NEXT GENERATION SAFETY PERFORMANCE MONITORING AT SIGNALIZED INTERSECTIONS USING CONNECTED VEHICLE TECHNOLOGY

A Thesis

by

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ABSTRACT

Crash-based safety evaluation is often hampered by randomness, lack of timeliness, and rarity of crash occurrences. Surrogate safety data are commonly used as an alternative to crash data; however, its current practice is still resource intensive and prone to human errors. The advent of connected vehicle technology allows vehicles to communicate with each other as well as infrastructure wirelessly. Through this platform, vehicle movements and signal status at the facilities can be automatically and continually monitored in real time.

This study explores the viability of long-term safety performance evaluation at signalized intersection using connected vehicle technology. The development focuses on vehicle-to-infrastructure (V2I) communications which require one road-side equipment (RSE) and some level of on-board equipment to be successful. To accomplish the objective, the researchers defined useful safety measures and developed specific algorithms to derive them in real time from the V2I communication data sets. The safety measures were categorized into single-OBE measures and dual-OBE measure based on the number of the equipped vehicle needed to be monitored. We used vehicles trapped in dilemma zone as the single-OBE measure. The dual-OBE measures included rear-end and crossing conflicts. Different simulation scenarios were designed in VISSIM to test the effectiveness of the proposed framework, effect of market penetration rate as well as required observation period for effective implementation.

The evaluation results indicated that the application can effectively detect changes in safety performance at full market penetration. It can detect a shift of crash pattern from rear-end crashes to right-angle crashes due to the shorted inter green interval at low traffic volume as well as the mitigation of this pattern during the medium-to-high traffic volume. The selected measures can also identify the increasing risk of rear-end and right-angle crashes after removing advance detectors at the major approaches. Sensitivity analysis from the 60 simulation hours' data showed that more than 40% and 60% penetration rate is likely to be required for a reliable detection in the low volume level and medium-to-high volume level, respectively. Increase of traffic volume activated the corresponding phases more frequently and may result in fewer safety measures being collected. Although losing the power of detection, single-OBE measure was demonstrated to be more reliable at lower penetration rate. Under low OBE market penetrations, observation period can be extended to compensate for small sample size. However, the required observation periods vary with the types of safety indicators being collected and the levels of OBE saturation.

DEDICATION

To my dear father Yiqiang Zha, and mother Yufeng Chen, for their selfless love

To my distant but beloved motherland: People's Republic of China

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NOMENCLATURE

ITS	Intelligent Transportation Systems
DSRC	Dedicated Short-Range Communications
V2V	Vehicle-to-Vehicle Communications
V2I	Vehicle-to-Infrastructure Communications
OBE	On-board Equipment
RSE	Roadside Equipment
VII	Vehicle Infrastructure Integration
WAVE	Wireless Access in Vehicular Environments
BSM	Basic Safety Message
MAP	Map Data
SPaT	Signal Phase and Timing
VSC-A	Vehicle Safety Communications – Applications
GID	Geometric Intersection Description Layer
CICAS	Cooperative Intersection Collision Avoidance Framework
CICAS-V	Cooperative Intersection Collision Avoidance-Traffic Signal Violation
CICAS-SLTA	Cooperative Intersection Collision Avoidance- Signalized Left-Turn Assist
CICAS-TSA	Cooperative Intersection Collision Avoidance- Traffic Signal Adaptation
P2P	Point to Point
PKI	Public Key Infrastructure
TCT	Traffic Conflict Technique
SSAM	Surrogate Safety Assessment Model
TTC	Time-to-Collision
PET	Post-Encroachment Time
DR	Initial Deceleration Rate
DeltaS	Maximum Speed Differential
DeltaV	Change of Speed

MaxD	Maximum Deceleration Rate
RBR	Required Braking Rate
C2X	Car2X
API	Application Programming Interface

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1. INTRODUCTION

1.1. Overview

Safety performance at signalized intersections is an outcome of complex interactions among several contributing factors including signal operations, geometric design, drivers' behavior and vehicular performance. While crash-based analyses are commonly used in safety evaluation, they have several shortcomings including randomness, lack of timeliness, and rarity of crash occurrences. In addition, crash-based approaches are considered reactive in that crashes must occur before the analyses can be conducted. This limitation renders crash-based approaches impractical for evaluating safety of new transportation facilities or unconventional traffic control strategies. An alternative approach to crash-based analyses relies on surrogate safety data. However, the current practice of collecting surrogate data at signalized intersection relies primarily on video recordings that require labor-intensive back-office processing and manual review. These procedures are not always desirable due to lack of resources and potential human errors. Some emerging technologies exist to assist with surrogate safety data collection but they are still in its early stage and mostly developed as a stand-alone add-on system instead of integrated intelligent transportation systems (ITS) solution.

Connected vehicle technology allows vehicles to talk to each other and to infrastructure wirelessly using the dedicated short-range communications (DSRC). Existing connected vehicle safety applications mostly focus on providing in-vehicle advisory or warning information based on the monitored or predicted hazardous events; or even takes control of the signal controller to mitigate crash risks. Many of these safety applications require vehicle-to-vehicle (V2V) communications and high saturation of on-board equipment (OBE) which does not exist currently. In the near term, it is envisioned that a separate computing unit can be installed at signalized intersections to process the data received at the roadside equipment (RSE) from connected vehicle applications to provide safety performance monitoring capability. This study proposes to investigate the capability to mine vehicle movement, intersection description, and signal status data available at the RSE for the purpose of safety performance monitoring and evaluation. The proposed safety performance monitoring application would require only the vehicle-to-infrastructure (V2I) communications, RSE, and some levels of OBE. This constant exchange of V2I data stream can be potentially mined for information that can be used to indicate the safety performance of the signal operation.

1.2. Research Tasks

The goal of is this study is to propose and evaluate a framework for continuously monitoring the safety performance of signalized intersections via V2I communications.
The researchers conducted the following tasks to achieve this goal.

- Define useful safety measures that can comprehensively represent the safety performance of the signalized intersection operation.
- Design specific algorithms to derive the proposed safety measures by integrating and synchronizing the recorded vehicles' kinematics data, geometric data of intersection and signal phases.
- Develop the simulation test bed which enables the V2I communications along with different simulation scenarios which represent degrading safety performance.
- Evaluate and compare the effectiveness of measurements in detecting safety deficiency of intersection operation between simulation scenarios.
- Investigate the effect of market penetration on effectiveness of the framework through sensitivity analysis.
- Examine the effect of observation period for the effective implementation of the proposed framework.

1.3. Scope of the Study

The proposed signalized intersection safety performance monitoring framework only requires V2I communications. In other words, only the data received at the RSE located at the signalized intersection of interest needs to be processed. For communication security and privacy issues, the temporary IDs of the OBEs may change at certain intervals which may complicate the procedures for processing safety measures of interest. To simplify the development, we assume that the temporary IDs of the OBEs remain the same throughout its communication with the RSE in this study. The proof of concept the test bed features a fully-actuated isolated high-speed signalized intersection, which is modeled after a real signalized intersection (FM 2818 and George Bush Dr, College Station, Texas). The researchers only consider the equipped vehicles on the through movements due to their relatively well-defined travel paths and conflict regions. Therefore, two primary types of crash risks accounted for in this study are rear-end and right-angle crashes.

1.4. Organization of the Report

The content of this report is organized into the following Sections:

- Section 1 presents a brief overview, research objectives and scope of this study.
- Section 2 summarizes the related literatures in connected vehicle technology, safety applications and surrogate safety measures.
- Section 3 proposes a safety performance monitoring framework at signalized intersections based on V2I communications. Safety indicators were defined to quantify the safety performance and the related algorithms were developed to extract these Indicators in real time.
- Section 4 describes the simulation evaluation approaches to demonstrate the effectiveness of the proposed monitoring framework. A proof-of-concept test bed was built along with specific simulation scenarios. The methodology for demonstrating the effectiveness of the proposed application was also provided.
- Section 5 discusses the evaluation from the simulation results. The validation of the monitoring framework was conducted followed by analysis on the effect of market penetration rate and the required observation period for the framework to be successful.
- Section 6 summarizes the findings of this research and discusses potential directions for future study.

2. LITERATURE REVIEW

Generally, safety applications of connected technology such as driver advisories, driver warnings have gone through concept development to field demonstrations via vehicle-to vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. However, none of the applications developed to date have utilized connected vehicle data for long-term safety performance monitoring. While numerous studies have examined surrogate safety measures for safety performance assessment at signalized intersections, majority of these have been limited to the application of existing technologies (e.g. post-processing of video recordings, detector/signal status analysis). These technologies are limited in their capability to provide long-term, continuous, accurate, reliable, and automated measurements in real time.

This section provides literature review related to recent research on connected vehicle framework, existing safety applications and surrogate safety studies at signalized intersections.

2.1. Connected Vehicle Technology

2.1.1. Background

The history of connected vehicle can be traced back to 2003 when the U.S. Department of Transportation (USDOT) first launched the Vehicle-Infrastructure-Integration (VII) program. The initial objective of VII is to address the traffic safety problems through high-speed wireless communications among vehicles to vehicles (V2V) and vehicles to infrastructures (V2I). Different applications such as driver advisories, driver warnings and even vehicle controls have been proposed (*1*).

Later in 2009, VII was rebranded as IntelliDrive^{SM} mainly to provide better public outreach. Moreover, extra attention was given to its applications on transportation mobility as well as environment. The real-time data captured in connected vehicle framework could create valuable information for transportation managers to optimize the performance of transportation. Travelers could also make their route choice more fuel-efficient and eco-friendly based on the provided real time traffic information.

Until recently, the brand name IntelliDrive^{SM} was abandoned again and changed to connected vehicle due to the reason that IntelliDrive^{SM} has already been trademarked before its wireless communications application in the Intelligent Transportation System (ITS). Despite the name being changed, its vision and focus remain the same (*2*).

2.1.2. Elements of Connected Vehicle

Connected vehicle framework relies on three critical elements that are onboard equipments (OBE), roadside equipment (RSE) and back office servers (*3*).

- Onboard equipment (OBE) consists of devices embedded in the vehicle that support dedicated short-range wireless communications (DSRC) with nearby vehicles as well as RSE. It also has computer and in-vehicle display modules. The kinematics information of a vehicle is usually recorded by OBE for safety and mobility applications.
- Roadside equipment (RSE) consists of roadside devices that support DSRC communications with nearby OBE-equipped vehicles within the communications distance, other RSEs as well as the control centers. RSEs are often located in point locations such as intersections.
- Back office server represents the center that connects RSEs and monitors the traffic network. Information could be pushed from the back office server to the appropriate RSE and then broadcasted to OBE-equipped vehicles.

2.1.3. Dedicated short-range wireless communications (DSRC)

Dedicated short-range wireless communications (DSRC) is a particular channel for connected vehicle applications. Liu et al. summarized the history background of wireless communications standard (*4*). Among the three types of DSRC service, 5.9GHz DSRC (5.85-5.925 GHz) was highly recommended for transportation applications due to its large outdoor range (1000 m), high transmission data rate (27 Mbps) as well as the low likelihood for interference.

2.1.4. SAE J2735 Standard

The format for data generation and transmission is defined by the Society of Automotive Engineers in the SAE J2735 standard (*5*). The SAE J2735 standard specifies message sets, data frames, and data elements for applications intended to utilize the 5.9 GHz DSRC for Wireless Access in Vehicular Environments (DSRC/WAVE) communications systems. A total of 15 message sets are defined in the SAE J2735 standard (November 2009) (*5*). Table 1 lists three primary standard message sets from the standard that will be considered for developing a safety performance monitoring application in this study.

Table 1: Summary of Message Sets from SAE J2735 Standard.

Message Sets	Descriptions
Basic Safety Message (BSM)	BSM is used to exchange real-time state of vehicles typically at 10 Hz. Part I BSM includes information such as ID, time, latitude, longitude, speed, heading, acceleration, yaw rate, length, and brake status. Part II BSM is optional. Under the Vehicle Safety Communications – Applications (VSC-A) project(*6*), Part II BSM is designed to include information such as vehicle events, path history, and path prediction
Map Data (MAP)	The MAP message is used to concisely define the geometries of a complex intersection, a highway curve or a segment of roadway. This message is sometimes informally referred to as the Geometric Intersection Description (GID) layer.
Signal Phase and Timing (SPaT)	The SPaT message is used to convey the current state of all available lane movements/paths at signalized intersections. The SPaT message sends the current movement state of each active phase in the system. The state of inactive movements (typically all red) is not normally transmitted, but can be if an application requires it.

2.1.5. Test Bed for Connected Vehicle

The evaluation of various connected vehicle applications relies on the connected vehicle test bed. The prototype test bed and simulation test bed are most commonly used. Despite the increasing numbers of on-going prototype test beds, they are limited by the high cost for operation and the scale of these test beds is not large enough for analysis at systematical level. The simulation approach, which mainly focuses on the traffic flow and wireless communications modules, seems to be more cost-effective and convenient. However, the reliability of simulation results is often doubted for the various drawbacks of simulation environment.

2.1.6. Prototype Test Bed

Initially two prototype test beds were developed in the US, one is in Michigan and the other is in California (*7; 8*). The test bed in Michigan includes 57 RSEs and 25 vehicles equipped with OBEs. The test bed covers 45 square mile area with a total of 75 center-line miles. The one in California is relatively small in scale which consists of 30 RSEs yet planned to be 40 (*8; 9*). A few other states which include Virginia, Florida, Arizona, and New York are also building their test beds for connected vehicle (*10*).

Generally, supported features provided by the connected vehicle test bed include: probe date services, signal phase and timing services (SPaT), V2I communications services, V2V communications services, tolling transaction service, OBE application hosting, RSE application hosting. More capabilities such as interoperability components and security issues are also planned in the development of these test beds (*11*).

2.1.7. Simulation Test Bed

Early simulation approaches include using either microscopic simulation software such as CORSIM and PARAMICS or vehicular wireless communications simulators such as NS-2 to mimic the connected vehicle systems. The former relies on post-processing traffic-simulation data due to the lack of wireless communications simulator. This "static" approach cannot fully replicate the dynamic wireless data transmission and its impact on traffic flow characteristics. When communications delays or failures occur, the position of targeted vehicle in the next time step might not be the same as what is predicted from the pre-computed trajectories. The latter suffers from very simple traffic stream model and car-flowing model, which do not perform well under complicated traffic conditions (*8; 12*).

Two more promising approaches are the hybrid simulation and integrated simulation. Hybrid simulation links the established microscopic traffic simulator with existed wireless communications simulator. This approach features the comprehensive capabilities of both simulators. A few researches have connected, for examples, VISSIM with NCTUns or PARAMICS with NS-2 to build connected vehicle simulation test bed (*8; 12*). However, additional interfaces have to be added to connect both simulators in simulation at each time step, since the traffic simulator is "time based" and the wireless communications simulator is "event based." Simulation speed and capacity for wireless communications may be limited.

Integrated simulation sounds more appealing which integrates both the traffic simulator and wireless communications simulator in one module (*13*). However, this approach is often criticized by the simplified functionalities of the traffic simulation model and wireless communications model, which cannot fully represent the complexity of both traffic behaviors and wireless communications process.

2.2. Connected Vehicle Safety Applications

The report from Wassim et al. showed the percentage of crashes that could be addressed by connected vehicle system (*14*). Through safety applications such as cooperative forward collision warning and emergency electronic brake lights, V2V communications could potentially deal with 4,409,000 police-reported crashes annually which account for 79% of total crashes. For V2I communications, 1,465,000 police-reported crashes could be addressed by countermeasures such as stop sign violation warning, left turn assistant, intersection collision warning. This counts for 26% of total crashes. A combination of V2I and V2Vwould address 81% of the total crashes.

2.2.1. Safety Application via Vehicle-to-Vehicle (V2V) Communications

V2Vcommunications is the most straightforward way for transmitting information such as speed, location among OBE-equipped vehicles. Different types of safety applications via V2V communications have gone through concept development to field demonstration (*6; 15*). Basically, decreasing safety condition event is transmitted among vehicles as in-vehicle warnings to drivers and therefore reminding drivers of the potential crash. These warnings include cooperative forward collision warning, lane change warning, do-not-pass warning as well as control loss warning.

2.2.2. Safety Application via Vehicle-to-Infrastructure (V2I) Communications

The primary purpose of V2I safety applications is to address the crashes that cannot be addressed using V2V (*14*). In addition, the large-scale deployment of RSE could promote the adoption of the technology and increase the market penetration rate of OBEs and thus also advancing the deployment of V2V. Besides, RSE is also a necessary element in the communication security of connected vehicle framework.

Safety applications using V2I require only RSEs at targeted facilities such as intersections and do not require full saturation of OBE to be functional. Several V2I safety applications at intersections have been developed and their effectiveness has been demonstrated both by simulation study and prototype field test. Featured applications include Cooperative Intersection Collision Avoidance Framework (CICAS) and its variants such as CICAS-V (traffic signal violation), CICAS-SLTA (Signalized Left-Turn Assist) and CICAS-TSA (Traffic Signal Adaptation) (*16-18*).

2.2.3. Issues Related to V2V and V2I Safety Applications

Communications Delay and Communications Success Rate

Communications delay and communications success rate are critical elements for building robust V2V and V2I communications system. Potential Factors which may affect communications delay and communications success rates were studied and compared though simulation experiments (*8*). These factors usually include number of RSEs, snapshot generation interval, market share, buffer size of OBEs, and communication range.

Liu et al. conducted safety assessment of information delay among V2V wireless communications (*13*). Simulation was done in three different scenarios which include emergency braking with point to point (P2P) communications, brick wall with P2P communications and brick wall with point to multipoint communications. All simulation scenarios consisted of 30 vehicles in a platoon corresponding to an emergency deceleration of the first leading vehicles. Analysis indicated the safety conditions became worse when communications delays were introduced for all three scenarios. Point to multipoint communications produced more stable traffic flow than P2P condition, which lead to a reduction on communications delay.

Communications Security

The final success of the connected vehicle applications cannot be achieved without fully considering the public issues such as security and privacy. The topic of security is particularly addressed in Kim et al.'s report (*19*). The report defined two types of risks: "attacks on the user" and "attacks on the communications system." The former one means the attacker creates false messages and distributes them to neighboring vehicles or the attacker suppresses the valid message from being received by the vehicle; the latter one includes the violation of privacy of the system users by tracking their routes and falsely reporting misbehavior from a vehicle. Messages are required to be digitally signed and accompanied by valid certificates, which could be issued through some periodic contact with RSEs. Accordingly, Public Key Infrastructure (PKI), which is commonly used to authenticate the sender in the wireless communications, is enhanced to have the capability of providing anonymity for private vehicles (*6*).

