection	
	Conflict duration (0.1 s)	Percent changed	Conflict duration (0.1 s)	Percent changed	# of red-light runners	Percent changed
Base	159		91		24	
W-G	115	-27.7%	55	-39.6%	14	-41.7%
W-D	125	-21.4%	67	-26.4%	15	-37.5%
W-D-RTK/High	118	-25.8%	63	-30.8%	16	-33.3%
W-D-RTK/Low	129	-18.9%	62	-31.9%	15	-37.5%
W-D-Omni/High	117	-26.4%	66	-27.5%	17	-29.2%
W-D-Omni/Low	120	-24.5%	64	-29.7%	16	-33.3%
W-D-DGPS/High	124	-22.0%	72	-20.9%	18	-25.0%
W-D-DGPS/Low	138	-13.2%	66	-27.5%	18	-25.0%
W-D-Auto/High	161	1.3%	85	-6.6%	26	8.3%
W-D-Auto/Low	150	-5.7%	81	-11.0%	26	8.3%

*Shaded areas: worse than the base scenario (i.e., no driver warnings)

5.2. Mobility Impact

With respect to mobility, both in the peak and non-peak periods, the total delays of the two driver warning scenarios were slightly bigger than those of the base case while the average speeds were slightly lower. This is because the driver deceleration followed by driver warnings occurred more often in the two driver warning scenarios than the base case. However, the differences between the base case and the warning scenarios were not significant by having a less than 5% difference. Figures 31 and Figure 32 show the total delays and the average speed per vehicle obtained from the base and two driver warning scenarios.



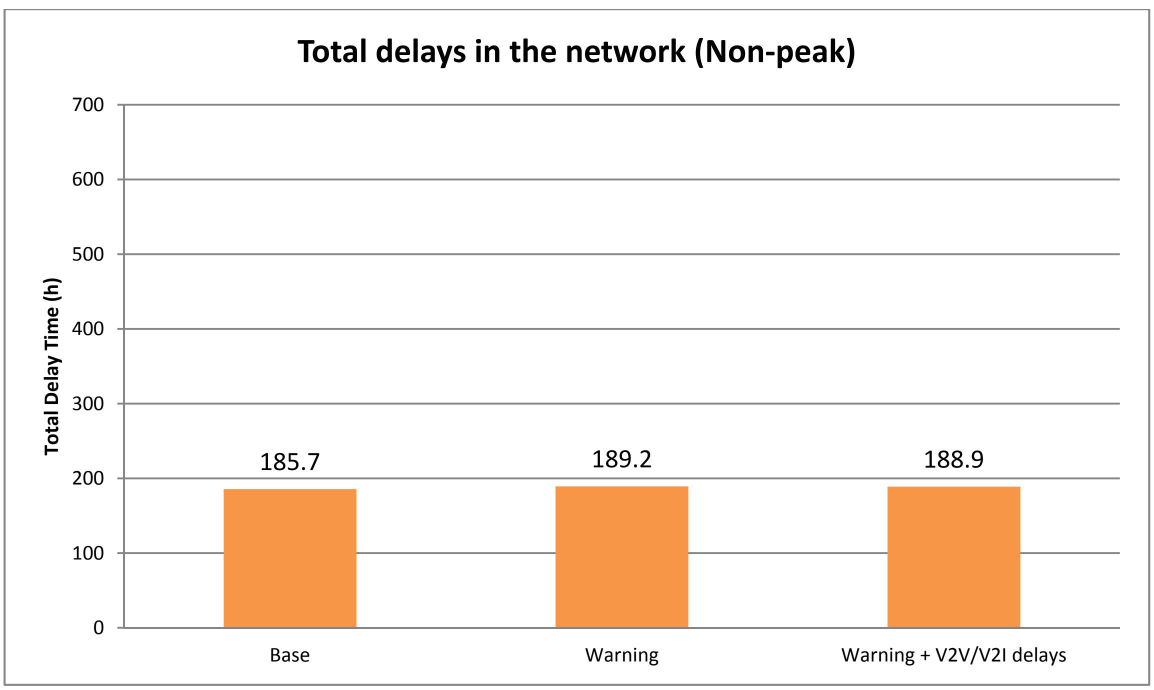


Figure 31. Total delays in the network (up-Peak) (down-Non-peak)

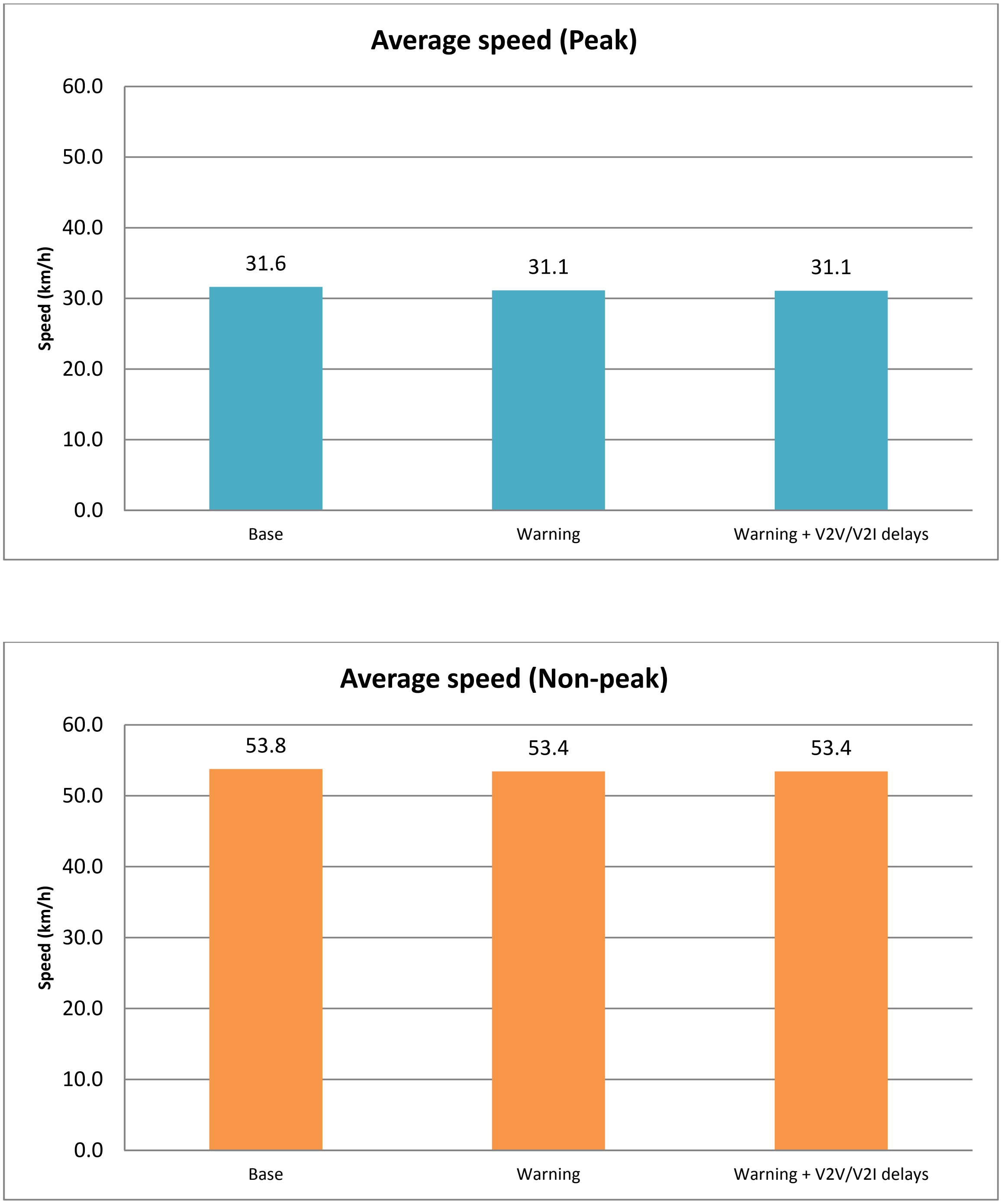


Figure 32. Average speed in the network (up-Peak) (down-Non-peak)

When the GPS/INU positioning errors-added driver warning scenarios are included for the peak and non-peak demand, all driver warning scenarios indicated a slightly bigger network-wide total delays ranging from 0.5% to 6.4% and smaller average speed ranging from -6.1% to -0.6% per vehicle than those of the base scenario. However, there was no obvious indication that the different GPS/INUs and the mobility results were correlated. Tables 18 and 19 show the mobility evaluation results for the all the GPS/INU errors-added driver warning scenarios during the peak and non-peak periods.

Table 18. Mobility Evaluation Results for GPS/INU Scenarios – Peak demand

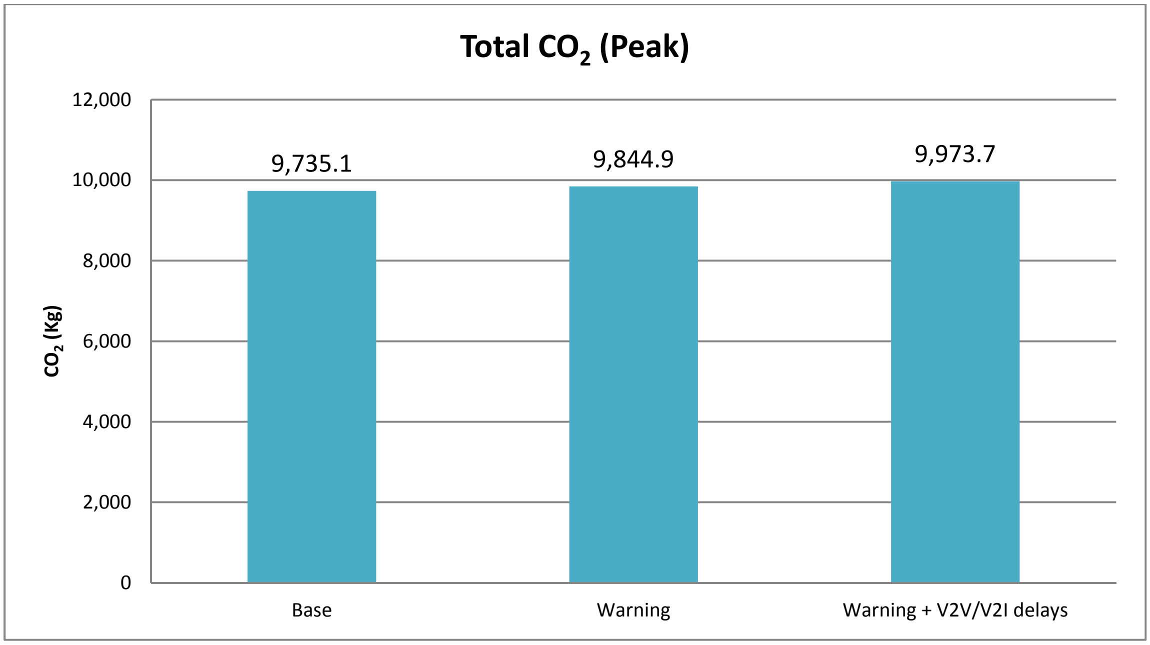
Scenarios	Peak			
	Total Delay (h)	Percent Changed (%)	Average Speed (km/h)	Percent Changed (%)
Base	588.6		31	
W-G	593.4	0.8%	29.5	-4.8%
W-D	602.7	2.4%	29.7	-4.2%
W-D-RTK/High	598.8	1.7%	30	-3.2%
W-D-RTK/Low	596.1	1.3%	29.4	-5.2%
W-D-Omni/High	603	2.4%	30.3	-2.3%
W-D-Omni/Low	601.2	2.1%	30.4	-1.9%
W-D-DGPS/High	594.6	1.0%	29.9	-3.5%
W-D-DGPS/Low	591.6	0.5%	29.8	-3.9%
W-D-Auto/High	606.3	3.0%	30.8	-0.6%
W-D-Auto/Low	600.6	2.0%	29.1	-6.1%

Table 19. Mobility Evaluation Results for GPS/INU Scenarios – Non-peak demand

Scenarios	Non-Peak			
	Total Delay (h)	Percent Changed (%)	Average Speed (km/h)	Percent Changed (%)
Base	165.2		53.9	
W-G	169.2	2.4%	53.3	-1.1%
W-D	170.2	3.0%	53.2	-1.3%
W-D-RTK/High	171.4	3.8%	52.5	-2.6%
W-D-RTK/Low	172.2	4.2%	52.6	-2.4%
W-D-Omni/High	172	4.1%	51.9	-3.7%
W-D-Omni/Low	169.2	2.4%	53.4	-0.9%
W-D-DGPS/High	171.8	4.0%	51.9	-3.7%
W-D-DGPS/Low	167.8	1.6%	52.7	-2.2%
W-D-Auto/High	167.4	1.3%	52.2	-3.2%
W-D-Auto/Low	175.8	6.4%	52.8	-2.0%

5.3. Energy and Environmental Impact

With respect to the environmental impact, both in the non-peak and peak periods, although the difference was not significant, the two driver warning scenarios not only emitted more CO_2 in the range of 1.6% and 2.5%, but also consumed more fuel in the range of 1.4% and 2.7%, compared to the base scenario (i.., no driver warnings). This is because driver deceleration occurred more often in the two driver warning scenarios than the base case. Figures 33 and Figure 34 show the CO_2 emissions and the fuel consumptions in the network.



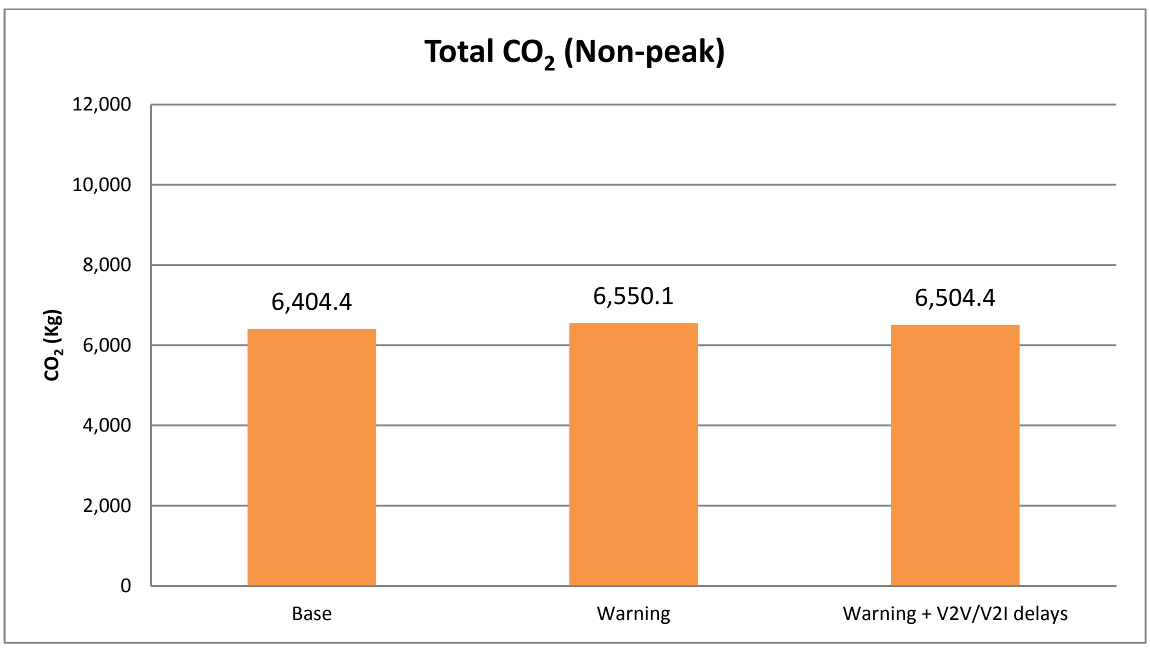
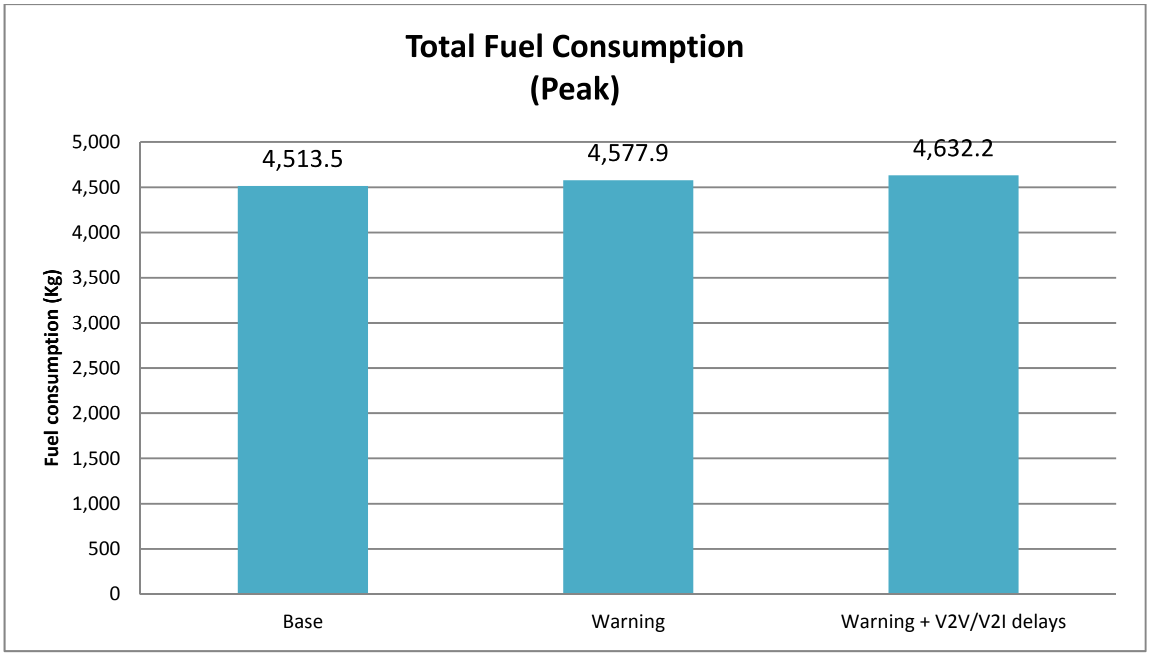


Figure 33. Total CO_2 emission in the network (up-Peak) (down-Non-peak)