2.3. Surrogate Safety Measurements at Signalized Intersections

Crash-based evaluation approach is hampered by randomness, lack of timeliness and rarity of the occurrence of crash. Surrogate safety measurements are commonly used to address these shortcomings. The principle of surrogate safety measurement relies on correlation between crash occurrences and safety surrogates. Effective safety surrogates are the ones that not only strongly correlate with but also more frequent than crashes. Rear-end and right-angle crashes are typically the most concerned types of crashes at signalized intersections. Commonly used safety surrogates for these two types of crashes include variations of traffic conflicts and dilemma zone related measures.

2.3.1. Traffic Conflict Technique (TCT)

Definition of conflict is provided as "*an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged*" (*20*).The working definitions of traffic conflicts are often defined by applying specific thresholds to measurable traffic events such as time to collision.

Traffic conflict technique (TCT) traditionally relies on post-processing of video recordings, which involves human subjectivity in extracting conflict data and is criticized for prohibitive cost for data reduction efforts. Some analysts have therefore resorted to the use of surrogate safety from simulation to perform safety evaluation. The Surrogate Safety Assessment Model (SSAM) developed by Federal Highway Administration (FHWA), for instance, provides a framework for evaluating safety using surrogate measures obtainable from major traffic simulation packages such as VISSIM and PARAMICS (*21; 22*). The simulation-based safety evaluation may be applicable for some types of analyses such as comparative evaluation of design alternatives but it is not capable of capturing all the intricacy of drivers' behaviors and local operating conditions expected in the real world.

Extensive studies have been conducted to explore indicators that strongly correlate with frequency of crash occurrences and the severity of the resulting crashes. The safety indicators representing the probability of crashes measure the proximity of the current conflict event to a crash event. For example, SSAM provides definitions for the following indicators (*22*).

- Minimum time-to-collision (TTC): *"Expected time for two vehicles to collide if they remain at their present speed and on the same path during the conflict."*

- Minimum post-encroachment time (PET): *"Time between when the first vehicle last occupied a position and the time when the second vehicle subsequently arrived to the same position during the conflict."*
- Initial deceleration rate (DR): *"Initial deceleration rate of the second vehicle during the conflict."*

Lower TTC or lower PET value or higher DR value indicates higher risk of getting involved in crashes.

There is no clear consensus on the definitions of what constitutes the severity of traffic conflicts from a number of studies (*23*). Most commonly, the severity of conflict is defined as "*the probability of crashing, the magnitude of the damages from the potential collision, or both.*" As suggested by Shelby et al., severity of the conflict is better defined as the probability of crashing which measures the proximity of the conflict event to the crash event (*23*). Thus, lower values of TTC and PET represent more severity of the conflict. Speed- or deceleration-related indicators are commonly used as severity measures for the outcome of potential crashes. These indicators characterize the energy of the potential collision, which are:

- Maximum speed differential (DeltaS): *"Difference in vehicle speeds at the moment when Minimum TTC is observed (22)."*
- Change of speed (DeltaV): Average change of velocity between pre-collision and post-collision trajectories of conflicting vehicles assuming that the collision is inelastic (*23*).
- Maximum deceleration rate (MaxD): *"Maximum deceleration of the second vehicle, recorded as the minimum instantaneous acceleration rate observed during the conflict (22)."*
- Required braking rate (RBR): The minimum braking rate required for the approaching vehicle to arrive at the collision point (crossing conflicts) or the back of the leading vehicle (rear-end conflicts) (*24*).

It is conceivable that higher value of the listed indicators, higher energy the collision would have. This indicates more severe outcome of the resulting crash. However, the mechanism and sensitivity of these indicators are not necessarily the same. Sometimes, different severity indicators can represent completely opposite implications on the severity of a conflict event, as illustrated in the SSAM's validation examples (*22*). For instance, in on page 49 of the SSAM final report, MaxD (deceleration-related indicators) shows that left-turning movement with left-turn bay will have severe resulting crashes compared to that without left-turn bay. However, both DeltaS and DeltaV (speed-related indicators) confirmed the opposite direction. As a result, the authors have to admit that *"In general, the data in the Table 20 have some counter-indicative results. Some of the average surrogate measures of safety are better with the left-turn bay, and others are worse"*. Further work is still needed to validate the effectiveness of these severity measures and conditions which where they most suites.

2.3.2. Dilemma Zone

Dilemma zone is a special area of signalized intersection where the driver can neither stop comfortably nor clear safely at the onset of yellow indication. Initially, dilemma zone was defined based on deterministic values (*25*). The stopping distance (X_s) and clearing distances (X_c) of a vehicle are calculated using the following equations to determine the location of dilemma zone.

$$X_c = v_0\tau + \frac{1}{2}a_1^*(\tau-\delta)^2 - (w+L) \tag{1}$$

$$X_s = v_0\delta + \frac{{v_0}^2}{2a_2^*} \tag{2}$$

where

τ : Yellow duration (*sec*);

δ : Perception-reaction time (*sec*);

v_0 : Approaching speed at the start of yellow indication (*ft/sec*);

a_1^* : Maximum acceleration (*ft/s²*) (Recommended value: 0.5g~0.8g (*25*));

a_2^* : Maximum deceleration (*ft/s^2*) (Recommended value: 0.3g~0.5g (*25*); 14.8 (*26*));

W : Intersection width (*ft*);

L : Vehicle length (*ft*).

Accordingly, three possible scenarios could occur. If $X_s > X_c$, a dilemma zone exists with length X_s-X_c, which is termed Type I dilemma zone; else if $X_s = X_c$, there exists no dilemma zone; at last, if $X_s < X_c$, an option zone exists.

However, the boundary of dilemma zone is dynamic in nature and should be adjusted by factors such as roadway grade, driver gender, driver age, travel time to the intersection, time-of-day, as well as the weather condition. This definition also suffers from the assumption that the driver knows these distances perfectly well. In reality, even in the case where $X_s < X_c$ holds, drivers may still have difficulty in determining whether to proceed or not (*27*). To better capture the indecision of drivers at the end of green indication, Zegeer et al. defined the dilemma zone as an area where 10% to 90% of drivers would stop if presented a yellow indication and is termed as the Type II dilemma zone (*28*). Bonneson et al. defined this zone based on the time to reach the stop bar, which begins at 5.5 s and ends at 2.5 s from the stop bar for passenger cars and 7.0 s to 2.5 s for trucks (*29*).

The indecision of drivers in the dilemma zone is likely to result in harder braking or running-on-red events which increases the likelihood of rear-end and right-angle crashes. Therefore, some dilemma-zone related measures such as the rate of vehicles trapped in dilemma zone and rate of vehicles running-on-red are often used as safety indicators particularly at isolated high speed intersections where the resulting crashes are more severe (*30*). In fact, some safety enhancement systems have been developed for intelligently providing green extension or clearance extension to the vehicle trapped in dilemma zone (*29; 31; 32*).

To quantify the dilemma zone risk, several researchers have investigated various indicators beyond the rates of vehicle trapped in dilemma zone, since this metric equalizes the crash risk as long as the vehicle is trapped in the dilemma zone. However, the risk of crashes can vary depending on vehicle locations. For example, a vehicle trapped in the middle of the dilemma zone will likely be the most indecisive whether or not to proceed and thus is more likely to get involved in a crash than the vehicle trapped at the either end of dilemma zone. Sharma et al. proposed a hazard function for quantifying the risk at different locations in the dilemma zone (*33*). More recently, Li et al. introduced a term called dilemma hazard which is an overall evaluation statistics for the crash risk based on the probability of vehicles in dilemma zone ending in rear-end and right-angle crashes (*34*).

2.4. Multiple Advance Detector System

The multiple advance detector system is most wildly used for dilemma zone protection. It usually consists of two or three advance detectors with or without stop line detector. The location of the advance detector is determined by speed distribution, with the leading edge of each at the start of the dilemma zone. The basic objective for such a system is to prevent vehicles in a designed speed range (e.g., 15th - 85th percentile speed) from being trapped in dilemma zone via providing green extension at the end of green. The passage time is selected such that vehicles in the detection zone with fast speed can be carried over through green extension while the controller will gap out the green phase for low-speed vehicles. The layout for such system based on 60 mph design speed is shown in Figure 1. Some of the suggested layout and settings for detection design are shown in Table 2 and more details can be found in the Traffic Signal Operation Handbook (*35*).

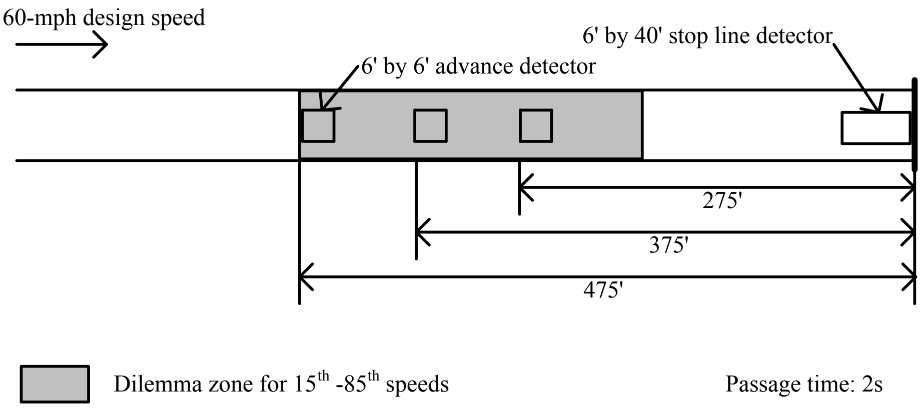


Figure 1: Multiple Advance Detector System.

The operation for the stop line detector (if exists) is in deactivated fashion which means it is active only for initial queue discharge and disconnected after its first gap-out. This operation will guarantee the most efficiency by avoiding unnecessary green extension. In case of no stop bar detector, minimum recall must be set in the controller and the minimum green should be set appropriately for initial queue service.

Table 2: Layout and Settings for Multiple Advance Detector System.

85% Approach Speed (*mph*)	**Distance to 1st Detector (*ft*)**	**Distance to 2nd Detector (*ft*)**	**Distance to 3rd Detector (*ft*)**	**Passage Time (*sec*)**
70	600	475	350	1.4-2.0
65	540	430	320	1.6-2.0
60	475	357	275	1.6-2.0
55	415	320	225	1.4-2.0
50	350	220	-	2.0
45	330	210	-	2.0

Although commonly used in real-world practice, mainly two limitations are associated with the multiple advance detector system. Firstly, it can only provide dilemma zone protection for a portion of the vehicles. Protection will be given to 70% of the vehicles if the system is designed for the 15th to 85th speed range. Green extension may not be provided to vehicles trapped in dilemma zone travelling faster than the 85th percentile speed, since they are yet to reach the most upstream detector while the phase may gap out before the vehicles with speed lower than 15th percentile speed reaching the nearest detectors downstream. Secondly, in mediate or high traffic volume condition, the max-out (phase is extended till maximum green) will be more frequent where no more green extension could be provided. The frequent occurrence of max-out indicates not only more delay for vehicles in minor streets but increasing risk of crashes for vehicles in major through movement as well. In fact, most recent dilemma zone protection systems are designed to intelligently terminate the through phase at certain "proper" moment before max-out (*29; 32*). These green termination systems have been demonstrated to improve the both efficiency and safety for signalized intersection operation.

3. SAFTY PERFORMANCE MONITORING USING V2I DATA

This methodological framework was designed to extract and compute safety indicators from vehicle, intersection description, and signal data available at the RSE. It is envisioned that this application will reside in a separate field-hardened computer that interfaces with the RSE and require only V2I communications. For conceptual development, it is assumed that the vehicular movement data, intersection description, and signal status data can be derived from BSM, MAP, and SPaT messages respectively. It is beyond the scope of this study to develop procedures for extracting these data elements from actual message sets.

This section first proposed the safety indicators that are related to rear-end and right-angle crashes for quantifying the safety performance at signalized intersections. Then, we describe algorithms for processing the safety indicators from V2I communication data. The proposed algorithm currently focuses on through vehicle movements due to their relatively well-defined travel paths and conflict regions.

3.1. Proposed Safety Indicators

Safety indicators are critical ingredients for measuring the safety performance of signalized intersection operation. This section first describes how the safety indicators were categorized for connected vehicle safety application. Then, we explained the process of selecting various safety indicators in each category. At last, safety indicators that have causal relationships with crashes and can be derived from V2I communications data elements were proposed for this study.

3.1.1. Categorization of Safety Indicators

Safety indicators could be roughly categorized into two types based on the number of OBE equipped vehicles that need to be monitored which are single-OBE measures and dual-OBE measures. Single-OBE measures indicate the computation of safety indicators only requires one OBE while dual-OBE measures are those that require two OBEs. For example, to determine whether a vehicle is in dilemma zone (Type II), only information of that single equipped vehicle (current speed and distance to the stop bar) is needed. Thus, number of vehicle trapped in dilemma zone is a single-OBE measure. However, for rear-end conflict, location and speed of both leading and following vehicles (vehicle pair) is needed in order to compute the time-to-collision (TTC) which serves as the threshold of traffic conflict. Therefore, frequency of rear-end conflict is a dual-OBE measure.

3.1.2. Single-OBE Measures

Single-OBE measures are expected to be relatively more effective in detecting safety-critical events at lower OBE saturation rates. Type II dilemma zone defines the area of drivers' indecision of whether to go or to stop at the end of green. The zone can be defined based on projected travel time to reach the stop bar. This definition is used to define the vehicles being trapped in the dilemma zone as the speed and location of vehicles available from BSMs can be used to compute projected travel time to stop bar. Rate of vehicles trapped in dilemma zone correlates with both rear-end and right-angle crash risk and is often used to define the risk related to signal operation at high-speed signalized intersections *(30).* Since Type II dilemma zone exists at every onset of yellow indication, the rate of vehicles trapped in the dilemma zone is computed by normalizing the number of vehicles being trapped with the approach traffic volume and number of cycles.

The researchers also examined the feasibility of extracting maximum deceleration (MaxD)-based event as another indicator for single-OBE measure. Specifically, when the deceleration rate grows larger than a given threshold, a MaxD-based event is assumed to begin and the single vehicle is continuously monitored with deceleration rate updated to the maximum one. This process continues until the moment deceleration rate drops below the threshold. Literatures have confirmed the usage of the emergent deceleration event in quantifying the safety performance at the signalized intersection (*24; 36*). More frequent MaxD-based events indicate more interruption of the traffic flow and thus higher risk for rear-end crashes; higher MaxD value signifies more severe the resulting crash could be. However, MaxD-based events are not always a valid precursor of all rear-end crashes. For instance, a trailing vehicle may swerve to the adjacent lane rather than decelerate to avoid the potential crash and thus does not trigger a MaxD-based event. Our preliminary investigation of MaxD events in a simulation also showed mixed results as a potential indicator for unsafe scenarios. Therefore, it is excluded from our consideration as a candidate safety indicator in this study.

3.1.3. Dual-OBE Measures

For dual-OBE measures, higher market penetration of OBEs is required for effectively calculating TTCs as the data from OBE pairs transmitted to the RSE may not be from the most critical ones for the purpose of trajectory projection. As a consequence, the riskiest situation based on critical TTCs may not be recorded if either vehicle of the pair is not equipped with an OBE. TTC is the projected time for two vehicles to collide if their current speeds and paths remain unchanged. Whenever the TTC value drops below a specified threshold (e.g., 1.5 s), a traffic conflict event is considered initiated. The tracking of the event continues until the TTC is higher than the specified threshold. The lowest value of TTCs designates a critical TTC which signifies the collision risk of the conflict event.

For crossing conflict, post-encroachment time (PET) is also collected as suggested by Allen et al (*36*). PET is the elapsed time from the moment an encroaching vehicle leaves and an approaching vehicle arrives at the conflicting area, which also measures the proximity of a crash. PETs can be collected for each conflict zone. One crossing event generates only one PET. Smaller PET values indicate higher probability of crash. Zero or negative PETs indicate real crash occurrences. In contrast, projected measures like TTCs cannot be computed and therefore undefined for real crash scenarios. Due to its relative ease of filed data collection and well-defined continuum between crashes and conflicts, PETs are increasingly adopted in real-world traffic conflict studies.

The frequency of the conflict data alone may not provide a complete picture of the safety performance of signalized intersection operations. The facility with higher conflict frequencies may associate with less severity of conflict events. In this framework, we used TTC to measure the severity of the conflict events (both rear-end and crossing conflicts) and PETs are also computed for crossing conflicts. Smaller TTCs and PETs indicate more proximity of a conflict event to a crash and therefore measure the risk of getting involved in a crash.

To complete the framework for safety evaluation, initially we considered speed related and deceleration related Indicators for measuring the magnitude of the resulting crashes. We used maximum speed differential (DeltaS) as the speed related severity indicator. Two deceleration related indicators considered in this study were maximum deceleration rate (MaxD) and required braking rate (RBR). Their definitions are given as follows:

- Maximum speed differential (DeltaS): *"Difference in vehicle speeds at the moment when Minimum TTC is observed (22)."*
- Maximum deceleration rate (MaxD): *"Maximum deceleration of the second vehicle, recorded as the minimum instantaneous acceleration rate observed during the conflict (22)."*
- Required Braking Rate (RBR): The minimum braking rate required for the approaching vehicle to arrive at the collision point (crossing conflicts) or the back of the leading vehicle (rear-end conflicts) (*24*).

Different from that defined in single-OBE measure, MaxD for dual-OBE measures is TTC-dependent. It has to be collected during the conflict event where the TTC value is smaller than the threshold (e.g. 1.5s). Overall, larger values of those three severity indicators generally signify higher collision energy if a crash occurs.

However, our preliminary examination shows that deceleration related indicators are not good candidates for measuring the severity of the resulting crash because simulated vehicles do not always decelerate during the conflict event. As aforementioned, the trailing vehicle can sometimes swerve to the other lane to avoid the collision. Besides, technical limitations of simulation model can prevent proper interactions between conflicting vehicles. For instance, if two conflicting vehicles are modeled on separate links in a VISSIM simulation, they will not interact with each other unless a proper conflict area is defined between the two links. These technical limitations produce undesirable behavior of simulated vehicles which prevent us from further consideration of deceleration related severity indicators in this simulation study.

3.1.4. Summary of the Proposed Safety Indicators

Based on the discussion in the last two subsections, we proposed the following safety indicators. These measures are considered for evaluating safety at signalized intersections because they have causal relationships with crashes and they can be derived from data elements that are readily available from connected vehicle data.

The single-OBE measure:

- Frequency of vehicles trapped in dilemma zone

The dual-OBE measures:

- Frequency of rear-end conflicts based on time-to-collision (TTC)
- Frequency of crossing conflicts based on time-to-collision (TTC)

In addition to the frequency, both types of measures can be normalized by appropriate exposure available from the connected vehicle data such as time duration, number of cycles and traffic volume. Also, we defined the following severity indicators along with the dual-OBE measures to provide a comprehensive safety evaluation of signalized intersection operations.

- Minimum TTC
- Post-Encroachment Time (PET) (only for crossing conflicts)
- Maximum Speed Differential (DeltaS)

TTC and PET measure the severity of the conflict event, which is the proximity of a conflict event to the crash; while DeltaS measures the severity of the potential crashes.

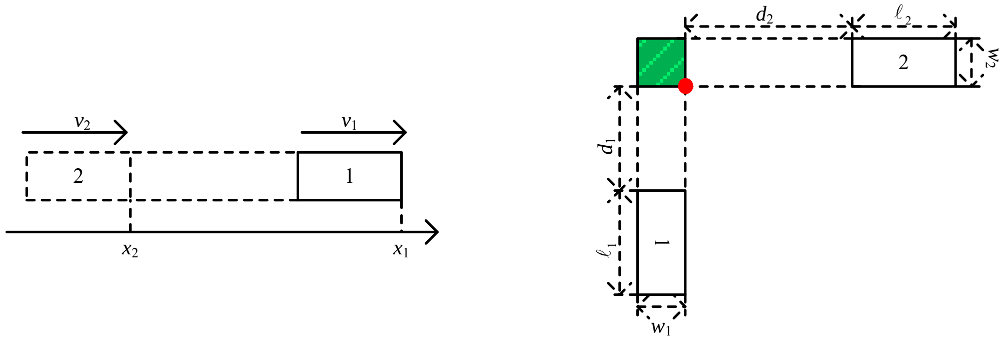
3.2. Computation for TTC and PET

Computation of the safety indicators is based on their definitions. This section explains the methods for computing TTC and PET which are critical for describing conflict measures.

Even though definition of TTC is the same for both rear-end and crossing conflict, the way of calculation varies. This is attributed to the different trajectories for rear-end conflict and crossing conflict, which are parallel and perpendicular, respectively (Figure 2). Notice that the trajectories are assumed in the ideal condition to simplify calculation. In reality, trajectories of a rear-end vehicle pair will probably not perfectly parallel and the crossing angle of two conflicting vehicles is not necessarily to be right-angle. Particularly, we will treat it as a rear-end conflict as long as two consecutive vehicles remain at the same movement at the moment minimum TTC is monitored.

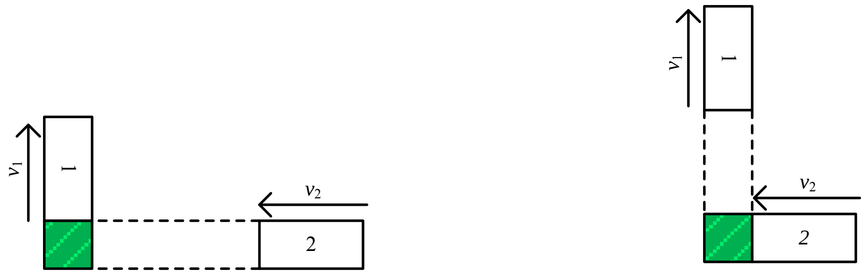
Unlike rear-end conflict, crossing conflict can only occur at certain fixed area. We define conflict zone as the fixed area generated by two crossing movements as is highlighted by the shaded area in Figure 2(b). A four-leg signalized intersection typically has four conflict zones. Conflict point is then defined as the point location in a conflict zone where two conflicting vehicles will first meet, as is circled in the same picture. It is envisioned that locations of conflict zone and conflict point are availbe in the MAP data. Equation (3) and (4) are used for computing TTC for rear-end and crossing conflicts. Information such as vehicle's speed, length, width and coordinate is available from the BSM (*5*).

PET is exclusively computed for crossing conflict due to the well-defined conflict zone and conflict point. It is the elapsed time from the moment an encroaching vehicle leaves and an approaching vehicle arrives at the conflicting area. The trajectory profiles of two vehicles are shown in Figure 3. Calculation of PET is straightforward and given in Equation (5).



(a) Rear-End Conflict **(b) Crossing Conflict**

Figure 2: Trajectories of (a) Rear-End Conflict and (b) Crossing Conflict for Computation of TTC



(a) Time (t_1) of the First Vehicle Leaving Encroaching area **(b) Time (t_2) of the Second Vehicle Arriving at Encroaching Area**

Figure 3: Trajectories of Crossing Conflict for Computation of PET.

$$\text{Rear-End TTC} = \frac{x_1 - x_2 - \ell_1}{v_2 - v_1}, if \ v_2 > v_1 \tag{3}$$

$$\text{Crossing TTC} = \begin{cases} \dfrac{d_2}{v_2}, if \ \dfrac{d_1}{v_1} < \dfrac{d_2}{v_2} < \dfrac{d_1 + \ell_1 + w_2}{v_1} \\ \dfrac{d_1}{v_1}, if \ \dfrac{d_2}{v_2} < \dfrac{d_1}{v_1} < \dfrac{d_2 + \ell_2 + w_1}{v_2} \end{cases} \tag{4}$$

$$PET = t_2 - t_1 \tag{5}$$

where

x_1 = Location of the vehicle 1 in the current lane, *ft*

x_2 = Location of the vehicle 2 in the current lane, *ft*

v_1 = Speed of vehicle 1, *ft/s*

v_2 = Speed of vehicle 2, *ft/s*

d_1 = Distance to the conflict point from the front of vehicle 1, *ft*

d_2 = Distance to the conflict point from the front of vehicle 2, *ft*

ℓ_1 = Length of vehicle 1, *ft*

ℓ_2 = Length of vehicle 2, *ft*

w_1 = Width of vehicle 1, *ft*

w_2 = Width of vehicle 2, *ft*

t_1 = The moment when the encroaching vehicle leaves the conflicting area

t_2 = The moment when the approaching vehicle arrives at the conflict area

3.3. Algorithm for Extracting Safety Indicators from V2I Data Elements

This section describes the algorithm developed for extracting the proposed safety indicators from V2I communications data sets in real time. The algorithm is presented in a hierarchy structure. We will give an overview of the algorithm's general logic followed by detailed introduction of different parts of the algorithm and their functions.

3.3.1. Algorithm Logic

The objective of the algorithm is to extract and update (if necessary) the proposed safety indicators at each time step. Figure 4 presents a general logic of the algorithms which consists of two parts: categorization and data mining. Based on the raw data (BSM and MAP) received by the RSE via V2I communications at each time step, we first categorized these raw data into customized databases. Then, the task of extracting safety indicators became mining the corresponding databases.

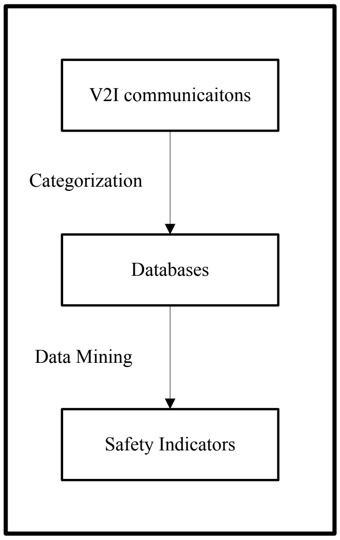


Figure 4: Algorithm Logic.

3.3.2. Categorization

Three databases are populated every time after the data are received at the RSE, which are:

- Movement Database – Record the received BSM of single vehicle according to the movement ID and lane ID.
- Rear-End Database – Record the received BSMs of two consecutive vehicles according to the movement ID and lane ID.
- Crossing Database – Record the received BSMs of two vehicles heading to the same conflict point according to the conflict zone where the point locates.

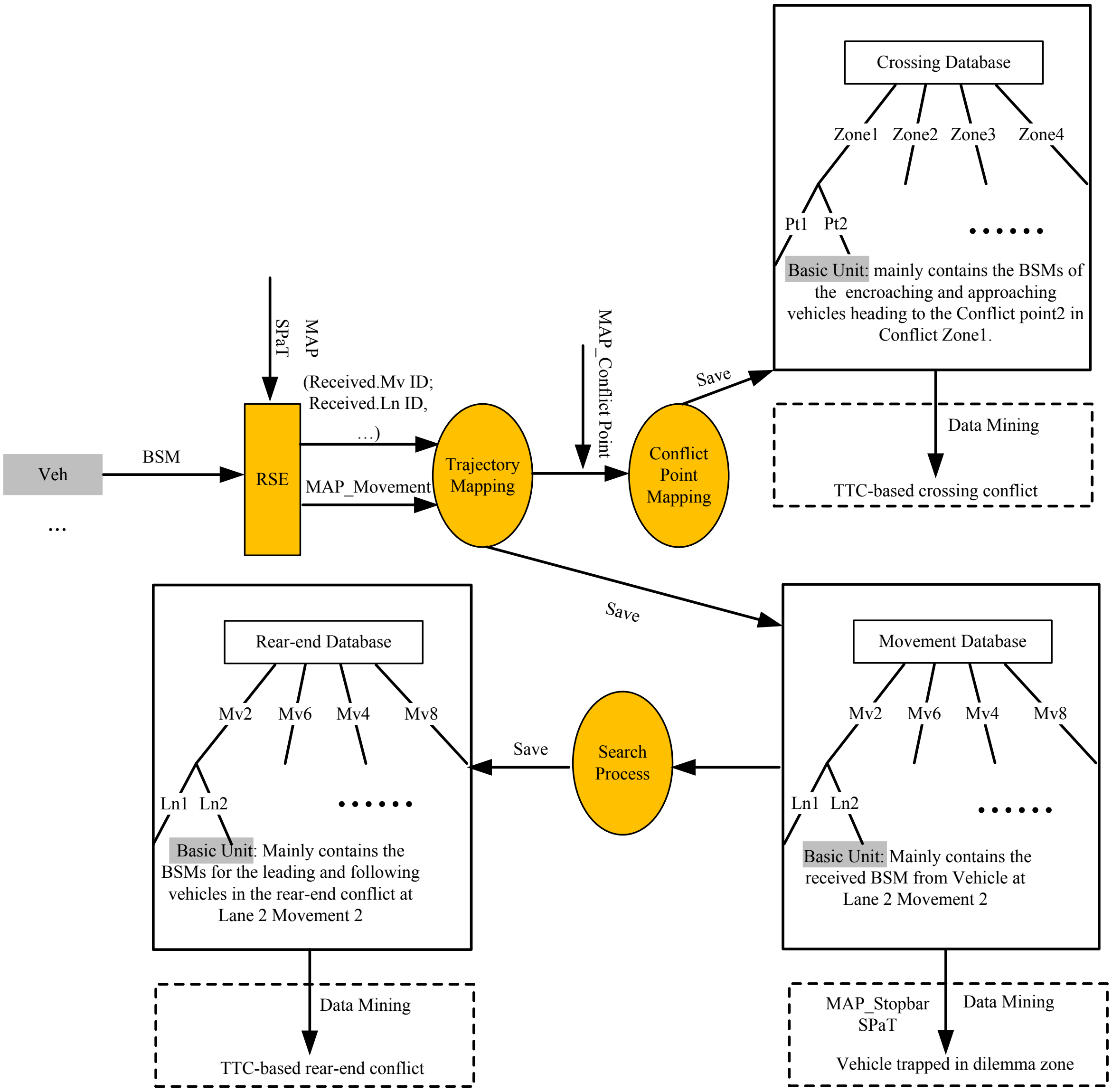


Figure 5: Overview of Algorithm for Extracting Safety Indicators.

In this simulation study, the identification and data counting of the equipped vehicles rely on the temporary ID of OBE. For policy issues, however, the temporary ID may change at certain interval in real-world applications of connected vehicle. To simply the process of extracting and evaluating safety indicators, we assume that the temporary ID of the OBE will not change during its communication with the RSE.

Overview of the algorithm of building these databases are shown in part of Figure 5. After RSE receives BSMs from OBE-equipped vehicles, a Trajectory Mapping Module is developed to match the movement and lane index in the BSM with those in the MAP data, which is critical for the RSE to recognize the instant location of the equipped vehicles. The vehicle's BSM is then stored as a basic unit to Movement Database. By integrating the signal status for each movement from SPaT, the kinematic information of any equipped vehicle under the current signal status can be continuously monitored. This provides all the necessary information for monitoring vehicle the vehicle is trapped in dilemma zone.

Computation of dual-OBE safety indicators requires information of a vehicle pair. The identification of TTC-based rear-end conflict requires a search process to find two consecutive vehicles (OBEs) in the same lane of each movement. The identified vehicle pair is then stored in the Rear-End Database as the basic unit. Crossing conflict identification requires capturing two vehicles heading towards a pre-defined conflict point on their paths. A Conflict Point Mapping Module is programmed to search two conflicting vehicles heading to the same conflict point, which is then stored as the basic unit in the Crossing Database.

3.3.3. Data Mining

This part of the algorithm is developed to efficiently extract and update (if necessary) the safety indicators from the corresponding databases that have been built, as is indicated in Figure 5. To determine whether a vehicle is trapped in dilemma zone, we first need to identify the projected travel time of the vehicle to reach the stop bar at the onset of yellow. This is computed as the ratio of vehicle's distance to the stop bar to the vehicle's current speed. The vehicle's distance to the stop bar is obtained as the distance of the vehicle's location (from the basic unit in Movement Database) to that of the stop bar (from MAP); the vehicle's speed is also a data element of the basic unit. Detailed algorithm flowchart for extraction is shown in Figure 6. An event of a vehicle trapped in a dilemma zone is recorded when this projected travel time falls within the boundaries of the Type II dilemma zone for specific recorded vehicle types. This research used the values recommended in Bonneson et al.'s study, which are 2.5 s to 5.5 s for cars and 2.5 s to 7 s for trucks (*29*).

Dual-OBE measures (conflict-related measures) could be easily extracted from the Rear-End Database and Crossing Database. The determination of conflict depends on the value of TTC. For rear-end conflict, TTCs are computed based on Equation (3). Vehicles' location, length and speed could be obtained from the basic unit of the Rear-End Database. Detailed algorithm for extracting safety indicators at rear-end conflict is depicted in Figure 7. When a TTC value first drops below the threshold, a conflict event is considered initiated and this moment serves as a time when the conflict event begins. The TTC value continues to be updated if lower ones are calculated. The conflict event is terminated when the TTC becomes larger than the threshold value. Based on the speed differential of the following and leading vehicle, DeltaS is computed at the time when minimum TTC is observed.

It should be noted that the case that the trailing vehicle swerves to the other lane to avoid the potential rear-end crash is also counted as the rear-end conflict as long as the TTC value below the threshold is observed when both of the vehicles are still on the same lane. Moreover, the same vehicle pair can produce multiple rear-end conflict events if the corresponding TTCs oscillates around the threshold values. The moments at which the conflict event starts and ends are also recorded along with subject vehicle IDs to generate unique conflict IDs.

For crossing conflict, TTCs are computed based on Equation (4). Similarly to Rear-end conflict, all the information needed for calculating crossing TTC from the two conflicting vehicles could be obtained directly from the basic unit of Crossing Database. Figure 8 describes the detailed algorithm for extracting surrogate safety indicators at crossing conflict. Whenever the TTC drops below the threshold, a conflict event is determined. The TTC value continues to be updated if lower ones are calculated. The conflict event is terminated when the encroaching vehicle leaves the conflict area or the approaching vehicle has already arrived at the conflict area. Based on the absolute speed differential of the encroaching and approaching vehicle, DeltaS is computed at the time when minimum TTC is observed.

PET is exclusively collected for the crossing conflict as complementary to TTC. PET is the difference of between the time the encroaching vehicle leaves and the approaching vehicle arrives at the conflict area. However, either the encroaching vehicle leaving or the approaching vehicle arriving at the conflict area would terminate the conflict event, since no TTC could be computed in this condition. A separate module is added to monitor the recorded crossing vehicle pairs and compute the PET in Figure 8.

It should be mentioned that unlike three databases which are reconstructed at each time step, all the extracted safety measures are updated during the collection period if necessary and stored for a specified observation.

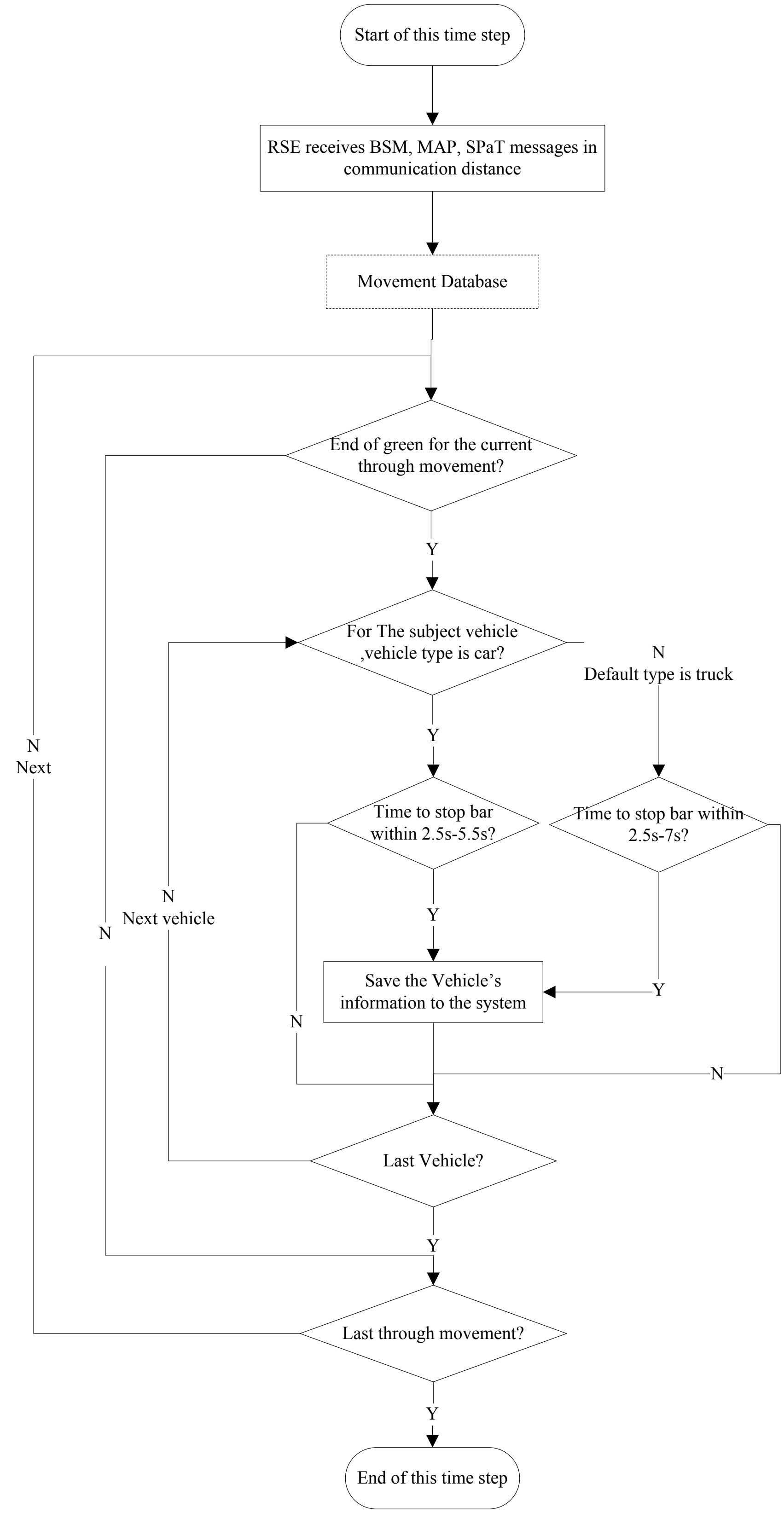


Figure 6: Algorithm for Extracting Vehicles Trapped in Dilemma Zone.