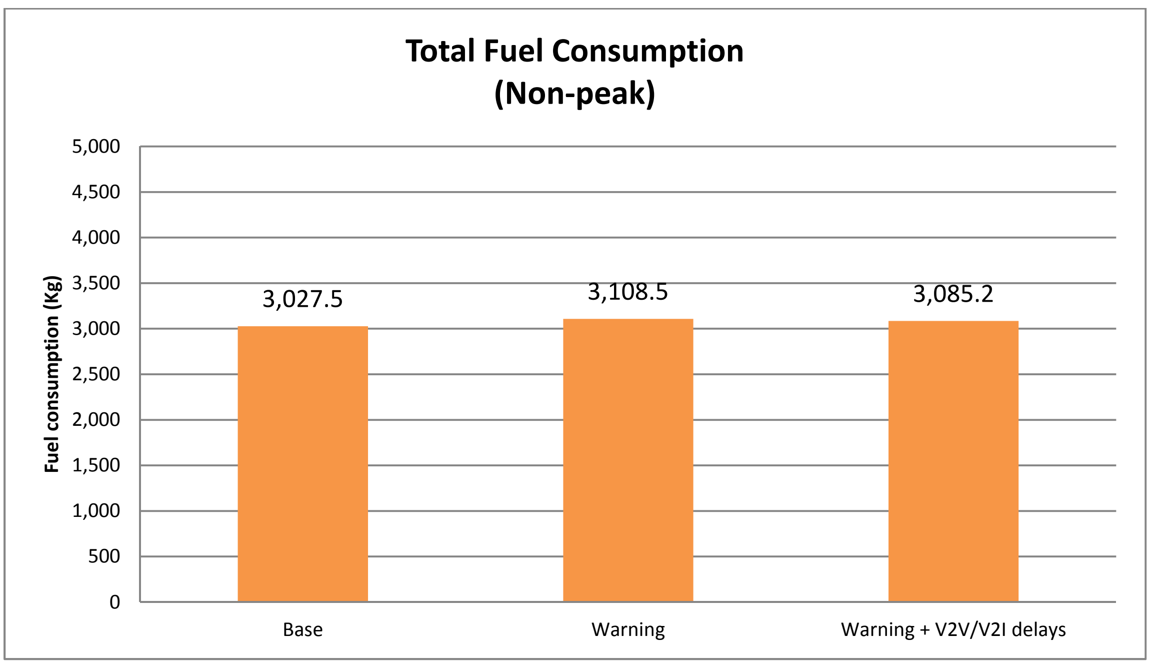


Figure 34. Total fuel consumption in network (up-Peak) (down-Non-peak)

In the GPS/INU positioning errors-added driver warning scenarios including the peak and non-peak demand, all driver warning scenarios produced more CO_2 emissions in the range of 0.8% and 3.0% and consumed more fuel in the range of 0.6% and 4.6%. As with the mobility results, there was no obvious evidence that the different GPS/INU, corresponding to different accuracy levels are correlated with the environmental impact in the network. Tables 20 and 21 show the environmental impact of the evaluation results obtained from the GPS/INU errors-added driver warning scenarios during the peak and non-peak periods.

Table 20. Environment Evaluation Results for GPS/INU Scenarios – Peak demand

Scenarios	Peak			
	Total CO2 (kg)	Percent Changed (%)	Total FUEL (kg)	Percent Changed (%)
Base	9103.9		3909.5	
W-G	9210.9	1.2%	3989.7	2.1%
W-D	9345.6	2.7%	4035.1	3.2%
W-D-RTK/High	9331	2.5%	4011.1	2.6%
W-D-RTK/Low	9359.8	2.8%	4082.2	4.4%
W-D-Omni/High	9178.5	0.8%	3934.4	0.6%
W-D-Omni/Low	9355.1	2.8%	4077.2	4.3%
W-D-DGPS/High	9261.5	1.7%	3994.6	2.2%
W-D-DGPS/Low	9349.7	2.7%	4067.3	4.0%
W-D-Auto/High	9350.1	2.7%	4075.5	4.2%
W-D-Auto/Low	9367.8	2.9%	4089	4.6%

Table 21. Environment Evaluation for GPS/INU Scenarios – Non-peak demand

Scenarios	Non-Peak			
	Total CO2 (kg)	Percent Changed (%)	Total FUEL (kg)	Percent Changed (%)
Base	5778.8		2423.6	
W-G	5948.5	2.9%	2490.1	2.7%
W-D	5874.8	1.7%	2478.6	2.3%
W-D-RTK/High	5822.3	0.8%	2455.9	1.3%
W-D-RTK/Low	5833.9	1.0%	2461.6	1.6%
W-D-Omni/High	5877.4	1.7%	2486.7	2.6%
W-D-Omni/Low	5876.9	1.7%	2482.7	2.4%
W-D-DGPS/High	5883.5	1.8%	2487.6	2.6%
W-D-DGPS/Low	5911.6	2.3%	2512.3	3.7%
W-D-Auto/High	5945.9	2.9%	2526.9	4.3%
W-D-Auto/Low	5950.1	3.0%	2529.3	4.4%

Chapter 7

CONCLUSIONS, CONTRIBUTIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

1. Conclusions and Findings

This study was motivated by the need to use more realistic vehicle trajectories in estimating more reliable surrogate safety measures. A further point of interest was to validate the potentiality of the new traffic conflict estimation result obtained from a vehicle dynamics model-integrated simulation environment. In addition, this study developed and implemented the integrated traffic safety assessment framework for considering the impacts of the vehicle positioning errors and communication delays in vehicle safety applications.

To achieve the goal of this study, lane-change vehicle trajectories collected for the NGSIM project were investigated as a function of the lane change duration; this lane change duration distribution was incorporated into the VISSIM lane changes in order to reflect drivers' aggressiveness in traffic simulations. These vehicle trajectories incorporating drivers' aggressiveness were then fed into CarSim to simulate vehicle dynamics according to the vehicles' maneuvers (e.g., speed, acceleration, and deceleration), and ultimately to generate more realistic vehicle trajectories. Consequently, these CarSim-simulated vehicle trajectories were used to identify traffic conflicts by computing surrogate safety measures in SSAM. As a result, the new conflict estimation showed a different number of traffic conflicts (i.e., 9.5 % fewer traffic conflicts) compared to the estimation from the existing VISSIM-only approach.

This newly developed vehicle dynamics model-integrated simulation environment showed the potential to be more promising in terms of computing surrogate safety metrics. This is because the traffic conflict estimation was conducted using more realistic vehicle trajectories incorporating field-collected lane change duration distribution (i.e., driver aggressiveness) and simulated by the vehicle dynamics model (i.e., CarSim). These advantages of the proposed VISSIM-CarSim integrated simulation approach are expected to generate more reliable surrogate safety measures, although the relationship between surrogate safety measures and actual crashes still needs to be validated.

With this in mind, both conflict estimation results, one from the proposed VISSIM-CarSim integrated approach and the other from the VISSIM-only approach (i.e., no driver aggressiveness and the CarSim simulation), were analyzed to quantify their correlation with actual traffic crashes. To this end, the number of traffic crashes and traffic conflicts obtained and estimated within a peak hour (i.e., 5 P.M. to 6 P.M.) in the two freeway corridors (i.e., I-495 and SR-267) were used to conduct the correlation analysis. There was a statistically significant relationship between traffic conflicts and traffic crashes when either approach was used. A cross-validation test on the confidence intervals of the correlation coefficients showed fairly small confidence intervals (i.e., 0.02 for both cases). However, the traffic conflicts obtained from the proposed approach showed a stronger correlation (i.e., 0.72 of correlation coefficient) with traffic crashes than the existing approach did (i.e., 0.61 of correlation coefficient), indicating that the proposed approach can be more effective in generating the surrogate safety metrics. In other words, the proposed vehicle dynamics model-integrated traffic simulation environment was found to be a superior and valid alternative for assessing the surrogate safety.

In addition, a network-wide traffic safety impact using different positioning accuracy levels corresponding to different GPS/INU devices and the V2V/V2I communication delays was assessed based on three different driver warning scenarios[2] and driver responses (i.e., deceleration). The GPS/INU simulator which generates erroneous trajectories based on the ground-truth trajectories and the V2V/V2I communication delays simulator which generates a connection success/fail probability rate were developed. These developed positioning errors and delays simulators were integrated into the safety assessment framework and implemented with driver warning scenarios. The mobility and environmental impacts were also evaluated by directly analyzing the simulation outputs and applying a VT-Micro model which is a microscopic level model for estimating emissions and fuel consumption.

The study results indicated that V2V/V2I communication delays degrade the effectiveness of driver warnings by 8% to 15% while the driver warnings under ideal conditions (i.e., error-free vehicle positions and no V2V/V2I communication delays) reduce dangerous conditions by 28% to 35%. Regarding the driver warning scenarios with different positioning accuracy levels, as expected, the most accurate GPS/INU device (i.e., Real-time kinematic GPS) is best for use with vehicle safety applications as

[2] Rear-end type warning for lane changes and sudden stops, red-light running warning at a signalized intersection, and road departure warning

the RTK case was the closest to the ground truth-based warning scenario. Meanwhile, the device with the lowest accuracy (i.e., Autonomous GPS) was not very relevant for deployment in the safety application as this case showed even worse results than the base case (i.e., no driver warnings). Therefore, two important findings are highlighted: 1) the probability of false alarm will decrease as the high-accuracy positioning system is deployed in the vehicle safety applications, and 2) the traffic safety estimation result can be different according to the accuracy level of the positioning systems assumed. Accordingly, this dissertation research conveys to the traffic safety research community that the potential positioning errors need to be considered when the traffic safety is estimated under the advanced vehicle safety applications scenarios (e.g., Connected Vehicles applications)

In summary, this dissertation research not only developed a vehicle dynamics model-integrated traffic simulation environment but also validated the performance of the developed simulation environment by comparing the traffic conflict estimation results to the traffic crash data collected in the field. This research shows the potential benefit that can be obtained through the integration of the traffic simulation model and the vehicle dynamics model used for different disciplines (i.e., mechanical engineering). In addition, this study has attempted to directly link the traffic conflicts to the traffic crash data whereas previous studies have only focused on the number of traffic conflicts, without validating their representativeness of traffic crashes. Furthermore, the integrated safety assessment framework is expected to be beneficial for traffic safety engineers and researchers in evaluating the impact of vehicle safety applications under Connected Vehicles environment.

2. Research Contributions

This dissertation provided several contributions to the state-of-the-art knowledge in the surrogate safety measures-based traffic safety research. Specific contributions are discussed here.

Incorporated driver aggressiveness into the microscopic traffic simulation model.

This dissertation research represents a new attempt to incorporate driver aggressiveness into the microscopic traffic simulation model. In reality, every driver has different driving characteristics in terms of driver aggressiveness. However, previous traffic safety assessment studies using the microscopic traffic simulation models could not reflect driver aggressiveness in the simulation as the off-the-shelf driver model of the traffic simulation tools does not support drivers' characteristics. The technique developed in this research to reflect driver aggressiveness in the traffic simulation model provides a useful reference for traffic safety engineers and researchers seeking to assess traffic safety while considering the aspects of the drivers.