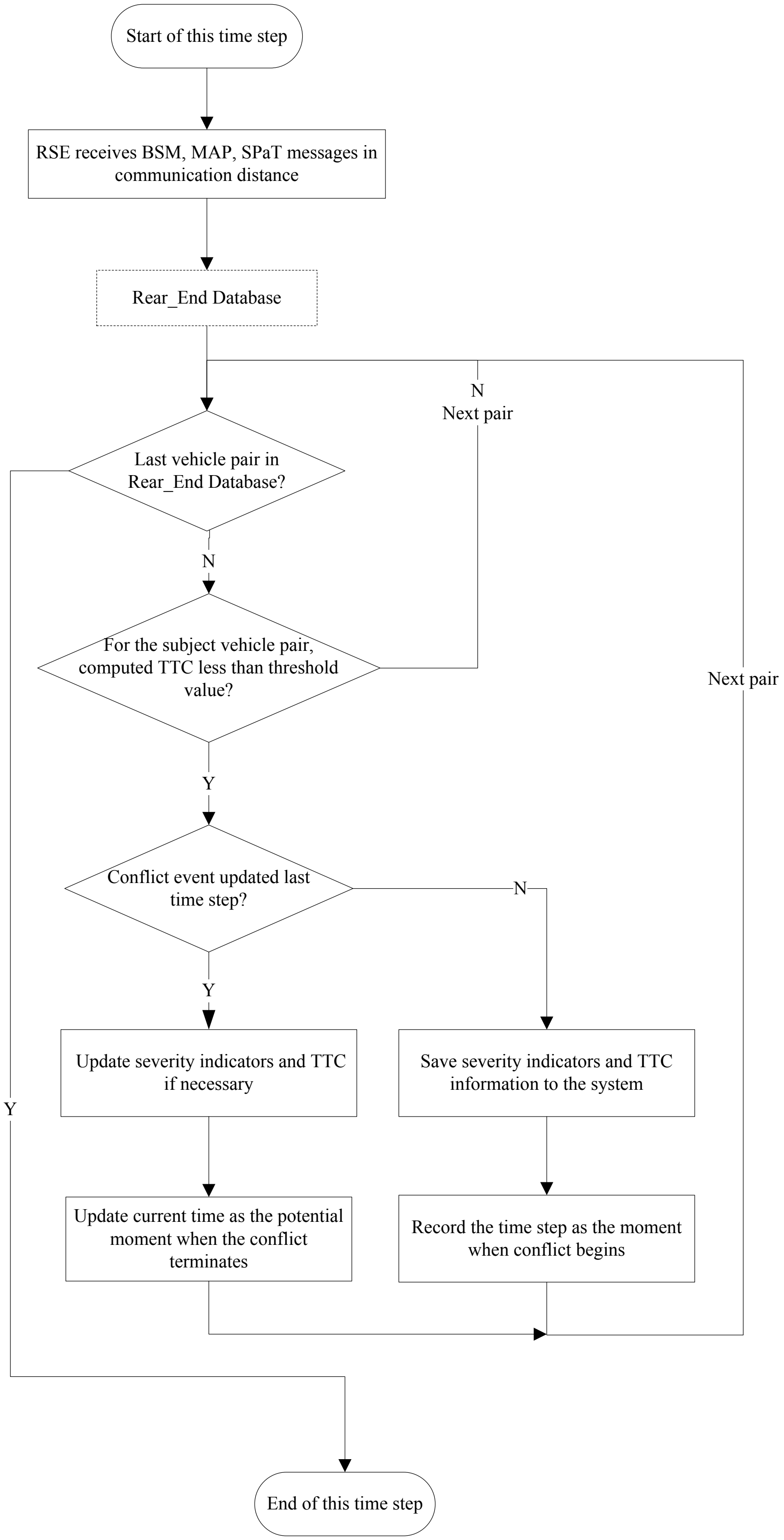


Figure 7: Algorithm for Extracting Rear-End Conflict.

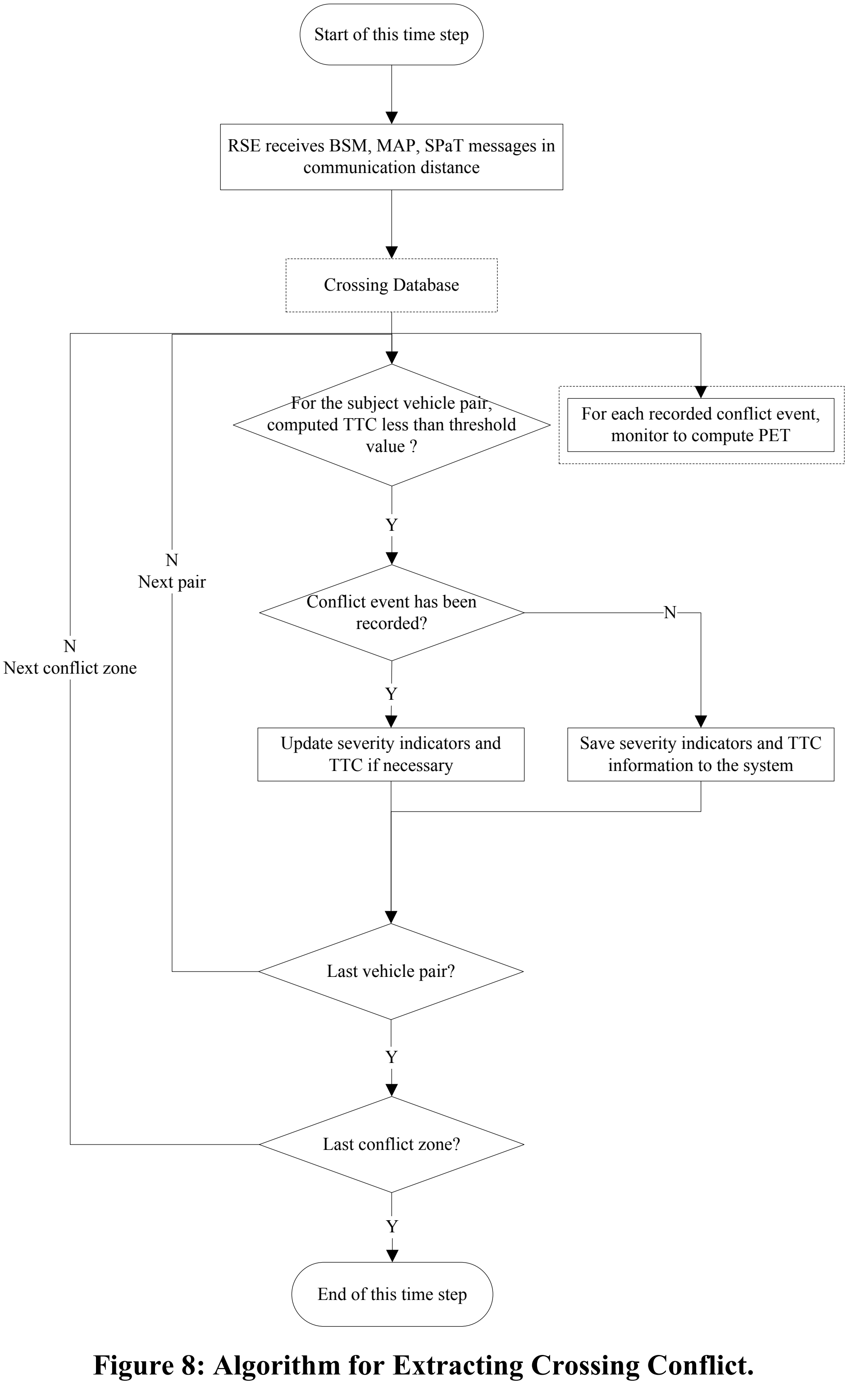


Figure 8: Algorithm for Extracting Crossing Conflict.

4. SIMULATION EVALUATION APPROACH

A simulation evaluation approach is used to evaluate the effectiveness of the proposed signalized intersection safety performance monitoring framework. Its ability in the detecting the safety changes with varying operational settings is comprehensively studied. This study utilizes VISSIM microscopic simulation because of our extensive experience with the software. First, we developed a signalized intersection test bed in VISSIM designed with optimal signal timings and proper dilemma zone protection. Then, we modified the test bed by shortening the inter-green interval and removing the dilemma zone protection to evaluate if the proposed safety measures can detect the degradation in safety performance. All the scenarios were examined during both the low/medium-to-high traffic conditions.

In real-world application, market penetration rate as well as observation period is likely to affect the performance of the proposed framework. Therefore, the researchers developed methodologies to analyze (a) the effect of market penetration rate on the effectiveness of the framework and (b) the observation time required to effectively implement the framework.

4.1. Proof of Concept Simulation Test Bed

4.1.1. V2I Communications Simulation

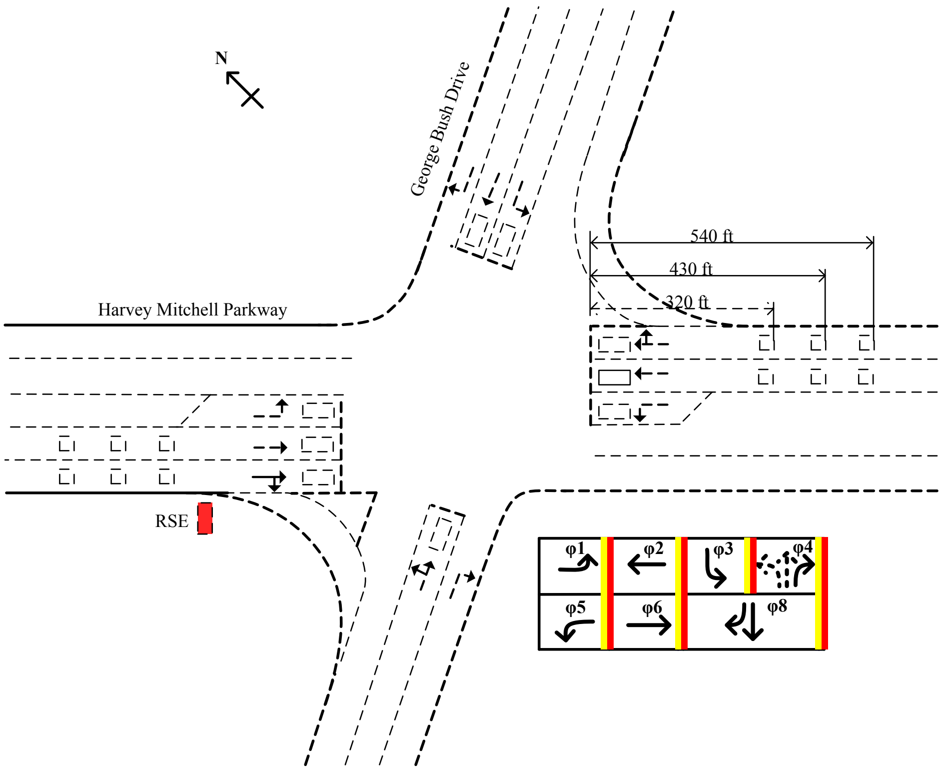
The vehicle-to-infrastructure wireless communications were developed using VISSIM C2X Application Programming Interface (API) module. The VISSIM C2X application module is designed as part of hybrid simulation architecture to simulate inter-vehicle communications, which connects traffic flow module VISSIM and packet transmission module VCOM (*37*).

The codes required for C2X were written in Python. Simulation time step was set as 0.1 simulation seconds, which is equivalent to the frequency of 10 Hz for BSM transmission. The C2X module already integrates the wireless communication model; thus enabling the effect of communication delay and the wireless transmission. The C2X module was found to deliver faster simulation speed and perform better with large-scale wireless communications than the wireless communications simulator NS-2 (*38*).

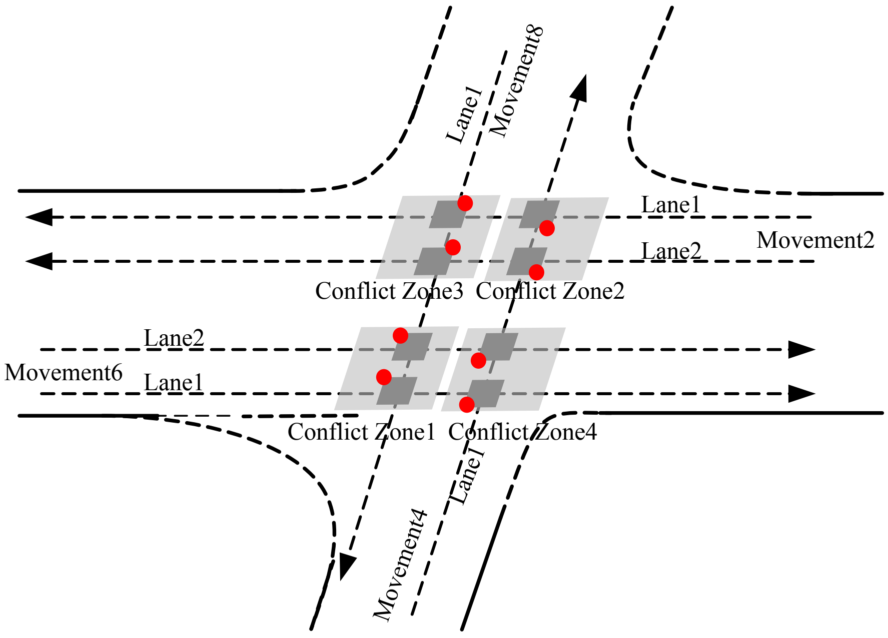
4.1.2. Development of Test Bed

The intersection layout and phase sequence is shown in Figure 9 (a). The studied intersection is located at George Bush Drive and Harvey Mitchell Parkway in College Station, Texas. Figure 9 (b) shows the reference conflict points (larger dots) for locating the potential crossing conflicts. There are four conflict zones and each of them is generated by the intersection of two conflicting movements. Accordingly, each zone characterizes two conflict points, which represent the location where two conflicting vehicles are expected to collide.

This test bed is modeled as a fully-actuated signal control with stop bar and advance detectors for dilemma zone protection. Design speed for passenger cars was set at 60 mph and 45 mph on the major approaches (Harvey Mitchell Parkway) and the minor approaches (George Bush Drive) respectively. Design speed for trucks was set at 5 mph less than that of passenger cars. Appropriate rules were chosen in VISSIM for merging areas and diverging areas, which features proper driving behavior (e.g. speed reduction, gap acceptance). The speed of turning movements was decreased according to the Traffic Signal Operations Handbook (*35*). We used the “Urban” driving behavior set with the Wiedemann 74 car following model. Default values were used for all the other driving behavior parameters including maximum deceleration and desired deceleration rates.



(a) Intersection Layout and Signal Phasing.



(b) Conflict Observation Regions.

Figure 9: Signalized Intersection Test Bed.

In order to simulate the V2I communications, we made some critical operational assumptions and settings which are listed as follows:

- Safety measures are extracted within the central intersection area and segments 650 *ft* from the stop bar for each approach to better reflect the effect of signalized intersection operations, though default range of effective V2I communications in C2X is over 2000 *ft*.
- At the beginning of each simulation time step, RSE is assumed to process all the required data elements from SPaT and MAP messages. Only the interactions between OBEs and RSE are simulated.
- It is assumed that the lane and movement ID, location of the stop bar and the location of conflict point are derived from MAP message set.
- Temporary IDs of the OBEs remain the same while they are transmitting data to the RSE.

4.2. Simulation Scenarios

Four simulation scenarios were set up in VISSIM. The baseline operation features well-designed timings and proper dilemma zone protection. Two comparison scenarios were developed by modifying the baseline scenario to produce two suboptimal operations. To ensure sufficient sample size, each scenario was simulated for 20.5 hours with the first half an hour allocated for simulation stabilization period. By allocating three random seeds for each scenario, the simulation run produced a total of 60 effective simulation hours for each scenario.

4.2.1. Baseline Scenario

Traffic volume input for both low volume and medium-to-high volume conditions is given in Table 3. The saturation ratio of through movements for the former is around 0.3-0.4 while that for the latter is around 0.8-0.9. Table 4 shows the signal timings, and detector settings for the baseline scenario. Advance detectors were used to provide dilemma zone protection on major approaches. Specific signal timing and detector settings are based on the guidelines provided in the Traffic Signal Operations Handbook (*35*).

Table 3: Traffic Volume Input for Baseline Scenario.

Phase Number	1	2		3	4			5	6		8	
Lane Type	LT	TH	RT	LT	LT	TH	RT	LT	TH	RT	TH	RT
Light Traffic Condition												
Volume (*veh/h*)[1]	60	480	60	30	6	285	9	60	480	60	240	30
Medium-to-High Traffic Condition												
Volume (*veh/h*)[1]	135	1080	135	80	9	428	13	135	1080	135	640	80

Notes:

1. Vehicle composition is 90% cars and 10% trucks.

Table 4: Signal and Detection Parameters for Baseline Scenario.