Integrated the vehicle dynamics model with the microscopic traffic simulation model.

This research represents the first attempt to integrate the vehicle dynamics model, being used in a different discipline (i.e., mechanical engineering), with the microscopic traffic simulation model to obtain realistic vehicle trajectories. This research focused on the utilization of the capabilities of the two heterogeneous simulation models. The microscopic traffic simulation model can make various traffic situations while the vehicle dynamics model can generate realistic vehicle movements and its trajectories. By taking advantage of the integration of the two simulation models, this research provides a new opportunity for assessing surrogate safety using realistic vehicle trajectories whereas existing microscopic traffic simulation models are limited in modeling realistic vehicle movements.

Verified the potential of traffic conflicts as a traffic safety estimator.

This research verified the potential of traffic conflict as a traffic safety estimator by comparing the traffic conflict estimation result to the traffic crash data in a given area. Previous efforts in the traffic conflict-based safety studies have focused on the development of new surrogate safety measures, but the traffic conflicts estimated from the surrogate safety measures have not been directly linked to the traffic crashes. This research identified the strength of correlation between traffic conflicts and traffic crashes obtained from specific roadway sections. It also demonstrated that the traffic conflict estimation result obtained from the proposed vehicle dynamics model-integrated safety simulation environment can more effectively represent the probability of traffic crashes than the conflict estimation results obtained from the existing traffic simulation model only approach. As the validation experiment showed a statistically significant relationship between traffic conflicts and traffic crashes, and the vehicle dynamics model-integrated traffic safety environment is effective in representing the surrogate safety, it can be concluded that this dissertation research provides credibility to the traffic conflict-based safety studies.

Enhanced the credibility of the surrogate safety assessment by considering the impact of the V2V/V2I communication delays on the vehicle safety applications

This dissertation research eases the need to consider the potentially negative impact of communication delays when safety estimation is conducted with vehicle safety applications scenarios. Previously, most of the Connected Vehicles (CV) technology-based studies have overlooked the potential impact of V2V/V2I communication delays while the communication performance can be affected by external factors including the distance between receivers and the number of receivers in a specific area in real-life. This dissertation research developed the V2V/V2I communication delays simulator and implemented them with various driver warning scenarios. The results indicate that the V2V/V2I communication delays can affect the performance of driver warnings; thus, this dissertation research highlights the importance of considering communication delays for the traffic safety community.

Enhances the credibility of the surrogate safety assessment by considering the impacts of different vehicle positioning accuracy levels on the vehicle safety applications

Similarly, vehicle positioning errors can negatively affect the performance of vehicle safety applications due to false alarms. Despite the advances in positioning systems, the accuracy is not yet perfect. Rather, the autonomous GPS, widely used in vehicle safety applications, is not satisfying for a lane-distinguished accuracy level. Note that Dedes [125] published that the autonomous GPS has approximately 7 meters of horizontal errors and 10 meters of vertical errors. Obviously, this positioning accuracy level can be crucial to the traffic safety applications due to false alarms. With this in mind, this dissertation research has developed the GPS/INU simulator which can simulate vehicles' coordinates with different accuracy levels and be implemented with various driver warning scenarios. The experiment results show that the traffic safety assessment results can differ according to different vehicle positioning accuracy; the results can be even more biased as a lower accuracy level is assumed.

In the aspect of the automotive manufactures, they have adopted radar or lidar-based sensors for detecting adjacent vehicles. However, some automotive brands have initiated equipping GPS as well as the radar system in the perspective of more various safety applications. For example, Cadillac announced that various safety applications including a lane departure warning system, forward collision alert system, and cross traffic alert system will be deployed by mid-decade through the fusion of multiple sensors by relying on a fusion of radar, ultrasonic sensors, cameras, and GPS [126, 127]. The fusion of sensors could give more possibility, GPS can provide current position, heading angle, acceleration, speed, even the information of the other vehicles in a distantly located. In addition, many traffic safety applications including an intersection collision warning system, work zone warning system, lane change and lane departure warning system, and dilemma zone warning system have been studied in the Connected Vehicles research program by taking advantage of the V2V/V2I communication technology. These traffic safety applications are expected to be deployed in the near future. It is expected that this dissertation research can be applied to assess the safety impact of these safety applications since they are being developed based on the GPS and V2V/V2I technologies. The integrated safety assessment framework developed in this research will provide more reliable safety assessment results by considering the potential positioning errors, communication delays, and vehicle dynamics resulted in the driver warning systems and the drivers' responses.

3. Recommendations for Future Research

In the course of this research, an integrated safety assessment framework incorporating traffic simulator, vehicle dynamics model, GPS/INU, and V2V/V2I was developed and implemented with driver warning scenarios. However, some points of interest remain that are worth investigating. These points are listed here, sorted by general topic area.

Consideration of realistic road geometry

A more realistic VISSIM network that reflects road elevation and slope needs to be implemented in conjunction with the vehicle dynamics model (i.e., CarSim). Although the Tysons Corner VISSIM network does not reflect the road elevations and slopes, these geometric characteristics are obviously important factors that affect vehicles' kinematic movements: factors which can be simulated by creating 3D roads in CarSim. The conflict estimation with the realistic geometric conditions in a given area as well as the realistic vehicle trajectories are expected to provide even more promising results when assessing surrogate safety.

Traffic conflict severity estimator

The severity of traffic conflict is also important in the traffic safety research fields. However, extant traffic conflict-based studies have only focused on the number of traffic conflicts. Although a smaller value of TTC or PET represents a situation with temporally closer danger, it has not yet been directly linked to the severity of traffic conflicts. With this in mind, methodology that can evaluate the severity aspect through the developed VISSIM-CarSim integrated simulation environment would be an innovative and useful future research tool in the traffic conflict-based research area.

Safety assessment with the market penetration rate of equipped vehicles

For all the simulation experiments, it was assumed that all the vehicles in the network are equipped with GPS/INU devices. However, this is highly unlikely, especially in the initial stages of the GPS/INU technology deployment in the automotive industry. In addition, for each simulation, all the GPS/INU devices were assumed to have the same accuracy. Future research and simulations using various levels of GPS/INU sensor accuracy with various market penetration rates will provide more realistic estimates on the safety impact, mobility, and the environment.

Safety assessment with sophisticated driver warnings

For the simulation experiments, only rear-end collision, road departure, and dilemma zone warnings were considered for the analysis and the investigations of all of the scenarios. Furthermore, the vehicle response was implemented at a specific deceleration rate. However, more sophisticated warning systems have recently been recommended, and automobile companies are continuously developing more sophisticated warning systems for their vehicles. Therefore, additional research is recommended to study the effectiveness and the impact of the different warning systems on safety, mobility, and the environment.

Consideration of additional vehicle sensors

This study considered the impact of the GPS/INU sensor. However, additional vehicle sensors including odometers, video cameras, radar and lidar, and V2V electromagnetic distance detection systems are being deployed in vehicle safety applications. An integrated vehicle sensor system would produce more accurate vehicle positioning information and distances between adjacent vehicles. Incorporating all these vehicle sensor systems into the proposed integrated safety assessment framework would be of interest to the traffic safety research community.

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Appendix #1. t-test Results (p-values) Between GPS/INU Scenarios

1. t-test Results (Peak Scenarios)

Scenario 1	Scenario 2	Lane Change	Sudden Stop	Signalized Intersection
Base	W-G	0.0018	0.0088	0.0028
W-G	W-D	0.0107	0.0018	0.0649
W-D	W-D-RTK/High	0.3078	0.0479	0.4633
W-D	W-D-RTK/Low	0.1548	0.5000	0.1965
W-D	W-D-Omni/High	0.0621	0.1854	0.3591
W-D	W-D-Omni/Low	0.1779	0.0920	0.2326
W-D	W-D-DGPS/High	0.0126	0.1506	0.1880
W-D	W-D-DGPS/Low	0.0065	0.0820	0.2278
W-D	W-D-Auto/High	0.0287	0.0416	0.0048
W-D	W-D-Auto/Low	0.0009	0.0074	0.0157

*Shaded areas: Statistically different between two scenarios (p-value less than 0.05)

2. t-test Results (Non-peak Scenarios)

Scenario 1	Scenario 2	Lane Change	Sudden Stop	Signalized Intersection
Base	W-G	0.0004	0.0053	0.0022
W-G	W-D	0.1173	0.0004	0.1288
W-D	W-D-RTK/High	0.4336	0.2919	0.4075
W-D	W-D-RTK/Low	0.0742	0.0482	0.3816
W-D	W-D-Omni/High	0.4681	0.0544	0.3890
W-D	W-D-Omni/Low	0.2510	0.1004	0.4384
W-D	W-D-DGPS/High	0.1594	0.0066	0.2923
W-D	W-D-DGPS/Low	0.0399	0.4005	0.3351
W-D	W-D-Auto/High	0.0075	0.0402	0.0609
W-D	W-D-Auto/Low	0.0451	0.0370	0.0139

*Shaded areas: Statistically different between two scenarios (p-value less than 0.05)

Appendix #2. Source Codes

1. Lane Change Driver Aggressiveness Simulation

Program.cs

```
using System;
using System.Collections;
using System.Collections.Generic;
using VISSIM_COMSERVERLib;
using System.IO;

namespace Vehicle_Trajectory_Analysis
{
    class Program
    {
        static void Main(string[] args)
        {
            VissimTools.InitVissim();
            while (true)
            {
                VissimTools.vissim.Simulation.RunSingleStep();
                VissimState.UpdateStatus();
                LCAggChanger.resetVehicles();
                Console.WriteLine(VissimState.currentTime);
            }
        }
    }
}
```

LaneChangeProgram.cs

```
using System;
using System.Collections.Generic;

namespace Vehicle_Trajectory_Analysis
{
    class LCAggChanger
    {
        public static Dictionary<int, List<int>> resetList = new Dictionary<int, List<int>>();
        public static List<int> resetIDsList = new List<int>();
        public static double[] Aggs = { 0.5, 1.5, 1.5, 1.5, 1.5, 1.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5,
2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5,
3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 3.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5,
4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 4.5, 5.5, 5.5, 5.5, 5.5, 5.5, 5.5, 5.5, 5.5, 6.5, 6.5, 6.5, 6.5, 6.5, 6.5,
6.5, 7.5, 7.5, 7.5, 7.5, 8.5, 8.5, 9.5, 10.5 };

        private static int AggNum = Aggs.Length - 1;
        public static void changeType(int vid)
        {
            if (resetIDsList.Contains(vid)) return;
            int aggIndex = new Random().Next(AggNum);
            double agg = Aggs[aggIndex];
            int aggvalue = Convert.ToInt32(agg + 0.5);
            int vehType = 100;
            switch (aggvalue)
            {
                case 1:
                    vehType = 101;
                    Console.WriteLine(vid + "   ----> LCAGG: vType 101");
                    break;
                case 2:
                    vehType = 102;
                    Console.WriteLine(vid + "   ----> LCAGG: vType 102");
```

```
                break;
            case 3:
                vehType = 103;
                Console.WriteLine(vid + "   ----> LCAGG: vType 103");
                break;
            case 4:
                vehType = 104;
                Console.WriteLine(vid + "   ----> LCAGG: vType 104");
                break;
            case 5:
                vehType = 105;
                Console.WriteLine(vid + "   ----> LCAGG: vType 105");
                break;
            case 6:
                vehType = 106;
                Console.WriteLine(vid + "   ----> LCAGG: vType 106");
                break;
            case 7:
                vehType = 107;
                Console.WriteLine(vid + "   ----> LCAGG: vType 107");
                break;
            case 8:
                vehType = 108;
                Console.WriteLine(vid + "   ----> LCAGG: vType 108");
                break;
            case 9:
                vehType = 109;
                Console.WriteLine(vid + "   ----> LCAGG: vType 109");
                break;
            case 10:
                vehType = 110;
                Console.WriteLine(vid + "   ----> LCAGG: vType 110");
                break;
            case 11:
                vehType = 111;
                Console.WriteLine(vid + "   ----> LCAGG: vType 111");
                break;
            default:
                Console.WriteLine("Please check the LC aggressiveness module");
                break;
        }
        VissimTools.Set_VehType(vid, vehType);
        agg = agg * 10; // Change time scale
        if (!resetList.ContainsKey(VissimState.currentTime + (int)(agg)))
        {
            resetList.Add(VissimState.currentTime + (int)(agg), new List<int>());
        }
        resetList[VissimState.currentTime + (int)(agg)].Add(vid);
        resetIDsList.Add(vid);
    }
    public static void resetVehicles()
    {
        if (resetList.ContainsKey(VissimState.currentTime))
        {
            foreach (int vid in resetList[VissimState.currentTime])
            {
                try
                {
                    VissimTools.Set_VehType(vid, 100);
                    resetIDsList.Remove(vid);
                    Console.WriteLine(vid + "   ----> LCAGG Recovering: vType 100");
                }
                catch (NullReferenceException e)
                {
                    resetIDsList.Remove(vid);
                    // The Vehicle has left
                }
            }
            resetList.Remove(VissimState.currentTime);
        }
    }
  }
}
```

2. Driver Warning Simulation with GPS/INU and V2V/V2I

Program.cs

```
using System;
using System.Collections;
using System.Collections.Generic;
using VISSIM_COMSERVERLib;
using System.IO;

namespace Vehicle_Trajectory_Analysis
{
   class Program
   {
      static void Main(string[] args)
      {
         //Initialize GPS/IMU Simulated Positions
         RealTimeGPSIMUSimulator.GPSIMUSimulatedPositions.Init("GPS_IMU_SIM.ini");

         VissimTools.InitVissim();
         SignalizedDetector.SignalizeDetectorInit();
         AnalysisLogger.Clear();

         while (true)
         {
            VissimState.UpdateCoordinate();
            VissimTools.vissim.Simulation.RunSingleStep();
            VissimState.UpdateStatus();

            LaneChangeUtiltiy.LaneChangeUpdate();
            LaneChangeUtiltiy.LaneChangeCheck();

               SuddenStopUtility.SuddenStopUpdate();
               SuddenStopUtility.SuddenStopCheck();

               foreach (SignalizedDetector currentSD in SignalizedDetector.sdList)
               {
                  int vid = currentSD.getRedLightVehicle();
                  if (vid != 0)
                  {
                     AnalysisLogger.WriteRedLightRunner(vid, currentSD, AnalysisLogger.SignalizedFileName);
                  }
               }

               SignalizedDetector.SignalizedDetectorCheck();
               SignalizedDetectorImmediateWarning.CheckWarnings();
            ImmediateWarning.CheckWarnings();
            Console.WriteLine(VissimState.currentTime);
         }
      }
   }
}
```

VehicleGroupInfo.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using VISSIM_COMSERVERLib;

namespace Vehicle_Trajectory_Analysis
{
  class VehicleGroupInfo
  {
    public Vehicle main;
    public Vehicle target;
    public int mainType;
    public double mainSpeed;
    public double mainAcc;
    public double mainLinkCord;
    public double targetLinkCord;
    public double distDiff;
    public double ittc;
    public double deltaVMain;
    public double deltaVTarget;
    public double ipet;
    public double drd;
    public double targetSpeed;
    public double targetAcc;
    public double mainVehXcoord;
    public double mainVehYcoord;
    public double targetVehXcoord;
    public double targetVehYcoord;

    public VehicleGroupInfo(Vehicle main, Vehicle target, int VehicleIDOffset)
    {
      this.main = main;
      this.target = target;
      Calculator.Calculate(this.main, this.target, VehicleIDOffset, out mainType, out mainSpeed, out
mainAcc, out mainLinkCord, out targetSpeed, out targetAcc, out targetLinkCord, out mainVehXcoord, out
mainVehYcoord,
        out targetVehXcoord, out targetVehYcoord, out distDiff, out ittc, out deltaVMain, out
deltaVTarget, out ipet, out drd);

    }

    public static VehicleGroupInfo getFrontGroupInfo(int vid, int VehicleIDOffset)
    {
      Vehicle front = null;
      Vehicle behind = null;
      Vehicle main = VissimState.Current_Vehicles[vid];
      if (main != null)
      {
        VissimState.GetAdjacentVehicles(main, out front, out behind);
        //Hazard Detection system needed
        if (front != null)
        {
          return new VehicleGroupInfo(main, front, VehicleIDOffset);
        }
      }
      return null;
    }
  }
}
```

LaneChangeUtility.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using VISSIM_COMSERVERLib;

namespace Vehicle_Trajectory_Analysis
{
    class LaneChangeUtiltiy
    {
        /// <summary>
        /// Update the lane changer
        /// </summary>
        public static void LaneChangeUpdate()
        {
            List<int> PreviousLCs = new List<int>(VissimState.LaneChangers);
            VissimState.LaneChangers.Clear();
            foreach (Vehicle veh in VissimState.Current_Vehicles.Values)
            {
                //Update Lanechange
                int lane = Convert.ToInt32(veh.get_AttValue("LANECHANGE"));
                if (lane != 0)
                {
                    if (!PreviousLCs.Contains(veh.ID))
                    {
                        LCAggChanger.changeType(veh.ID);
                    }
                    VissimState.LaneChangers.Add(veh.ID);
                }
            }
            LCAggChanger.resetVehicles(); // reset the vehicle type to 100 when out-dated
        }

        public static void LaneChangeCheck()
        {
            // Lane Change
            foreach (int vid in VissimState.LaneChangers)
            {
                Vehicle front;
                Vehicle behind;
                Vehicle main = VissimState.Current_Vehicles[vid];
                VissimState.GetAdjacentVehicles(main, out front, out behind);
                VehicleGroupInfo info;
                if (front != null)
                {
                    info = new VehicleGroupInfo(main, front, VehicleScenarioOffsets.LaneChangeVehicleIDOffset);
                    AnalysisLogger.WriteGroupInfo(info, AnalysisLogger.LaneChangeFileName);
                    ImmediateWarning.Register(info);
                }
                if (behind != null)
                {
                    info = new VehicleGroupInfo(main, behind,
VehicleScenarioOffsets.LaneChangeVehicleIDOffset);
                    AnalysisLogger.WriteGroupInfo(info, AnalysisLogger.LaneChangeFileName);
                    ImmediateWarning.Register(info);
                }
            }
        }
    }
}
```

SuddenStopUtility.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using VISSIM_COMSERVERLib;

namespace Vehicle_Trajectory_Analysis
{
   class SuddenStopUtility
   {
      private static double SuddenStopThreshold = -6.0;