Phase Number	1	2	3	4	5	6	8
Minimum Green (*s*)	5	5	5	5	5	5	5
Maximum Green (*s*)	20	50	15	40	20	50	60
Yellow Time (*s*)[1]	4.3	5	3.6	4.7	4.3	5	4.7
All Red (*s*)[2]	1.6	1.4	1.5	1.6	1.5	1.5	1.6
Advance Detector	No	Yes	No	Yes	No	Yes	Yes
Stop Bar Detector[3]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Passage Time (*s*)	2	2	2	2	2	2	2

Notes:

1. Yellow time is calculated based on the equation: $t + 1.47v/[2(a + 32.2g)]$, where t represents reaction time (1 *s*); v represents approach speed, mph; a represents deceleration rate (10 *ft/s*^{2}); g represents approach grade, *ft/ft*. The computed time in excess of 5 s is added to red clearance interval.
2. All red time is calculated based on the equation: $(W + L)/(1.47v)$, where W represents the width of the intersection; L represents the length of design vehicle (20 *ft*).
3. Stop line detectors are operated as queue service stop line detection, which are only activated for queue clearance and will be disconnected with the signal controller after the first gap-out. The carry over time is 2 *s*.

4.2.2. Simulation Scenario 1: Shortened Inter-Green Interval

This scenario shortens all-red and yellow intervals from the baseline scenario to 3 s and 1 s, respectively. Vehicles may not stop comfortably or clear the intersection safely due to the shortened inter-green interval. This scenario is expected to generate more frequent sudden decelerations and higher risk of right-angle crashes (*31; 39*).

4.2.3. Simulation Scenario 2: No Advance detectors and Shortened Inter-Green Interval

This scenario further modifies Scenario 1 by disabling the dilemma zone protection on major approaches. This scenario is expected to cause more vehicles to get trapped in the dilemma zone and thus creating higher risk of both crossing and rear-end crashes (*28*-*30*). The scenario creates a more hazardous situation than Scenario 1 by combining the effects of both unprotected dilemma zone and shortened inter-green intervals.

4.3. Analysis of Simulation Results

The researchers conducted three different types of analyses in this study to evaluate the effectiveness of the proposed monitoring framework, analyze the effect of market penetration rate and investigate the observation period for real-world application of the framework, respectively. The evaluation was conducted separately for low traffic volume condition and the medium-to-high volume condition.

4.3.1. Validation of the Safety Performance Monitoring Framework

The objective of this analysis is to determine if the collected data from connected vehicle can be used to detect changes in safety performance based on the proposed safety indicators. The ground truth analysis was based on 100% OBEs and all 60 hours of simulation results. By using the ground truth condition, the researchers analyzed the computed safety indicators and conducted statistical tests to determine if the changes in these indicators between the baseline and the first two scenarios can be detected and if they are statistically significant. The detection is considered valid and successful if the changes in safety indicators conform to our expectation (i.e., the modified operation should be less safe and the collected safety indicators should reflect those changes with statistical significance).

It should be noted that the evaluation of safety performance in this study is based on the risk of crashes. Indicators measuring potential crash severity are not fully investigated since they are beyond the scope of this study. It is possible that one scenario may have higher risk for crashes but lower severity of potential resulting crashes while another scenario may experience higher severity of potential crashes but lower risk for crashes. In this case, it can be difficult to rank the safety performance using only risk or severity indicators. Nevertheless, severity indicators are presented in this study to demonstrate the potential of the proposed application in providing a comprehensive safety evaluation.

4.3.2. Effect of Market Penetration Rate

The objective of this analysis is to evaluate the effect of market penetration rate on the performance of the proposed monitoring framework, since full market penetration may not be available at the initial deployment of the connected vehicle technology. Specifically, this evaluation examines the relationship between the rates of the safety measures and penetration rate. Market penetration rate was decreased from 100% to 20% with 20% decreasing interval. The results at 100% market penetration rate were used as the ground truth for reference. The researchers compared the rates of safety measures between different scenarios at each penetration level. An inconsistency of comparison result from the 100% penetration level indicates the safety measure becomes invalid at this penetration level. In other words, higher penetration rate is required for the effectiveness of this measure.

4.3.3. Effect of Observation Period

The purpose of this analysis is to examine the effect of observation periods on effective implementation of the framework. Particularly, we investigated the required observation period for specific safety indicators to be effective and the feasibility of extending observation period at lower penetration level to obtain sufficient data. Firstly, we investigated the relationship between the variation of rate of the safety measures and observation period for each scenario. The equivalent observation time was computed for lower penetration level to achieve the same variability as the 100% penetration condition. The feasibility of extending observation period at low penetration rate to collect sufficient data is demonstrated if the equivalent observation period increases at decreasing penetration rate. Then for each observation period, we computed the average variation over all penetration levels and compare between different the safety measures to see whether they were at the same level of variation. Measures with larger variation require longer observation period to be effective.

5. SIMULATION RESULTS AND DISCUSSIONS

This section documents the results from the simulation study based on the evaluation approach described in the previous section. In the first section, we discussed the effectiveness of the V2I safety performance monitoring framework in detecting the changes of safety performance of the signalized intersection. Then, we analyzed the effect of market penetration rate on the performance of safety degradation detection. Lastly, we examined the relationship between observation period, market penetration, and the variability of the detected safety indicators.

5.1. Detecting Changes in Safety Performance

The objective of this analysis is to determine if the collected data from connected vehicle can be used to detect changes in safety performance. Safety performance is measured by the risk of crashes. The analysis was based on 100% OBEs and 60 simulation hours, which is assumed to be the ground truth. By using the ground truth condition, the researchers analyzed the computed safety indicators and conducted statistical tests to determine if the changes in these indicators across the three simulation scenarios can be detected and if they are statistically significant. The detection is considered valid and successful if the changes in safety indicators conform to our expectation. Indicators addressing potential crash severities are also proposed and analyzed. However, they are not included in the safety performance analysis.

5.1.1. Selection of Threshold Value for Traffic Conflicts

The threshold for TTC-based conflicts was initially chosen as 1.5 s, which was recommended in several studies (*22; 40; 41*). However, our preliminary tests indicated that the 1.5 s threshold is likely to capture large percentage of usual traffic events rather than real conflicts. Rear-end conflicts, for instance, occurred at least one in every six vehicles on average. This is likely attributed to vehicles' frequent stop and go maneuvers at the simulated high-speed signalized intersection. In order to reduce the conflicts to only severe ones, 85% percentile of the collected TTC value (1.24s) across all three scenarios was used as a cut-off point for retaining the TTCs for subsequent analysis.

5.1.2. Comparing Rates of Safety Measures

Table 5 and Table 6 summarize the frequencies of observed safety measures, number of vehicles and number of cycles during simulation period for low traffic level and medium-to-high traffic level, respectively. Scenario 2 has the most number of cycles followed by Scenario 1. The baseline condition has the lowest number of cycles. The shortened inter-green interval in Scenario 1 reduced the cycle length and thus increased the number of cycles given the same simulation period. For Scenario 2, the total number of cycles was further increased by the reduced green extension resulting from the removal of advance detectors. Total traffic flows for all the scenarios are very close since the total volume in the simulation was set the same at each volume level.

Note that higher traffic volume does not necessarily guarantee more safety measures being detected. In fact, fewer vehicles were observed trapped in dilemma zone in Scenario 2 under the medium-to-high volume level. The increasing exposure brought by higher volume is offset by the fewer cycles. As for crossing conflict, the increasing left-turning volume can activate the left-turning phase more frequently which will block two conflicting through phases. Thus, fewer crossing conflicts are likely to be detected at higher volume level. A detailed validation of detected crossing conflicts for the two volume groups will be provided later in Subsection 5.1.4.

Table 5: Summary of Simulation Results for Low Traffic Volume.

Measures	Baseline	Scenario 1	Scenario 2
TTC-Based Rear-End Conflicts	2487	1850	2074
Number of Vehicles Trapped in Dilemma Zone	2674	3196	10406
TTC-Based Crossing Conflicts	9	62	82
Total Number of Vehicles	96659	96671	96718
Number of Cycles	4020	4980	6407
Simulation Duration (*hours*)	60	60	60

Table 6: Summary of Simulation Results for Medium-to-High Traffic Volume.

Measures	Baseline	Scenario 1	Scenario 2
TTC-Based Rear-End Conflicts	6135	6115	6364
Number of Vehicles Trapped in Dilemma Zone	5278	5534	8367
TTC-Based Crossing Conflicts	4	9	23
Total Number of Vehicles	203070	204042	203847
Number of Cycles	1790	1933	2390
Simulation Duration (*hours*)	60	60	60

The frequencies of safety indicators were normalized by appropriate exposure to ensure valid comparison between scenarios. Total objective volume was used as the exposure for rear-end conflicts. Both the number of cycle and objective volume were used to normalized the frequencies of vehicles trapped in the dilemma zone and crossing conflicts (*39*). We treat the OBE volume as the observed volume for all the analysis as it could be directly obtained through V2I communications. The number of OBE can be determined based on its temporary ID, which is transmitted as part of the BSM. We assume that the OBE's temporary ID will not change within its communications with RSE and thus the collected OBE volume is equal to the volume of equipped vehicles.

We conducted a statistical test to determine if the differences in detected safety indicators are statistically significant using the procedure suggested in Griffin and Flower (*42*). This statistical test compares the conflict rates before and after the treatment. It assumes that before and after conflict rates follow Poisson distribution and the normal distribution is used to approximate the Poisson distribution. It is appropriate even when the sample size is relative small. The equation for the test is written as:

$$Z = \frac{\left(\frac{A+0.5}{E_A} - \frac{B-0.5}{E_B}\right)}{\sqrt{\frac{A+B}{(E_A+E_B)E_A} + \frac{A+B}{(E_A+E_B)E_B}}} \qquad (6)$$

where A represents the total count in the “after” period; B represents the total count in the “before” period; E_A represents exposure in the “after” period; E_B represents exposure in the “before” period. The difference is considered statistically significant at 95% confidence level if *z* value is not within [-1.96, 1.96].

Comparing Rates of Safety Measures between Baseline and Scenario1

The results of the statistical test of the differences for low traffic volume are given in Table 7.

Table 7: Comparison of Safety Measures at Low Traffic Volume Level (100% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements[3]	**Baseline**	**Scenario 1**	**Z[3]**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate[1]	25.730	19.137	-9.662	<0.01	-25.6%	Yes
Rate of vehicles trapped in dilemma zone[2]	4.129	3.983	-1.359	0.174	-3.5%	No
Crossing conflict rate[2]	0.014	0.077	5.541	<0.01	456.0%	Yes
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z[3]**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate[1]	19.137	21.444	3.577	<0.01	12.1%	Yes
Rate of vehicles trapped in dilemma zone[2]	3.983	10.076	47.562	<0.01	153.0%	Yes
Crossing conflict rate[2]	0.077	0.079	0.245	0.806	2.8%	No

Notes:

1. Computed as: $\sum Count \,/\, (\sum veh / 1000)$ in count per 1000 vehicles. The denominator represents exposure.
2. Computed as: $\sum Count \,/ \left(\frac{\sum veh \times \sum Cycle}{10000 \times \sum Simulation\ Hour} \right)$, in count per 10,000 veh-cycle. The denominator represents exposure.
3. Units of the measurements for the remaining of the report are the same as defined above.

The rate of vehicles trapped in the dilemma zone slightly decreases by 4%. This result is expected because no change was made to the dilemma zone protection. This change is not statistically significant at 95% confidence level.

The changes in the two conflict types observed were found to be significant at 95% confidence level. Rear-end conflict rates decreased while the crossing conflicts increased. The increase in crossing conflict rates is likely attributed to the shortened inter-green interval which decreases the separation time between conflicting flows. It is also worth noting that crossing conflicts are typically rare and it can require long duration of observation to gather sufficient sample size. Connected vehicle platform is shown to be a potentially viable solution to monitor safety performance in this case. On the other hand, the shortened inter-green interval did not have negative impacts on rear-end conflicts because the intersection still has active dilemma zone protection and thus preventing the increase of traffic conflicts.

Further examination of the detailed outputs reveals that over 80 percent of the TTC-based rear-end conflict occurred within 60 *ft* upstream of the stop bar with the speed of the leading vehicle close to zero. This implies that the duration of stop caused by all-red interval may positively correlate with rear-end conflict rates for the light traffic condition. More abrupt deceleration is expected for vehicles encountering to the back of the stopped leading vehicle in this duration, which may result in rear-end conflict. The shortened all-red intervals in Scenario 1 reduced the all-red exposure which could be a contributing factor to the decrease in rear-end conflict rates.

Table 8: Comparison of Safety Measures at Medium-to-High Traffic Volume Level (100% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements	**Baseline**	**Scenario 1**	**Z^3**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	30.211	29.969	-0.44	0.66	-1%	No
Rate of vehicles trapped in dilemma zone	8.712	8.419	-1.77	0.08	-3%	No
Crossing conflict rate	0.007	0.014	1.52	0.13	107%	No
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z^3**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	29.969	31.219	2.29	0.02	4%	Yes
Rate of vehicles trapped in dilemma zone	8.419	10.304	11.69	<0.01	22%	Yes
Crossing conflict rate	0.014	0.028	2.07	0.04	107%	Yes

The results of the statistical test for medium-to-high traffic volume are given in Table 8. No significant difference was found for all selected safety measures. Observation from the simulation showed that, unlike in the low traffic condition, vehicles experienced long queue in the red duration. Rear-end conflicts at each approach is more evenly distributed from the stop bar to the tail of the queue, which can be as far as 650 *ft*. The effect of the difference in clearance time on the stop duration can be ignored when compared to the dwelling time after the vehicles join the long queue accumulated during the red time. Abrupt deceleration, acceleration and even lane change can occur during the expanding and receding of the queue. The same traffic volume and operational settings probably gave the similar queuing status during the red time for the two scenarios and thus the rates of rear-end conflicts are very close. Although crossing conflict rate in Scenario1 increased by 107%, this change is not significant. The comparison is likely to be inflated by the variation brought by the small sample size of collected crossing conflicts.

Comparing Rates of Safety Measures between Scenario 1 and Scenario 2

With the removal of advance detectors, the rates of vehicles trapped in dilemma zone in Scenario 2 increased for both two volume levels. The differences between the two scenarios were statistically significant at 95% confidence level. This result is anticipated since the green extension to dilemma-zone vehicles at the end of green is no longer available. 12% and 3% increase of rear-end and crossing conflict rates were respectively observed in Scenario 2 for the low volume level while the increase in these two measures for the medium-to-high volume level was 4% and 107%, respectively. This is likely attributed to the increasing number of vehicles trapped in dilemma zone. Results of the statistical test showed that the difference in rear-end conflict is significant for both volume levels while that of crossing conflict is only significant at the medium-to-high volume level.

5.1.3. Comparing Mean Value of Safety Indicators

Specific values of safety indicators for conflict measures are available for further evaluating safety performance at the signalized intersection. Average TTC measures the severity of the conflict event which quantifies the crash risks. Apart from TTC, PET was also computed for crossing conflicts. The severity of the potential resulting crashes was measured by average DeltaS. Table 9 and Table 10 summarize the statistics of those indicators under low volume level and medium-to-high volume level, respectively.

According to Table 9, for instance, Scenario 2 has the smallest average value of TTC for rear-end conflicts which indicates the highest crash risk. Scenario 1 was found to have the largest value of DeltaS, which implies the most severe outcomes of potential rear-end crashes. For crossing conflicts, Scenario1 has the smallest TTC and PET values while Scenario 2 has the largest DeltaS.

Table 9: Summary of Indicators for Conflict Measures for Low Volume Level (100% OBEs).

Safety Indicators for Rear-End Conflict						
	Baseline (2487)		**Scenario 1 (1850)**		**Scenario 2 (2074)**	
Indicators	Mean	S.D.	Mean	S.D.	Mean	S.D.
TTC (*s*)	1.015	0.304	1.009	0.306	0.949	0.338
DeltaS (*ft/s*)	20.395	5.978	20.877	6.375	20.275	6.493
Safety Indicators for Crossing Conflict						
	Baseline (9)		**Scenario 1 (62)**		**Scenario 2 (82)**	
Indicators	Mean	S.D.	Mean	S.D.	Mean	S.D.
TTC (*s*)	0.626	0.310	0.393	0.336	0.450	0.293
PET (*s*)	0.511	0.326	0.210	0.405	0.282	0.360
DeltaS (*ft/s*)	49.873	7.902	48.344	8.101	49.541	9.375

Notes: numbers in the parenthesis represent the sample size.

Table 10: Summary of Indicators for Conflict Measures for Medium-to-High Volume Level (100% OBEs).

Safety Indicators for Rear-End Conflict						
	Baseline (6135)		**Scenario 1 (6115)**		**Scenario 2 (6364)**	
Indicators	Mean	S.D.	Mean	S.D.	Mean	S.D.
TTC (*s*)	1.003	0.331	0.987	0.342	0.974	0.352
DeltaS (*ft/s*)	19.096	6.189	19.095	6.497	18.710	6.278
Safety Indicators for Crossing Conflict						
	Baseline (1)		**Scenario 1 (9)**		**Scenario 2 (23)**	
Indicators	Mean	S.D.	Mean	S.D.	Mean	S.D.
TTC (*s*)	0.091	0.183	0.337	0.361	0.216	0.263
PET (*s*)	-0.275	0.250	-0.033	0.589	0.014	0.318
DeltaS (*ft/s*)	32.328	3.993	38.695	8.568	39.061	7.006

Notes: numbers in the parenthesis represent the sample size.

We applied pooled t-test to examine the difference between the conflict-related severity indicators, since the standard deviations of each safety indicator for three test scenarios are similar. The equation for the statistical test is given below and test results are listed in Table 11 and Table 12 for two volume levels. Confidence interval (CI) for t distribution relies on the degree of freedom (DF). The t distribution converges to standard normal distribution at high DF.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{X_1X_2} \times \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{7}$$

where

$S_{X_1X_2} = \sqrt{\frac{(n_1 - 1)S_{X_1}^2 + (n_2 - 1)S_{X_2}^2}{n_1 + n_2 - 2}}$;

$\bar{X}_1$ = Mean of X_1;

$\bar{X}_2$ = Mean of X_2;

n_1 = Sample size of X_1;

n_2 = Sample size of X_2;

S_{X_1} = Standard deviation of X_1;

S_{X_2} = Standard deviation of X_2.

$\textit{Degree of Freedom} = n_1 + n_2 - 2$

Comparing Mean Value of Safety Indicators between Baseline and Scenario 1

First for the low volume level, no significant difference was found at the 95% confidence level for the average TTC of the rear-end conflicts, indicating no statistical evidence of the difference in the crash risks. Given that baseline scenario experiences significantly higher rear-end conflict rates, more rear-end crashes could be expected in this case. This result is reasonable considering that the shorter inter-green interval in Scenario 1 significantly reduced the stoppage duration, which is a contributing factor for rear-end crashes. The investigation of DeltaS, however, showed that Scenario1 had significantly higher value which means more severe the resulting crashes. In other words, the baseline is likely to have more rear-end crashes though the severity for the potential crashes is less.