      /// <summary>
      /// Update the sudden stoppers
      /// </summary>
      public static void SuddenStopUpdate()
      {
         VissimState.SuddenStoppers.Clear();
         foreach (Vehicle veh in VissimState.Current_Vehicles.Values)
         {
            double acc = Convert.ToDouble(veh.get_AttValue("ACCELERATION"));
            if (acc < SuddenStopThreshold)
            {
               VissimState.SuddenStoppers.Add(veh.ID);
            }
         }
      }

      public static void SuddenStopCheck()
      {
         // Sudden Stopper
         foreach (int vid in VissimState.SuddenStoppers)
         {
            Vehicle front;
            Vehicle behind;
            Vehicle main = VissimState.Current_Vehicles[vid];
            VissimState.GetAdjacentVehicles(main, out front, out behind);
            if (behind != null)
            {
               VehicleGroupInfo info = new VehicleGroupInfo(main, behind,
VehicleScenarioOffsets.SuddenStopVehicleIDOffset);
               AnalysisLogger.WriteGroupInfo(info, AnalysisLogger.SuddenStopFileName);
               ImmediateWarning.Register(info);
            }
         }
      }
   }
}
```

SignalizedDetector.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Collections;
using VISSIM_COMSERVERLib;

namespace Vehicle_Trajectory_Analysis
{
  class SignalizedDetector
  {
    public static List<SignalizedDetector> sdList;
    public static Dictionary<String, double> sdCoordinate;
    public static double intersectionWidth = 25;

    private static double SpeedLimit = 15;
    private static double MaxAcc = 5;
    private static double MaxDec = 9;
    static int decelerationProbability = 85; // Probability of getting warned

    public int signalControlNum;
    public int signalNum;
    public int detectorNum;
    public double yellowInterval;

    public SignalGroup signalGroup
    {
      get
      {
        return
VissimTools.vissim.Net.SignalControllers.GetSignalControllerByNumber(signalControlNum).SignalGroups.
GetSignalGroupByNumber(signalNum);
      }
    }

    private int previous;

    public SignalizedDetector(int sigConNum, int sigNum)
    {
      signalControlNum = sigConNum;
      signalNum = sigNum;
      previous = -1;
      detectorNum = (sigConNum * 1000) + (sigNum * 100) + 99;
      SignalGroup                                         sg                                         =
VissimTools.vissim.Net.SignalControllers.GetSignalControllerByNumber(sigConNum).SignalGroups.GetSign
alGroupByNumber(sigNum);
      IEnumerator en = sg.SignalHeads.GetEnumerator();
      while (en.MoveNext())
      {
        SignalHead sh = (SignalHead) en.Current;
        sdCoordinate.Add(getIdentifier(Convert.ToInt32(sh.get_AttValue("LINK")),
Convert.ToInt32(sh.get_AttValue("LANE"))), Convert.ToDouble(sh.get_AttValue("LINKCOORD")));
        yellowInterval = Convert.ToDouble(sg.get_AttValue("AMBER"));
      }
    }

    public void checkDilemmaZone()
    {
      int current = Convert.ToInt32(this.signalGroup.State);
      // When it changed from Green to Amber
      if (this.previous == 3 && current == 4)
      {
        //Console.WriteLine("Became Yellow!:{0},{1}", signalControlNum, signalNum);    // Comment-out
for speed-up
        foreach (String key in sdCoordinate.Keys)
        {
          double sdCoord = sdCoordinate[key];
          // if there is car
          if (VissimState.Link_Order_VID.ContainsKey(key))
          {
            SortedList<Double, int> vehList = VissimState.Link_Order_VID[key];
            for (int i = 0; i < vehList.Count; i++)
```

```
                {
                    double coord = vehList.Keys[i];
                    if (coord > sdCoord)
                    {
                        break;
                    }
                    int vid = vehList.Values[i];

                    bool SigV_gps_imu_simulated_position_exists = false;
                    double SigV_gps_imu_time_position_secs = -99999.0;
                    double SigV_veh_x_coord = 0;
                    double SigV_veh_y_coord = 0;
                    double SigV_veh_z_coord = 0;
                    double SigV_speed_mps = 0;
                    double SigV_hdop = 99999;

                    GPSIMUSimulationInterface.AddVehiclePositionToSimulation(vid,
VehicleScenarioOffsets.SignalizedIntersectionVehicleIDOffset, ref
SigV_gps_imu_simulated_position_exists,
        ref SigV_gps_imu_time_position_secs, ref SigV_veh_x_coord, ref SigV_veh_y_coord, ref
SigV_veh_z_coord, ref SigV_speed_mps, ref SigV_hdop);


                    double Xs = getXs(vid);
                    double Xc = getXc(vid);
                    if (Xc < 0) Xc = 0;

                    double Ori_x = VissimTools.Get_XCOORD(vid);
                    double Ori_y = VissimTools.Get_YCOORD(vid);
                    double error = Math.Sqrt(Math.Pow(SigV_veh_x_coord-
Ori_x,2)+Math.Pow(SigV_veh_y_coord-Ori_y,2));
                    coord = coord + error;
                    //Console.WriteLine("Xs : " + Xs + ". Xc : " + Xc);   // Comment-out for speed-up
                    if ( (coord < sdCoord - Xc) && (coord > sdCoord - Xs))
                    {
                        if (new Random().Next(100) < decelerationProbability)
                        {
                            // The Veh is in Dillema Zone
                            AnalysisLogger.WriteSignalizedDectector(vid, this,
AnalysisLogger.SignalizedFileName);
                            SignalizedDetectorImmediateWarning.Register(vid, this);
                        }
                    }
                }
            }
        }
    }
    // Yellow to Red
    else if(this.previous == 4 && current == 1)
    {
        SignalizedDetectorImmediateWarning.Clear();
    }
    this.previous = current;
}

public double getXs(int vid)
{
    return
((Convert.ToDouble(VissimTools.vissim.Net.Vehicles.GetVehicleByNumber(vid).get_AttValue("SPEED"))*(1
000.0/3600.0)) * PIEV.getPIEV(vid)) +
(Math.Pow(Convert.ToDouble(VissimTools.vissim.Net.Vehicles.GetVehicleByNumber(vid).get_AttValue("S
PEED")),2.0)/(2.0 * MaxDec));
}

public double getXc(int vid)
{
    return
(Convert.ToDouble(VissimTools.vissim.Net.Vehicles.GetVehicleByNumber(vid).get_AttValue("SPEED")) *
(1000.0 / 3600.0)) * yellowInterval - (intersectionWidth +
Convert.ToDouble(VissimTools.vissim.Net.Vehicles.GetVehicleByNumber(vid).get_AttValue("LENGTH")))+(
0.5*3.0*Math.Pow(yellowInterval-PIEV.getPIEV(vid),2.0));
}

public int getRedLightVehicle()
{
```

```
        if (VissimTools.Get_LightSignal(signalControlNum, signalNum) == 1)
        {
            return VissimTools.Get_VehicleIDOnDetectorByNumber(signalControlNum, detectorNum);
        }
        else
        {
            return 0;
        }
    }

    public static String getIdentifier(int link, int lane)
    {
        return link + "#" + lane;
    }

    public static void SignalizedDetectorCheck()
    {
        foreach (SignalizedDetector sd in sdList)
        {
            sd.checkDilemmaZone();
        }
    }

    public static double getDistanceFromVeh(int vid)
    {
        Vehicle currentVeh = VissimState.Current_Vehicles[vid];
        String identifier = getIdentifier(Convert.ToInt32(currentVeh.get_AttValue("LINK")),
Convert.ToInt32(currentVeh.get_AttValue("LANE")));
        try
        {
            return sdCoordinate[identifier] - Convert.ToDouble(currentVeh.get_AttValue("LINKCOORD"));
        }
        catch (Exception e)
        {
            return 20;
            Console.WriteLine(e);
        }
    }

    public static void SignalizeDetectorInit()
    {
        sdList = new List<SignalizedDetector>();
        sdCoordinate = new Dictionary<string, double>();

        sdList.Add(new SignalizedDetector(1, 1));
        sdList.Add(new SignalizedDetector(1, 2));
        sdList.Add(new SignalizedDetector(2, 1));
        sdList.Add(new SignalizedDetector(2, 2));
        sdList.Add(new SignalizedDetector(3, 1));
        sdList.Add(new SignalizedDetector(3, 2));
        sdList.Add(new SignalizedDetector(4, 1));
        sdList.Add(new SignalizedDetector(4, 2));
        sdList.Add(new SignalizedDetector(4, 3));
        sdList.Add(new SignalizedDetector(4, 4));
        sdList.Add(new SignalizedDetector(4, 5));
        sdList.Add(new SignalizedDetector(4, 6));
        sdList.Add(new SignalizedDetector(5, 1));
        sdList.Add(new SignalizedDetector(5, 2));
        sdList.Add(new SignalizedDetector(5, 3));
        sdList.Add(new SignalizedDetector(5, 4));
        sdList.Add(new SignalizedDetector(6, 1));
        sdList.Add(new SignalizedDetector(6, 2));
        sdList.Add(new SignalizedDetector(6, 3));
        sdList.Add(new SignalizedDetector(7, 1));
        sdList.Add(new SignalizedDetector(7, 2));
        sdList.Add(new SignalizedDetector(8, 1));
        sdList.Add(new SignalizedDetector(8, 2));
        sdList.Add(new SignalizedDetector(9, 1));
        sdList.Add(new SignalizedDetector(9, 2));
        sdList.Add(new SignalizedDetector(9, 3));
        sdList.Add(new SignalizedDetector(9, 4));
        sdList.Add(new SignalizedDetector(9, 5));
        sdList.Add(new SignalizedDetector(9, 6));
        sdList.Add(new SignalizedDetector(10, 1));
        sdList.Add(new SignalizedDetector(10, 2));
```

```
        sdList.Add(new SignalizedDetector(10, 3));
        sdList.Add(new SignalizedDetector(10, 4));
        sdList.Add(new SignalizedDetector(10, 5));
        sdList.Add(new SignalizedDetector(10, 6));
        sdList.Add(new SignalizedDetector(11, 1));
        sdList.Add(new SignalizedDetector(11, 2));
        sdList.Add(new SignalizedDetector(12, 1));
        sdList.Add(new SignalizedDetector(12, 2));
        sdList.Add(new SignalizedDetector(12, 3));
        sdList.Add(new SignalizedDetector(12, 4));
        sdList.Add(new SignalizedDetector(12, 5));
        sdList.Add(new SignalizedDetector(12, 6));
        sdList.Add(new SignalizedDetector(13, 1));
        sdList.Add(new SignalizedDetector(13, 2));
        sdList.Add(new SignalizedDetector(13, 3));
        sdList.Add(new SignalizedDetector(16, 2));
        sdList.Add(new SignalizedDetector(16, 3));
        sdList.Add(new SignalizedDetector(16, 4));
        sdList.Add(new SignalizedDetector(17, 1));
        sdList.Add(new SignalizedDetector(17, 2));
        sdList.Add(new SignalizedDetector(17, 3));
        sdList.Add(new SignalizedDetector(17, 4));
        sdList.Add(new SignalizedDetector(18, 1));
        sdList.Add(new SignalizedDetector(18, 2));
        sdList.Add(new SignalizedDetector(18, 3));
        sdList.Add(new SignalizedDetector(18, 4));
        sdList.Add(new SignalizedDetector(25, 1));
        sdList.Add(new SignalizedDetector(25, 2));
        sdList.Add(new SignalizedDetector(25, 3));
        sdList.Add(new SignalizedDetector(25, 4));
        sdList.Add(new SignalizedDetector(26, 1));
        sdList.Add(new SignalizedDetector(26, 2));
        sdList.Add(new SignalizedDetector(26, 3));
    }
  }
}
```

HazardDetetor.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace Vehicle_Trajectory_Analysis
{
   class HazardDetector
   {
      static double ittcThreshold = 1.0 / 2.5;
      static double drdThreshold = 4.5;

      /// <summary>
      /// return if two vehicles are in the hazard position
      /// </summary>
      /// <param name="ttc">time to collision</param>
      /// <param name="drd">deceleration rate difference</param>
      /// <param name="mainLink">link coordinate of the main vehicle</param>
      /// <param name="targetLink">link coordinate of the target vehicle</param>
      /// <param name="main">true if the main should decelerate</param>
      /// <returns></returns>
      public static Boolean isHazard(VehicleGroupInfo info, out Boolean main)
      {
         main = info.mainLinkCord < info.targetLinkCord;
         return info.ittc > ittcThreshold && info.drd > drdThreshold;
      }

      public static Boolean canRestore(VehicleGroupInfo info, out Boolean main)
      {
         main = info.mainLinkCord < info.targetLinkCord;
         return info.ittc < 0.0 && info.ittc > ittcRestoreThreshold;
      }
   }
}
```

Calculator.cs

```
using VISSIM_COMSERVERLib;
using System;

namespace Vehicle_Trajectory_Analysis
{
  class Calculator
  {
    public static double maxDecelerationRate = 7.5;
    public static double fixedPIEV = 1.0;
    public static double safeMargin = 2.0;

    /// <summary>
    /// Calculate approporiate measures for two vehicles on the same link
    /// </summary>
    /// <param name="main">Main vehicle</param>
    /// <param name="target">Target vehicle</param>
    /// <param name="mainType">type of the main vehicle</param>
    /// <param name="mainSpeed">speed of the main vehicle</param>
    /// <param name="mainAcc">acceleratino of the main vehicle</param>
    /// <param name="mainLinkCord">link coordinate of the main vehicle</param>
    /// <param name="targetLinkCord">link coordinate of the target vehicle</param>
    /// <param name="ittc">Inverse Time to collision</param>
    /// <param name="deltaVMain">deltaV for the main vehicle</param>
    /// <param name="deltaVTarget">deltaV for the target vehicle</param>
    /// <param name="ipet">Inverse post encroachment time</param>
    /// <param name="drd">deceleration rate difference</param>
    public static void Calculate(Vehicle main, Vehicle target, int VehicleIDOffset, out int mainType, out
double mainSpeed, out double mainAcc, out double mainLinkCord, out double targetSpeed,
      out double targetAcc, out double targetLinkCord, out double mainVehXcoord, out double
mainVehYcoord, out double targetVehXcoord, out double targetVehYcoord,
      out double distDiff, out double ittc, out double deltaVMain, out double deltaVTarget, out double
ipet, out double drd)
    {
      //Main Vehicle Info.
      int mainID = Convert.ToInt32(main.get_AttValue("ID"));
      mainLinkCord = VissimTools.Get_LinkCoord(mainID);
      mainType = VissimTools.Get_VehType(mainID);
      mainAcc = VissimTools.Get_Acc(mainID);

      bool main_gps_imu_simulated_position_exists = false;
      double main_gps_imu_time_position_secs = -99999.0;
      double main_veh_x_coord = 0;
      double main_veh_y_coord = 0;
      double main_veh_z_coord = 0;
      double main_speed_mps = 0;
      double main_hdop = 99999;

      GPSIMUSimulationInterface.AddVehiclePositionToSimulation(mainID, VehicleIDOffset, ref
main_gps_imu_simulated_position_exists,
        ref main_gps_imu_time_position_secs, ref main_veh_x_coord, ref main_veh_y_coord, ref
main_veh_z_coord, ref main_speed_mps, ref main_hdop);

      mainVehXcoord = main_veh_x_coord;
      mainVehYcoord = main_veh_y_coord;
      mainSpeed = main_speed_mps;

      //Target Vehicle Info.
      int targetID = Convert.ToInt32(target.get_AttValue("ID"));
      targetLinkCord = VissimTools.Get_LinkCoord(targetID);
      targetAcc = VissimTools.Get_Acc(targetID);

      bool target_gps_imu_simulated_position_exists = false;
      double target_gps_imu_time_position_secs = -99999.0;
      double target_veh_x_coord = 0;
      double target_veh_y_coord = 0;
      double target_veh_z_coord = 0;
      double target_speed_mps = 0;
      double target_hdop = 99999;

      GPSIMUSimulationInterface.AddVehiclePositionToSimulation(targetID, VehicleIDOffset, ref
target_gps_imu_simulated_position_exists,
        ref target_gps_imu_time_position_secs, ref target_veh_x_coord, ref target_veh_y_coord, ref
```

```
target_veh_z_coord, ref target_speed_mps, ref target_hdop);

        targetVehXcoord = target_veh_x_coord;
        targetVehYcoord = target_veh_y_coord;
        targetSpeed     = target_speed_mps;

        //Additional Info.
        distdiff = 99999.0;
        ittc = 99999.0;
        deltavmain = 99999.0;
        deltavtarget = 99999.0;
        ipet = 99999.0;
        drd = 99999.0;
        if  (main_gps_imu_simulated_position_exists  &&  target_gps_imu_simulated_position_exists  &&
(Math.Abs(main_gps_imu_time_position_secs-target_gps_imu_time_position_secs) > 1.0e-12))
        {
          double mainWeight = VissimTools.Get_Weight(mainID);
          double targetWeight = VissimTools.Get_Weight(targetID);
          distDiff      =      Math.Sqrt(Math.Pow(mainVehXcoord      -      targetVehXcoord,      2)      +
Math.Pow(mainVehYcoord - targetVehYcoord, 2));

          #region ittc Calculation

          // Main vehicle is ahead
          if (mainLinkCord > targetLinkCord)
          {
            double speedDiff = targetSpeed - mainSpeed;
            ittc = speedDiff / distDiff;

          }
          // Target Vehicle is ahead
          else if (mainLinkCord < targetLinkCord)
          {
            double speedDiff = mainSpeed - targetSpeed;
            ittc = speedDiff / distDiff;
          }
          // Both vehicles are at the same position (impossible)
          else
          {
            ittc = -999;
          }

          #endregion

          #region deltaV Calculation

          double  measure  =  (mainWeight  *  mainSpeed  +  targetWeight  *  targetSpeed)  /  (mainWeight  +
targetWeight);
          deltaVMain = measure - mainSpeed;
          deltaVTarget = measure - targetSpeed;

          #endregion

          // Post encroachment time
          #region ipet Calculation

          // main is ahead
          if (mainLinkCord > targetLinkCord)
          {
            ipet = targetSpeed / distDiff;
          }
          // target is ahead
          else if (mainLinkCord < targetLinkCord)
          {
            ipet = mainSpeed / distDiff;
          }
          else
          {
            ipet = -999;
          }

          #endregion

          // Deceleration rate difference
          #region DRD
```

```
            if (mainLinkCord > targetLinkCord)
            {
               drd = targetAcc - mainAcc;
            }
            else if (mainLinkCord < targetLinkCord)
            {
               drd = mainAcc - targetAcc;
            }
            else
            {
               drd = -999;
            }
            #endregion
         }
      }

      private static double V2V_LogicConstant = 0.848910;
      private static double V2V_DistanceCoef = -0.0008437;
      private static double V2V_VolumeCoef = -0.0114196;
      private static double V2V_SpeedCoef = 0.0354552;

      private static double V2I_LogicConstant = 0.333183;
      private static double V2I_DistanceCoef = -0.0032464;
      private static double V2I_VolumeCoef = -0.0041452;
      private static double V2I_SpeedCoef = 0.0775390;


      private static double Volumne = 230.0;

      public static double getPacketFailureRate(VehicleGroupInfo info, double mainSpd)
      {
         if (info != null)
         {
            double distance = info.distDiff;
            double speed = info.mainSpeed;
            double A = V2V_LogicConstant + V2V_DistanceCoef * distance + V2V_VolumeCoef * Volumne +
V2V_SpeedCoef * speed;
            double exp = Math.Exp(A);
            double percent = 1 - (exp / (1 + exp));  //success rate to failure rate
            return percent * 100;
         }
         else
         {
            double speed = mainSpd;
            double A = V2V_LogicConstant + V2V_VolumeCoef * Volumne + V2V_SpeedCoef * speed;
            double exp = Math.Exp(A);
            double percent = 1 - (exp / (1 + exp));  //success rate to failure rate
            return percent * 100;
         }
      }