Table 11: Statistical Comparisons of Safety Indicators for Conflict Measures for Low Volume Level (100%OBEs).

Comparison 1: Baseline and Scenario 1						
Indicators	**Baseline**	**Scenario1**	**%Change**	**t-statistics**	**P-value**	**Significant**
Rear-End Conflict						
TTC (*s*)	1.015	1.009	-0.5%	-0.59	0.56	No
DeltaS (*ft/s*)	20.395	20.877	2.4%	2.55	0.01	Yes
Crossing Conflict						
TTC (*s*)	0.626	0.393	-37.2%	-1.96	0.05	Yes
PET (*s*)	0.511	0.210	-59.0%	-2.13	0.04	Yes
DeltaS (*ft/s*)	49.873	48.344	-3.1%	-0.53	0.60	No
Comparison 2: Scenario 1 and Scenario 2						
Indicators	**Scenario1**	**Scenario2**	**% Change**	**t-statistics**	**P-value**	**Significant**
Rear-End Conflict						
TTC (*s*)	1.009	0.949	-5.9%	-5.80	<0.01	Yes
DeltaS (*ft/s*)	20.877	20.275	-2.9%	-2.92	<0.01	Yes
Crossing Conflict						
TTC (*s*)	0.393	0.450	14.4%	1.08	0.28	No
PET (*s*)	0.210	0.282	34.4%	1.13	0.26	No
DeltaS (*ft/s*)	48.344	49.541	2.5%	0.80	0.42	No

For crossing conflicts at low volume level, difference in TTC and PET values between Baseline and Scenario1 can be identified at the 95% confidence interval, while no significant difference was found in DeltaS. Scenario 1 may have more right-angle crash risks due to significantly higher crossing conflicts. The increase of the potential right-angle crashes is expected due to the shorter separation time between the conflicting movements as the inter-green intervals are shortened. Based on DeltaS, there is no difference in the severity of the potential crashes.

Table 12: Statistical Comparisons of Safety Indicators for Conflict Measures for Medium-to-High Volume Level (100%OBEs).

Comparison 1: Baseline and Scenario 1						
Indicators	**Baseline**	**Scenario1**	**%Change**	**t-statistics**	**P-value**	**Significant**
Rear-End Conflict						
TTC (*s*)	1.003	0.987	-1.7%	-2.749	<0.01	Yes
DeltaS (*ft/s*)	19.096	19.095	0.0%	-0.004	0.997	No
Crossing Conflict						
TTC (*s*)	0.091	0.337	268.9%	1.268	0.231	No
PET (*s*)	-0.275	-0.033	-87.9%	0.774	0.455	No
DeltaS (*ft/s*)	32.328	38.695	19.7%	1.394	0.191	No
Comparison 2: Scenario 1 and Scenario 2						
Indicators	**Scenario1**	**Scenario2**	**% Change**	**t-statistics**	**P-value**	**Significant**
Rear-End Conflict						
TTC (*s*)	0.987	0.974	-1.3%	-2.102	0.036	Yes
DeltaS (*ft/s*)	19.095	18.710	-2.0%	-3.338	<0.01	Yes
Crossing Conflict						
TTC (*s*)	0.337	0.216	-35.9%	-1.032	0.311	No
PET (*s*)	-0.033	0.014	-142.9%	0.289	0.775	No
DeltaS (*ft/s*)	38.695	39.061	0.9%	0.123	0.903	No

For the medium-to-high volume level, however, significantly lower rear-end TTC value was found for Scenario 1 at the 95% confidence interval. Although no difference was identified for the rear-end conflict rate between Baseline and Scenario 1, Scenario 1 is likely to have more rear-end crashes. The comparison of DeltaS from these two scenarios showed no significant difference, which indicated that the potential crashes would be generally at the same severity level.

The comparisons for crossing conflicts at medium-to-high level showed that the difference in all listed safety indicators was not significant. Considering the increase of crossing conflict rate in Scenario 1 was also insignificant, both scenarios may have similar safety performance in terms of the frequency and severity of right-angle crashes.

In summary, the results indicated more right-angle conflicts with less rear-end conflicts in Scenario 1 at the low volume condition. This may suggest a shift of crash patterns from rear-end to right-angle crashes at the low volume condition when the yellow and all red intervals were reduced. However, this shift of crash pattern was not obvious at the medium-to-high volume level, where the duration of stop (one contribution factor of the rear-end conflict) was mainly determined by the queuing status during the red period rather than the slight difference in the all-red time.

Comparing Mean Value of Safety Indicators between Scenario1 and Scenario2

The investigation at both low volume and medium-to-high volume group gave similar results in terms of the comparisons on the mean value of the selected safety indicators. Smaller rear-end TTC value was observed in Scenario 2. In addition, Scenario 2 also experienced significantly higher rear-end conflict rates. This increasing risk for rear-end crashes may be attributed to the removal of the advance detectors and thus causing more vehicles to get trapped in the dilemma zone. Despite higher risk for rear-end crashes, the severity for resulting crashes may be mitigated by significantly smaller DeltaS value observed in Scenario 2.

For crossing conflict, difference in neither average TTC and PET nor DeltaS was found significant for both volume groups. Scenario 2 was demonstrated to show significantly higher crossing conflicts rate, which in this case indicates more right-angle crashes.

In summary, the elimination of dilemma zone is more likely to have more potential rear-end and right-angle crashes based on the safety performance monitoring framework, which is consistent with previous findings (*25; 28; 30; 34*).

5.1.4. Analysis of the Distribution of Crossing Conflicts

Previous analyses have demonstrated the effectiveness of the proposed monitoring framework in detecting the degrading safety performance of the signalized intersection at an aggregate level. This section investigates the spatial distribution of the crossing conflicts and particularly addresses the phenomenon of fewer crossing conflict counts observed at the medium-to-high volume level.

The necessary component for a crossing conflict is a vehicle pair from two conflicting movements. This type of conflict often involves with one vehicle running on red (due to some inappropriate geometric/operational settings) while another conflicting vehicle already gets a green indication. Detailed configuration, signal timing sequence for the simulation test bed as well as possible reason for crossing conflicts at each conflict zone are summarized in Figure 10.

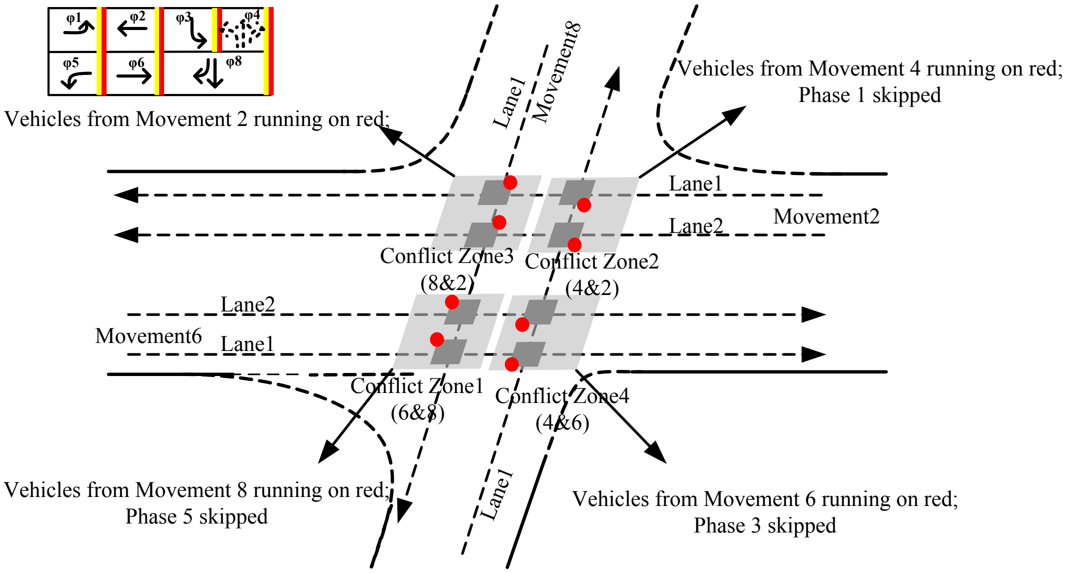


Figure 10: Operational Situations for Crossing Conflicts.

Operational situations in the simulation that are likely to generate crossing conflicts are also denoted in the figure. In fact, only one operational situation is most likely for the occurrence of crossing conflict at each conflict zone. For instance, crossing conflicts at Conflict Zone 1 (intersection of Movements 6 and 8) should result from a vehicle at Movement 8 running on red while the other vehicle coming from Movement 6 after seeing the green indication (Phase

5 is skipped). The case that a vehicle from Movement 6 is running on red while green indication is given to the vehicle from Movement 8 is not feasible. Considering that the vehicle from Movement 6 is closer to Conflict Zone 1 and has higher speed, it is almost to clear the intersection before the vehicle from Movement 8 arrives at the conflict zone. The recorded TTC value is much larger than the specified threshold.

Distribution of crossing conflicts for two tested volume levels is given in Figure 11. Scenario 2 was chosen for analysis since it has the largest sample size of crossing conflict. For the low volume group, the majority of the conflicts are located in Conflict Zone 1 and 2. The low volume condition created opportunities for frequent skipping of the left-turning phases (Phase 1 and Phase 5). Therefore, subsequent green indication is given to the adjacent through movements, which is necessary for the occurrence of crossing conflicts in Conflict Zone 1 and 2. Besides, the likelihood of vehicles running on red increases without the presence of dilemma zone protection. The number of vehicles from Movement 6 and 2 running on red was reduced since full dilemma zone protection was provided to the major approaches. This explains the fewer conflict counts in Conflict Zone 3 and 4.

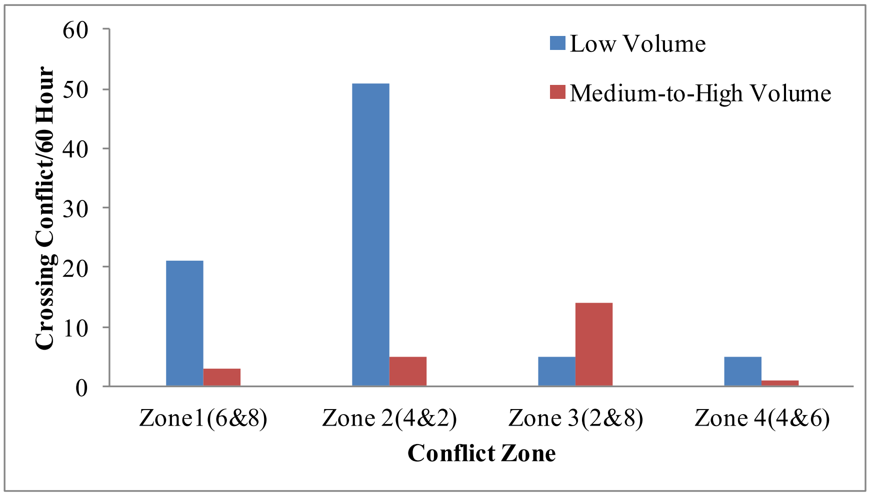


Figure 11: Distribution of Crossing Conflicts in Scenario 2 for Low Volume Level and Medium-to-High Volume Level.

After we increased traffic volume for each approach, left-turning phases were activated more frequently. Exposure brought by the increasing volume is largely offset by the diminished skipping of left-turning phases (Phase 1, Phase 5 and Phase 3). Accordingly, Conflict Zone 1, 2 and 4 saw a dramatic reduction of crossing conflicts. However, one exception occurred in Conflict Zone 3 where the occurrence of crossing conflict doesn't involve with left-turning phase but reflects the change of traffic volume from related movements. Over 100% increase of through input from Movement 2 and 8 probably led to the increase of crossing conflicts. At aggregate level, the total crossing conflicts saw a significant drop in the medium-to-high volume group due to the reduced skipping of left-turning phases.

Generally, the spatial distribution of collected crossing conflicts corresponds well with changes in traffic volume as well as the resulting actuated signal phases. The connected vehicle technology provides a highly capable platform for real-time safety performance monitoring and in-depth analysis at signalized intersections.

5.1.5. Spatial Distribution of Crossing Conflicts with Minimum Recall

Additional evaluation is required with settings eliminating the skipping of left-turning phases. Previous finding can be further validated if no crossing conflict is detected in Conflict Zone 1, 2, 4 for both volume levels and Conflict Zone 3 is demonstrated to have fewer crossing conflicted at low volume level.

Minimum recall is a parameter which results in a phase being called and timed for at least its minimum green time whether or not a vehicle is present. For demonstration purpose, it is initiated for all left-turning phases in scenario 2. Considering the intensive simulation time, a total 20 simulation hours were done for both low and medium-to-high volume levels.

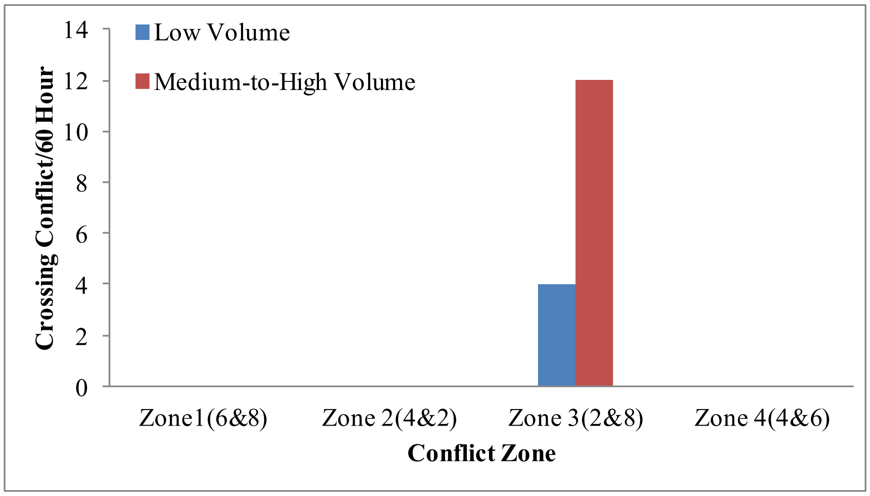


Figure 12: Distribution of Crossing Conflicts in Scenario 2 with Minimum Recall for 20 Simulation Hours.

Spatial distribution of crossing conflicts for two volume levels with minimum recall setting is given in Figure 12. No crossing conflicts were collected at Conflict Zone 1, 2 and 4, which demonstrated that the left-turning phases blocked two related conflicting movements. 12 and 4 crossing conflicts were detected for low volume and medium-to-high volume respectively in Conflict Zone 3 where the occurrence of crossing conflicts does not require the skipping of left-turning phase. Higher traffic volume at Movement 2 and 8 led to more crossing conflicts being collected at Conflict Zone 3.

5.1.6. Summary

Effectiveness of the V2I safety performance monitoring framework was evaluated based on its ability to detect changes in safety performance. Different simulation scenarios were designed to test whether the proposed framework could provide inference on the anticipated safety performance. The researchers applied statistical tests to compare the rates of the safety measures and the average value of the related safety indicators for all the scenarios. In addition, spatial distribution of the crossing conflicts was also analyzed for different traffic volume levels. It can be concluded that:

- The proposed framework can effectively monitor the safety performance of the signalized intersection. In the low volume group, it can effectively detect a shift in crash pattern from rear-end crashes to right-angle crashes due to reduced stop duration from shortened inter-green intervals. Besides, it can capture the mitigation of this shift in the medium-to-high volume group where stop duration is mainly determined by the long queue accumulated during the red time. It can also detect the increase in both rear-end and right-angle crash risks due to the removal of advance detectors. Related safety indicators demonstrated the potential of providing a comprehensive safety evaluation which can quantify crash frequency and severity
- There appears to be a trade-off between crash frequency and crash severity of each crash type. However, the mechanism for these changes was not clearly understood and will require further investigation effort.
- Spatial distribution of the collected crossing conflict at movement level corresponds well with changes in traffic volume and the resulting actuated signal phases. The increase of left-turning volume reduced the chances for skipping left-turning phases, which created a block for two conflicting through movements and generated fewer crossing conflicts.

So far, analyses are based on 100% OBE saturation to provide ground truth analysis of safety performance. The effectiveness of the proposed framework may be affected at lower market penetration level. The next section explores the impact of market penetration rate on the ability of the proposed framework to detect safety deficiency.

5.2. Sensitivity Analysis of Market Penetration Rate

The objective of this analysis is to evaluate the effect of market penetration rate on the performance of the proposed monitoring framework since only limited level of market penetration can be expected at the initial deployment of the connected vehicle technology. This evaluation first examined the missed safety measures due to the decreasing penetration rate as well as the relationship between the rates of the safety measures and penetration rate. Then, measured indicators at lower penetration levels are compared with those observed at full market penetration, which are considered as ground truth. The proposed framework is considered ineffective at certain levels of market penetration when the rankings of observed safety measures are inconsistent with those observed at full market penetration.

When the penetration rate is not 100%, the computation of the rates of safety measures may vary based on the choice of the volume data source, which could be the real traffic volume or the detected OBE volume. We used the OBE volume for the calculation due to its accessibility from V2I communications data sets. The calculated rates of safety measures include:

- Rates of vehicles trapped in dilemma zone
- Rear-end conflict rates
- Crossing conflict rates

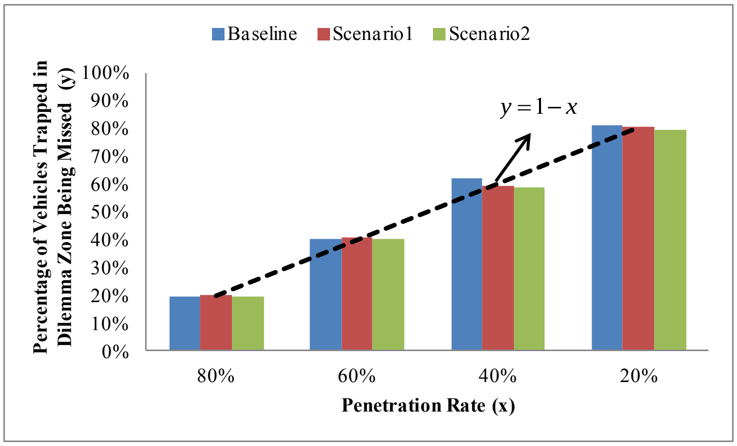
The relationship between the rates of the safety measures and market penetration rate was investigated for Baseline, Scenario 1 and Scenario 2. Market penetration rate was decreased from 100% to 20% at 20% decrement. At each penetration level, the proposed Z test was iteratively applied to statistically compare the difference of the rates between two scenarios.