      public static double getSignalizedPacketFailureRate(int vid)
      {
         Vehicle currentVeh = VissimState.Current_Vehicles[vid];
         double distance = SignalizedDetector.getDistanceFromVeh(vid);
         double speed = Convert.ToDouble(currentVeh.get_AttValue("SPEED"));
         double A = V2I_LogicConstant + V2I_DistanceCoef * distance + V2I_VolumeCoef * Volumne +
V2I_SpeedCoef * speed;
         double exp = Math.Exp(A);
         double percent = 1 - (exp / (1 + exp));  //success rate to failure rate
         return percent * 100;
      }
   }
}
```

3. VT-Micro Model Implementation

Program.cs

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.IO;

namespace VISSIM_Emission_Anal
{
  class Program
  {
    static double s = 0.0;
    static double a = 0.0;
    static double v = 0.0;
    static double[] HCP = new double[16] { -0.90907, 0.11863, 0.00379, 2.22E-04, 0.04189, -0.00066,
4.00E-06, -0.00883, 0.000236, -5.96E-07, 2.43E-03, 9.79E-06, -2.02E-07, -0.00018, 1.03E-06, -2.44E-08 };
    static double[] HCN = new double[16] { -0.90907, -0.14428, -0.01287, -1.00E-03, 0.03132, -0.00032,
1.77E-06, 0.02164, -0.00038, 1.82E-06, 3.14E-03, -4.40E-05, 1.79E-07, 0.000172, -1.20E-06, 3.32E-10 };
    static double[] COP = new double[16] { 0.536115, 0.34035, -0.01806, 0.00144, 0.09477, -0.00141,
7.67E-06, -0.03006, 0.000876, -4.71E-06, 0.00742, -0.00014, 8.09E-07, -0.00047, 1.02E-05, -9.09E-08 };
    static double[] CON = new double[16] { 0.536115, -0.02867, 0.03164, 0.00504, 0.08851, -0.00113,
5.50E-06, 0.0193, -0.00027, 1.05E-06, -0.00041, 3.31E-05, -2.36E-07, -0.00036, 8.85E-06, -4.90E-08 };
    static double[] NOXP = new double[16] { -1.08028, 0.23686, 0.00147, -7.80E-05, 0.01791, 0.000241, -
1.06E-06, 0.04053, -0.00041, 9.42E-07, -0.00375, -1.30E-05, 1.86E-07, 0.000105, 1.52E-06, 4.42E-09 };
    static double[] NOXN = new double[16] { -1.08028, 0.20845, 0.02193, 0.000882, 0.02111, 0.000163, -
5.83E-07, 0.01067, -3.20E-05, 1.83E-07, 0.00655, -9.40E-05, 4.47E-07, 0.000627, -1.01E-05, 4.57E-08 };
    static double[] CO2P = new double[16] { 6.914935, 0.2173, 0.000235, -0.00036, 0.02754, -0.00021,
9.80E-07, 0.00968, -0.0001, 3.66E-07, -0.00175, 1.97E-05, -1.08E-07, 8.35E-05, -1.02E-06, 8.50E-09 };
    static double[] CO2N = new double[16] { 6.914935, -0.03203, -0.00917, -0.00029, 0.02843, -0.00023,
1.11E-06, 0.00853, -6.60E-05, 3.20E-07, 0.00115, -1.30E-05, 7.56E-08, -3.06E-06, -2.68E-07, 2.95E-09 };
    static double[] FUELP = new double[16] { -7.73452, 0.22946, -0.00561, 9.77E-05, 0.02799, -0.00022,
1.09E-06, 0.0068, -4.40E-05, 4.80E-08, -0.00077, 7.90E-07, 3.27E-08, 8.38E-06, 8.17E-07, -7.79E-09 };
    static double[] FUELN = new double[16] { -7.73452, -0.01799, -0.00427, 0.000188, 0.02804, -0.00022,
1.08E-06, 0.00772, -5.20E-05, 2.47E-07, 0.000837, -7.44E-06, 4.87E-08, -3.40E-05, 2.77E-07, 3.79E-10 };
    static double[] C = new double[16];

    static double CalculateCO(ref double s, ref double a)
    {
      if (a >= 0)
      {
        for (int i = 0; i < 16; i++)
        {
          C[i] = COP[i];
        }

        v = 0;
        v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
        v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
        v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
        v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
        v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
        return Math.Exp(v);
      }
      else
      {
        for (int i = 0; i < 16; i++)
        {
          C[i] = CON[i];
        }
        v = 0;
        v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
        v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
        v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
        v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
        v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
        return Math.Exp(v);
      }
```

```
    }

    static double CalculateCO2(ref double s, ref double a)
    {
      if (a >= 0)
      {
        for (int i = 0; i < 16; i++)
        {
          C[i] = CO2P[i];
        }
        v = 0;
        v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
        v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
        v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
        v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
        v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
        return Math.Exp(v);
      }
      else
      {
        for (int i = 0; i < 16; i++)
        {
          C[i] = CO2N[i];
        }
        v = 0;
        v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
        v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
        v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
        v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
        v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
        return Math.Exp(v);
      }
    }

    static double CalculateHC(ref double s, ref double a)
    {
      if (a >= 0)
      {
        for (int i = 0; i < 16; i++)
        {
          C[i] = HCP[i];
        }
        v = 0;
        v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
        v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
        v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
        v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
        v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
        return Math.Exp(v);
      }
      else
      {
        for (int i = 0; i < 16; i++)
        {
          C[i] = HCN[i];
        }
        v = 0;
        v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
        v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
        v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
        v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
        v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
        return Math.Exp(v);
      }
    }

    static double CalculateFUEL(ref double s, ref double a)
    {
      if (a >= 0)
      {
        for (int i = 0; i < 16; i++)
        {
          C[i] = FUELP[i];
        }
        v = 0;
```

```
            v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
            v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
            v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
            v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
            v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
            return Math.Exp(v);
            //return v;
        }
        else
        {
            for (int i = 0; i < 16; i++)
            {
                C[i] = FUELN[i];
            }
            v = 0;
            v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
            v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
            v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
            v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
            v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
            return Math.Exp(v);
            //return v;
        }
    }

    static double CalculateNOX(ref double s, ref double a)
    {
        if (a >= 0)
        {
            for (int i = 0; i < 16; i++)
            {
                C[i] = NOXP[i];
            }
            v = 0;
            v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
            v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
            v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
            v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
            v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
            return Math.Exp(v);
        }
        else
        {
            for (int i = 0; i < 16; i++)
            {
                C[i] = NOXN[i];
            }
            v = 0;
            v = v + C[0] + C[1] * a + C[2] * a * a + C[3] * a * a * a;
            v = v + C[4] * s + C[5] * s * s + C[6] * s * s * s;
            v = v + C[7] * a * s + C[8] * a * s * s + C[9] * a * s * s * s;
            v = v + C[10] * a * a * s + C[11] * a * a * s * s + C[12] * a * a * s * s * s;
            v = v + C[13] * a * a * a * s + C[14] * a * a * a * s * s + C[15] * a * a * a * s * s * s;
            return Math.Exp(v);
        }
    }

    static String FilePath = @"I:\Jason\EAR_Output_02272013\MobilityAndEmission\";
    static char[] delimit = { ',', ';' };

    static void Main(string[] args)
    {
        Clear();

        using (StreamWriter sw = new StreamWriter("emission.csv", true))
        {
            sw.WriteLine("FilePath" + "," + "Total CO2 (kg)" + "," + "CO2 (kg/unit)" + "," + "Total FUEL (kg)" +
"," + "FUEL (kg/unit)" + "," + "# of units");
        }

        foreach (string fn in Directory.EnumerateFiles(FilePath, "*.fzp", SearchOption.AllDirectories))
        {
            double CO = 0.0;
            double CO2 = 0.0;
            double HC = 0.0;
```

```
double FUEL = 0.0;
double NMOG = 0.0;
double NMHC, PART, SOOT, SO2, EVAP;
double NOX = 0.0;

int count = 0;
double simtime;

double sumCO = 0.0;
double sumCO2 = 0.0;
double sumHC = 0.0;
double sumFUEL = 0.0;
double sumNMOG = 0.0;
double sumNMHC = 0.0;
double sumPART = 0.0;
double sumSOOT = 0.0;
double sumSO2 = 0.0;
double sumEVAP = 0.0;
double sumNOX = 0.0;
string temp;

double sc = 0.0;
double scc = 0.0;
double sf = 0.0;
double sfc = 0.0;

using (StreamReader sr = new StreamReader(fn))
{

   for (int i = 0; i < 29; i++)
   {
      String line = sr.ReadLine();
   }

   while (!sr.EndOfStream)
   {
      String line = sr.ReadLine();
      String[] sLine = line.Split(delimit);
      temp = sLine[0];
      if (temp.Contains(".0"))   // --> Only to consider the trajectories collected at #.0 second
      {
         simtime = Convert.ToDouble(sLine[0]);
         Console.WriteLine(simtime);

         s = Convert.ToDouble(sLine[10]);  // km/h

         if (s >= 120.0)
         {
            s = 120.0;
         }

         a = Convert.ToDouble(sLine[11]) * 3.6;  // convert from m/s/s to km/hr/s

         if (a > -0.0926 * s + 14.383)
         {
            a = -0.0926 * s + 14.383;
         }
         else if (a > 13.0)
         {
            a = 13.0;
         }
         else if (a < -5.0)
         {
            a = -5.0;
         }
         CO2 = CalculateCO2(ref s, ref a) / 1000000; //g to kg
         FUEL = CalculateFUEL(ref s, ref a); //mg to kg
         sumCO2 += CO2;
         sumFUEL += FUEL;
         count++;
      }

   }
   int deci = 3;
```

```
                sc = Math.Round(Convert.ToDouble(sumCO2), deci);
                scc = Math.Round(Convert.ToDouble(sumCO2 / count), deci + 5);
                sf = Math.Round(Convert.ToDouble(sumFUEL), deci);
                sfc = Math.Round(Convert.ToDouble(sumFUEL / count), deci + 5);

            }
            using (StreamWriter sw = new StreamWriter("emission.csv", true))
            {
                sw.WriteLine(fn + "," + sc + "," + scc + "," + sf + "," + sfc + "," + count);
            }
            Console.WriteLine(fn + "," + sc + "," + scc + "," + sf + "," + sfc + "," + count);
            //Console.ReadKey();

        }
    }
    public static void Clear()
    {
        using (StreamWriter sw = new StreamWriter("emission.csv", false))
        {
            sw.Write("");
        }
    }
  }
}
```