5.2.1. Percentage of Missed Safety Measures at Lower Penetration Level

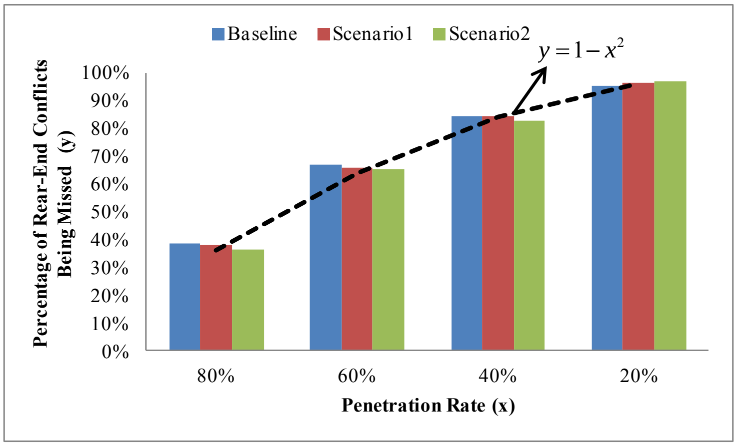
With decreasing penetration rate, fewer safety measures were collected which can bring variation to the true safety performance. This section analyzed the percentage of safety measures being missed at lower penetration levels.

At lower penetration rate, fewer safety measures were collected. However, the tendency of the missed safety measures may vary for single-OBE and dual-OBE measures. Let x, y represent the penetration rate and percentage of missed safety measures. The possibility of an equipped vehicle being detected can be assumed to be proportional to the penetration rate. For single-OBE measure which requires the information of only one vehicle, the detected counts should be linearly related to x. While for dual-OBE measures, two equipped vehicles have to be detected simultaneously. Thus, the detected safety measures should be quadratic to x. As a rough estimation, the percentage of missed counts y due to the decreasing penetration rate can be represented as $1-x$ and $1-x^2$ for single-OBE and dual-OBE measures, respectively.

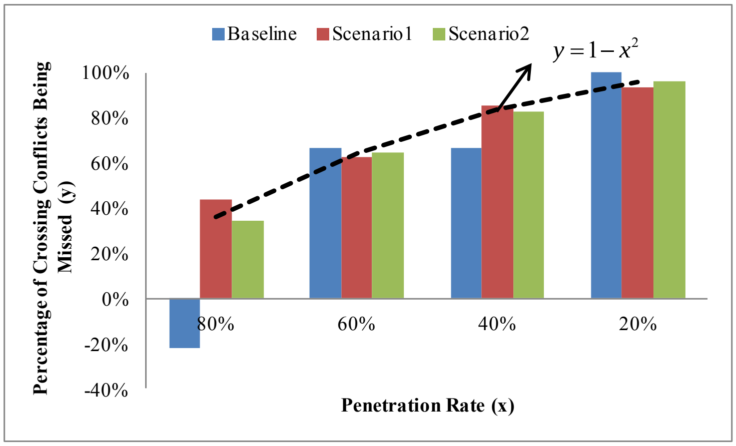
The relationship between the percentage of missed safety measures and penetration rate for the two volume levels was shown in Figure 13 and Figure 14. Proposed estimation lines fitted well with the tendency for the percentages of missed vehicles trapped in dilemma zone as well as rear-end conflicts. The small sample size for crossing conflicts introduced lots of randomness and uncertainty which is particularly true for crossing conflicts at medium-to-high volume level (Figure 14 (c)). The fitness of the proposed quartic line is even worse for Baseline and Scenario 1 where fewer crossing conflicts were collected.



(a) Vehicles Trapped in Dilemma Zone at Low Volume Level

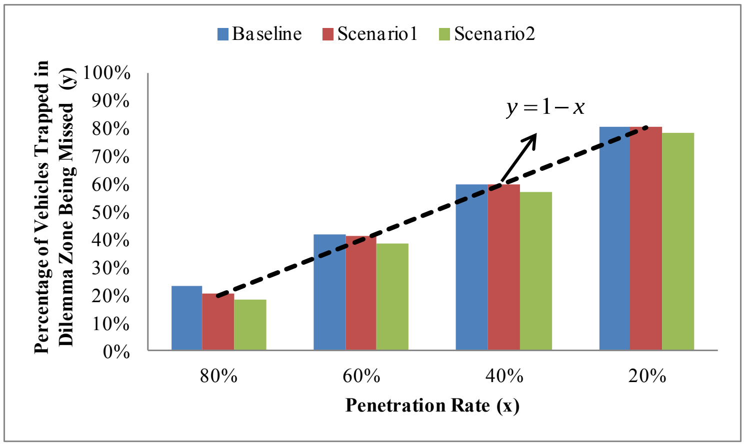


(b) Rear-End Conflicts at Low Volume Level

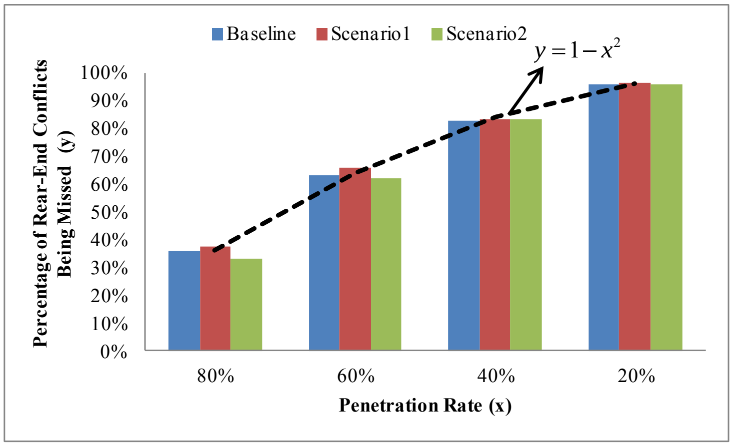


(c) Crossing Conflicts at Low Volume Level

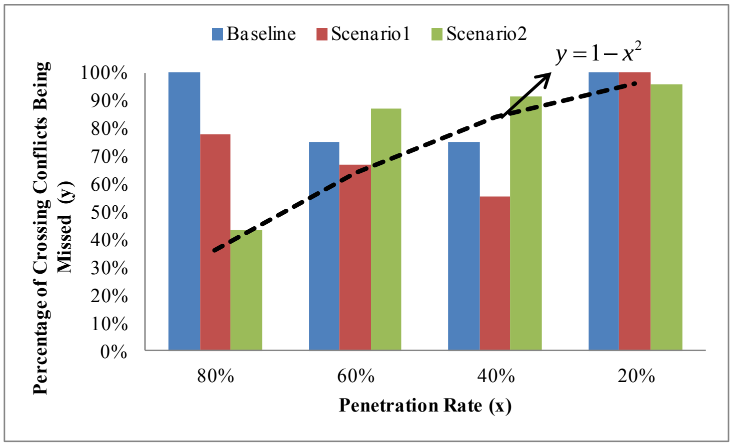
Figure 13: Percentage of Safety Measures Being Missed under Low Volume Level.



(a) Vehicles Trapped in Dilemma Zone at Medium-to-High Volume Level



(b) Rear-End Conflicts at Medium-to-High Volume Level



(c) Crossing Conflicts at Medium-to-High Volume Level

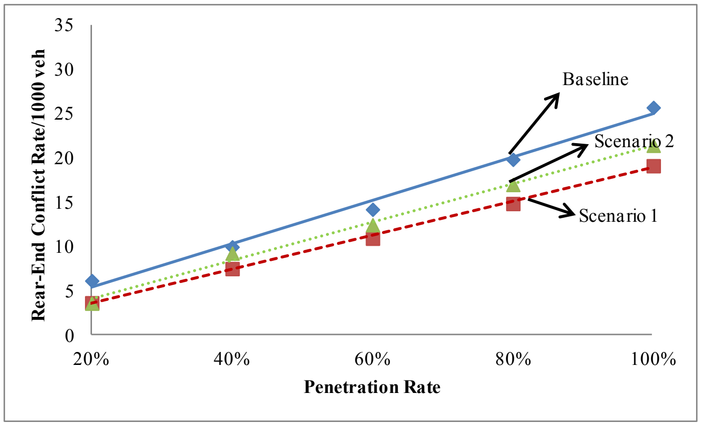
Figure 14: Percentage of Safety Measures Being Missed under Medium-to-High Volume Level.

5.2.2. Relationship between the Rates of Safety Measures and Penetration Rate

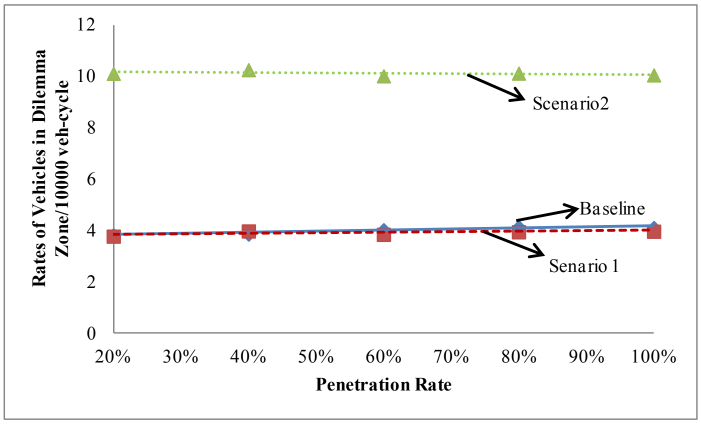
Figure 15 and Figure 16 display the relationship between the penetration rate and the mean rates of collected safety measures for both low and medium-to-high volume levels. Generally, the rate of single-OBE measure (rate of vehicles trapped in dilemma zone) seems to be stable at different penetration rate level. While the rates of dual-OBE measures (crossing and rear-end conflicts) decrease linearly as penetration rate decreases.

The computation for single-OBE measure requires the only one vehicle's information. Although the framework captured fewer safety measures at lower penetration rate, the total OBE volume collected also decreased at the same percentage. The calculated rate therefore remains the same. For the dual-OBE measures, the detected safety measures decreased quadratically since the information of two conflicting vehicles needs to be detected at the same time. Given that total equipped vehicles decreased linearly in the denominator, the rates of dual-OBE measures also decreased linearly as the final result.

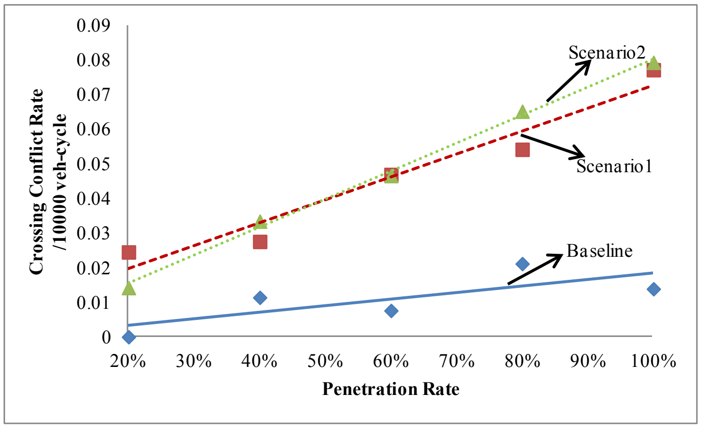
If the real traffic volume is used as the denominator for computing the rates, we could expect that single-OBE measure will decrease linearly and dual-OBE will decrease quadratically. In this case, the collected real traffic volume would approximately be constant, which means the rates are only determined by the number of detected safety indicators. This relationship has been documented in our previous paper (*43*).



(a) Rear-End Conflicts for Low Volume Level

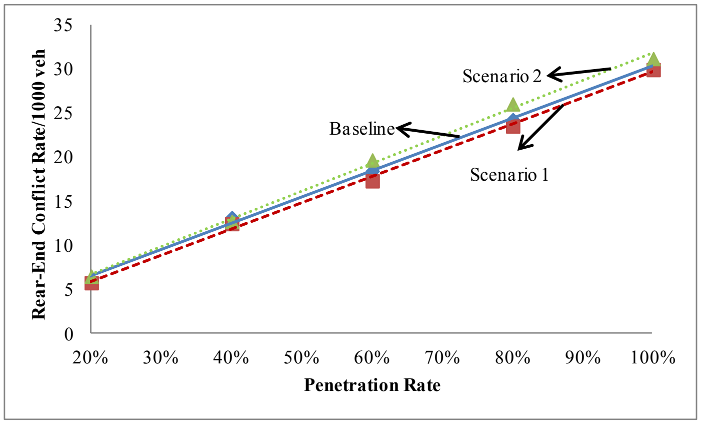


(b) Vehicles Trapped in Dilemma Zone for Low Volume Level

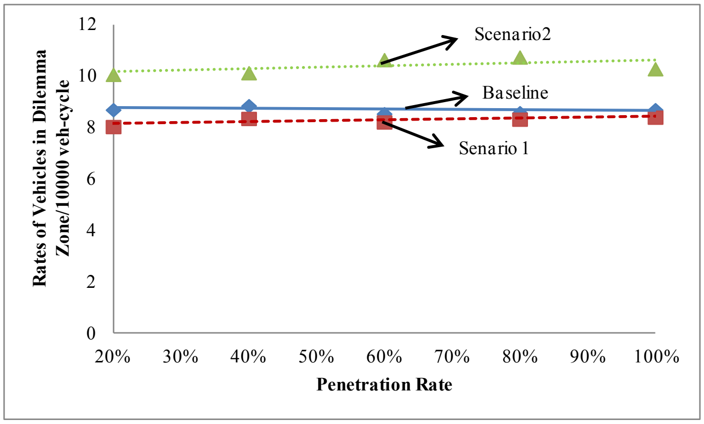


(c) Crossing Conflicts for Low Volume Level

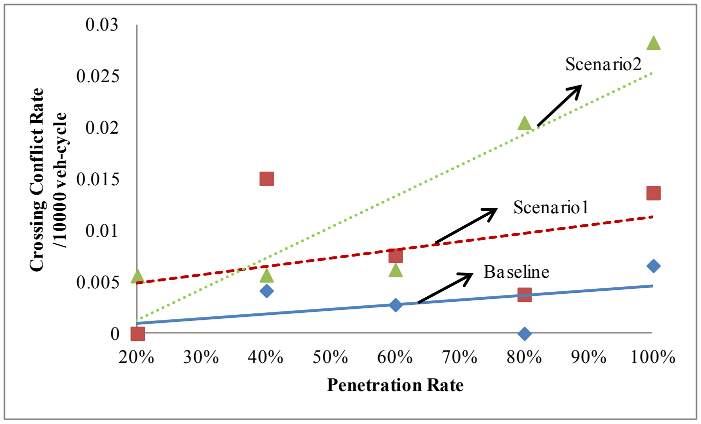
Figure 15: Penetration Rates versus Rates of Detected Safety Measures at Low Volume Level.



(a) Rear-End Conflicts for Medium-to-High Volume Level



(b) Vehicles Trapped in Dilemma Zone for Medium-to-High Volume Level



(c) Crossing Conflicts for Medium-to-High Volume Level

Figure 16: Penetration Rates versus Rates of Detected Safety Measures at Medium-to-High Volume Level.

5.2.3. Effect of the Penetration Rate on the Performance of the Proposed Framework

To examine the effect of market penetration on the performance of the framework in detecting the degrading safety performance, we iteratively applied Equation (6) to examine the difference in the rates of safety measures at lower penetration level and compared the results under the full penetration rate to see whether they are consistent. The results are exhibited in Table 13 through Table 16 for the low volume group and Table 17 through Table 20 for the medium-to-high volume group. The following describes the findings.

Firstly, the proposed framework could perform effectively in detecting the changes of safety performance when the penetration rate is above 40% for the low volume group and 60% for the higher volume group. The power of statistical test in general decreases with decreasing penetration levels.

For the low volume group, at 40% or less OBEs, the difference in crossing conflict rates between Baseline and Scenario 1 was unable to detect at the 95% confidence level (p-value = 0.097). At 20% or less OBEs level, the difference in rear-end conflict rates between Scenario 1 and Scenario 2 became insignificant (p-value = 1.000). The inconsistencies are highlighted in bold. For the medium-to-high volume group, At least 60% and 40% OBEs should be guaranteed to identify the difference in crossing conflict rates and rear-end conflict rates respectively between Scenaior1 and Scenario 2.

Secondly, single-OBE measure is more reliable than dual-OBE measures at lower market penetration level. Although still losing the power of test, comparison of rates of vehicles trapped in dilemma zone between Scenario 1 and Scenario 2 at the 20% OBEs level could still give the p-value far less than 0.01.

Table 13: Statistical Comparison of Safety Measures for Low Traffic Volume Level (80% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements	**Baseline**	**Scenario 1**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	19.856	14.866	-7.428	<0.01	-25.1%	Yes (Yes)
Rate of vehicles trapped in dilemma zone	4.153	3.961	-1.603	0.109	-4.6%	No (No)
Crossing conflict rate	0.021	0.054	2.970	<0.01	156.1%	Yes (Yes)
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	14.866	17.017	3.371	<0.01	14.5%	Yes (Yes)
Rate of vehicles trapped in dilemma zone	3.961	10.145	43.195	<0.01	156.1%	Yes (Yes)
Crossing conflict rate	0.054	0.065	0.961	0.337	20.3%	No (No)

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

Table 14: Statistical Comparison of Safety Measures for Low Traffic Volume Level (60% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements	**Baseline**	**Scenario 1**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	14.211	10.940	-4.943	<0.01	-23.0%	Yes (Yes)
Rate of vehicles trapped in dilemma zone	4.043	3.862	-1.326	0.185	-4.5%	No (No)
Crossing conflict rate	0.008	0.047	3.587	<0.01	516.6%	Yes (Yes)
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	10.940	12.463	2.427	0.015	13.9%	Yes (Yes)
Rate of vehicles trapped in dilemma zone	3.862	10.041	37.811	<0.01	160.0%	Yes (Yes)
Crossing conflict rate	0.047	0.047	0.114	0.910	-0.7%	No (No)

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

Table 15: Statistical Comparison of Safety Measures for Low Traffic Volume Level (40% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements	**Baseline**	**Scenario 1**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	9.972	7.510	-3.626	<0.01	-24.7%	Yes (Yes)
Rate of vehicles trapped in dilemma zone	3.870	3.994	0.771	0.441	3.2%	No (No)
Crossing conflict rate	**0.011**	**0.028**	**1.659**	**0.097**	**141.9%**	**No (Yes)**
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	7.510	9.257	2.696	<0.01	23.3%	Yes (Yes)
Rate of vehicles trapped in dilemma zone	3.994	10.280	31.039	<0.01	157.4%	Yes (Yes)
Crossing conflict rate	0.028	0.033	0.663	0.507	21.3%	No (No)

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

Table 16: Statistical Comparison of Safety Measures for Low Traffic Volume Level (20% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements	**Baseline**	**Scenario 1**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	6.153	3.649	-3.456	<0.01	-40.7%	Yes (Yes)
Rate of vehicles trapped in dilemma zone	3.843	3.791	-0.195	0.845	-1.3%	No (No)
Crossing conflict rate	0.000	0.025	2.307	0.021	N/A	Yes (Yes)
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	**3.649**	**3.598**	**0.000**	**1.000**	**-1.4%**	**No (Yes)**
Rate of vehicles trapped in dilemma zone	3.791	10.137	22.431	<0.01	167.4%	Yes (Yes)
Crossing conflict rate	0.025	0.014	-0.342	0.732	-42.0%	No (No)

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

Table 17: Statistical Comparison of Safety Measures for Medium-to-High Volume Level (80% OBEs).

<table>
<tr><th colspan="7">Comparison 1: Baseline and Scenario 1</th></tr>
<tr><th>Measurements</th><th>Baseline</th><th>Scenario 1</th><th>Z</th><th>p-value</th><th>%Change</th><th>Significant</th></tr>
<tr><td>Rear-end conflict rate</td><td>24.291</td><td>23.556</td><td>-1.34</td><td>0.18</td><td>-3%</td><td>No (No)</td></tr>
<tr><td>Rate of vehicles trapped in dilemma zone</td><td>8.594</td><td>8.341</td><td>-1.36</td><td>0.17</td><td>-3%</td><td>No (No)</td></tr>
<tr><td>Crossing conflict rate</td><td>0</td><td>0.004</td><td>2.05</td><td>0.04</td><td>N/A</td><td>Yes (No)</td></tr>
<tr><th colspan="7">Comparison 2: Scenario 1 and Scenario 2</th></tr>
<tr><th>Measurements</th><th>Scenario 1</th><th>Scenario 2</th><th>Z</th><th>p-value</th><th>%Change</th><th>Significant</th></tr>
<tr><td>Rear-end conflict rate</td><td>23.556</td><td>26.071</td><td>4.57</td><td><0.01</td><td>11%</td><td>Yes (Yes)</td></tr>
<tr><td>Rate of vehicles trapped in dilemma zone</td><td>8.341</td><td>10.760</td><td>13.20</td><td><0.01</td><td>29%</td><td>Yes (Yes)</td></tr>
<tr><td>Crossing conflict rate</td><td>0.004</td><td>0.021</td><td>2.75</td><td>0.01</td><td>440%</td><td>Yes (Yes)</td></tr>
</table>

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

Table 18: Statistical Comparison of Safety Measures for Medium-to-High Volume Level (60% OBEs).

<table>
<tr><th colspan="7">Comparison 1: Baseline and Scenario 1</th></tr>
<tr><th>Measurements</th><th>Baseline</th><th>Scenario 1</th><th>Z</th><th>p-value</th><th>%Change</th><th>Significant</th></tr>
<tr><td>Rear-end conflict rate</td><td>18.459</td><td>17.336</td><td>-2.06</td><td>0.04</td><td>-6%</td><td>Yes (No)</td></tr>
<tr><td>Rate of vehicles trapped in dilemma zone</td><td>8.555</td><td>8.232</td><td>-1.51</td><td>0.13</td><td>-4%</td><td>No (No)</td></tr>
<tr><td>Crossing conflict rate</td><td>0.003</td><td>0.008</td><td>1.40</td><td>0.16</td><td>172%</td><td>No (No)</td></tr>
<tr><th colspan="7">Comparison 2: Scenario 1 and Scenario 2</th></tr>
<tr><th>Measurements</th><th>Scenario 1</th><th>Scenario 2</th><th>Z</th><th>p-value</th><th>%Change</th><th>Significant</th></tr>
<tr><td>Rear-end conflict rate</td><td>17.336</td><td>19.710</td><td>4.32</td><td><0.01</td><td>14%</td><td>Yes (Yes)</td></tr>
<tr><td>Rate of vehicles trapped in dilemma zone</td><td>8.232</td><td>10.659</td><td>11.57</td><td><0.01</td><td>29%</td><td>Yes (Yes)</td></tr>
<tr><td>Crossing conflict rate</td><td>0.008</td><td>0.006</td><td>0.16</td><td>0.87</td><td>-18%</td><td>No (Yes)</td></tr>
</table>

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

Table 19: Statistical Comparison of Safety Measures for Medium-to-High Volume Level (40% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements	**Baseline**	**Scenario 1**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	13.169	12.477	-1.21	0.22	-5%	No (No)
Rate of vehicles trapped in dilemma zone	8.867	8.370	-1.89	0.06	-6%	No (No)
Crossing conflict rate	0.004	0.015	1.68	0.09	262%	No (No)
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	**12.477**	**12.742**	**0.50**	**0.62**	**2%**	**No (Yes)**
Rate of vehicles trapped in dilemma zone	8.370	10.150	7.16	<0.01	21%	Yes (Yes)
Crossing conflict rate	0.015	0.006	-0.76	0.45	-62%	No (Yes)

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

Table 20: Statistical Comparison of Safety Measures for Medium-to-High Volume Level (20% OBEs).

Comparison 1: Baseline and Scenario 1						
Measurements	**Baseline**	**Scenario 1**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	6.014	5.766	-0.42	0.68	-4%	No (No)
Rate of vehicles trapped in dilemma zone	8.710	8.053	-1.78	0.08	-8%	No (No)
Crossing conflict rate	0	0	N/A	N/A	N/A	No (No)
Comparison 2: Scenario 1 and Scenario 2						
Measurements	**Scenario 1**	**Scenario 2**	**Z**	**p-value**	**%Change**	**Significant**
Rear-end conflict rate	5.766	6.512	1.41	0.16	13%	No (Yes)
Rate of vehicles trapped in dilemma zone	8.053	10.086	5.86	<0.01	25%	Yes (Yes)
Crossing conflict rate	0	0.006	1.87	0.06	N/A	No (Yes)

Notes: Comparison results for the 100% OBEs case are listed in the parenthesis.

5.2.4. Summary

The decrease in the number of the safety measures collected by RSE attributes to the decreasing market penetration rate. As the result, difference between the rates of the detected safety measures can be incorrectly concluded as insignificant at lower penetration levels where in fact it should be. The effect of market penetration on the performance of the proposed framework was thoroughly analyzed in this section. The researchers examined the tendency of the rates of the safety measures with decreasing penetration rate. We also statistically compared the rates at lower penetration levels with those at full market penetration to identify an approximate boundary above which the performance of the proposed framework could still be guaranteed. The analysis results indicated the following:

- As penetration rate decreases, the rates of single-OBE measures stay almost the same while the rates of dual-OBE measures decrease linearly.
- Single-OBE measure is more reliable than dual-OBE measures at lower market penetration level.
- More than 40% and 60% OBEs would likely be needed to ensure effective application of the proposed framework under low volume and medium-to-high volume, respectively.

Generally, we have demonstrated the monitoring framework does not require full market penetration to be successful based on extensive simulation runs. However, the observation period for effective implementation of the framework has not been addressed. The requirement for observation period may vary for different penetration levels and types of safety measures. Since market penetration may not be high at the initial deployment of the connected vehicle facilities, a more challenging task is investigate if and how we can effectively apply the framework by extending the duration of observation to ensure sufficient sample size even at low OBE penetration levels. The next section investigates this issue.

5.3. Analysis of Observation Period

The purpose of this analysis is to examine the effect of observation period on effective implementation of the proposed framework. We examined the relationships between penetration rate, observation period and the variability of the computed safety measures under low volume and medium-to high volume levels. Specifically, we investigated if longer observation period would be able to provide sufficient sample sizes usually obtained with higher market penetrations for different safety measures.

Considering that traffic volume in simulation is fixed, the extended hours of simulation may only reflect one hour's operation in real world. Observation period can be extended by increasing the observation frequency of a studied period. For instance, let us consider the observation period of from 7 a.m. to 8 a.m. for 1 day versus 10 days at 50% penetration rate. The data collected for 10 hours over 10 days would be expected to be more reliable and potentially converge closer to true safety performance than 1 hour of data collection. If the penetration rate increases to 100%, more data would be collected in both cases and the variability in the observed safety measures would be reduced. Even with the same observation period, the reliability for different safety measures may also vary. Those that are more frequent and require only one OBE will likely have less variation.

We utilized coefficient of variation (CV) to measure the variability of the rates detected by the proposed framework for different observation periods. Lower CV value means less variability of the collected data which thus could provide more reliable analysis. The definition of CV is given as:

$$CV = 100 \times \frac{\sigma}{\mu} \tag{8}$$

where

σ = Standard deviation of the population, which is substituted by the standard deviation of the rate of the safety measure;

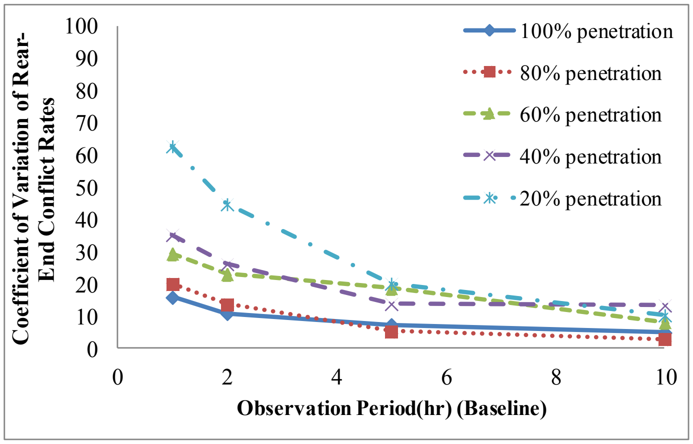
μ = Population mean, which is substituted by the mean of the rate of the safety measure.

Accordingly, we first investigated the relationship between the variation of rate of the safety measures and observation period for each scenario. Based on this, we estimated and compared equivalent observation time needed at lower penetration levels to achieve the same variability as the 100% penetration level. Then, we computed the average variation over all penetration levels and compared across the safety measures to see whether they are at the same level. Measures with larger variation require longer observation period to be effective.

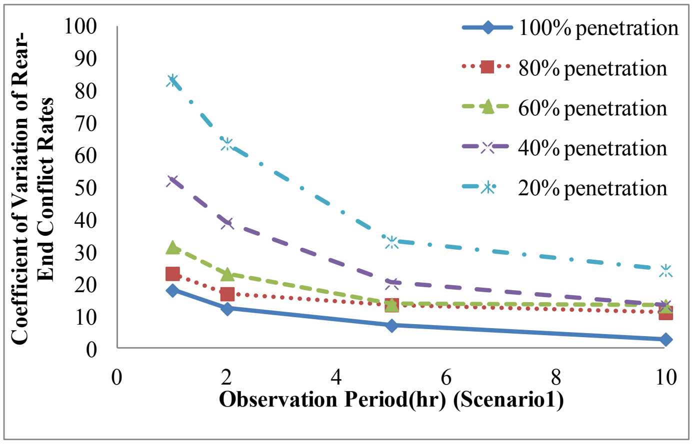
Considered observation periods range from 1 hour, 2 hours, 5 hours and 10 hours, which is the integer interval to block the data collected from 60 simulation hours into smaller observation periods. Sample sizes generated for each observation period are therefore 60, 30, 12 and 6 intervals respectively. Rates of the safety measures were calculated for each observation period. They are defined as the number of collected safety measures over the total detected OBE volume during the observation period.

5.3.1. Analysis of Observation Periods Required for Different Penetration Levels

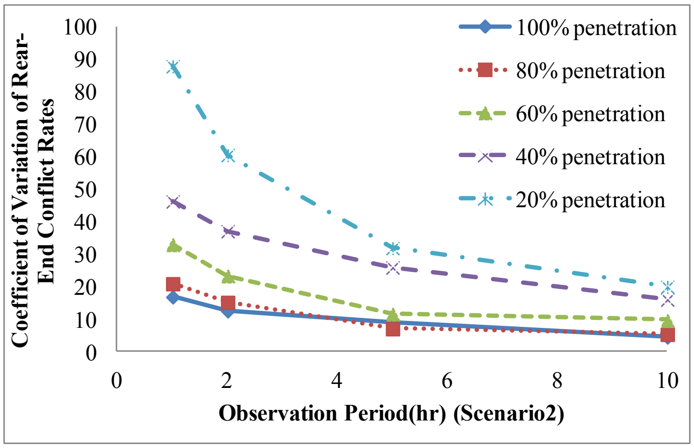
Figure 17 through Figure 22 demonstrates the relationship between coefficient of variation (CV) and observation period for selected safety measures in different volume groups. Curves for different penetration levels are also shown in each figure. Note that the curve for crossing conflict rate at 20% penetration level in the low volume group is not available in Figure 21 (a) as no crossing conflict was observed. It is the same case for curves for crossing conflict rate in Figure 22 (a) (at penetration rate 20% and 80%) and Figure 22 (b) (at penetration rate 20%).



(a) Baseline at Low Volume Level

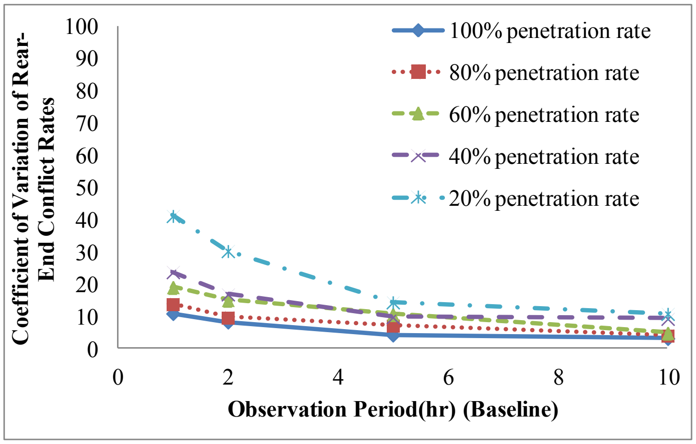


(b) Scenario 1 at Low Volume Level

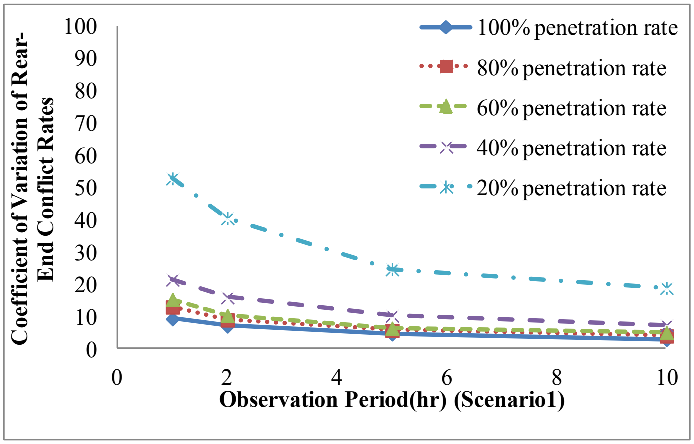


(c) Scenario 2 at Low Volume Level

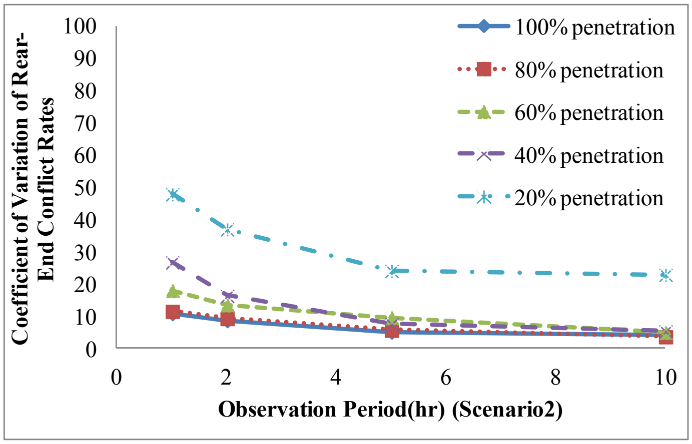
Figure 17: CV of Rear-End Conflict Rates versus Observation Period at Low Volume.



(a) Baseline at Medium-to-High Volume Level

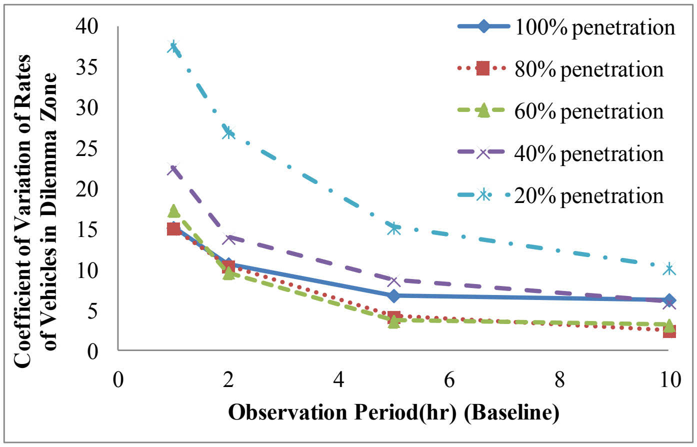


(b) Scenario 1 at Medium-to-High Volume Level

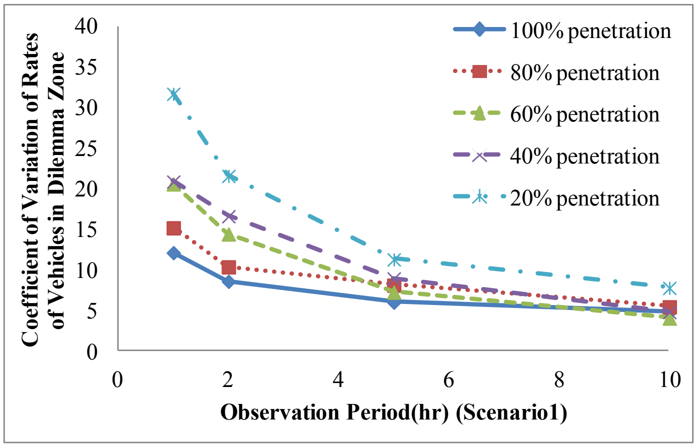


(c) Scenario 2 at Medium-to-High Volume Level

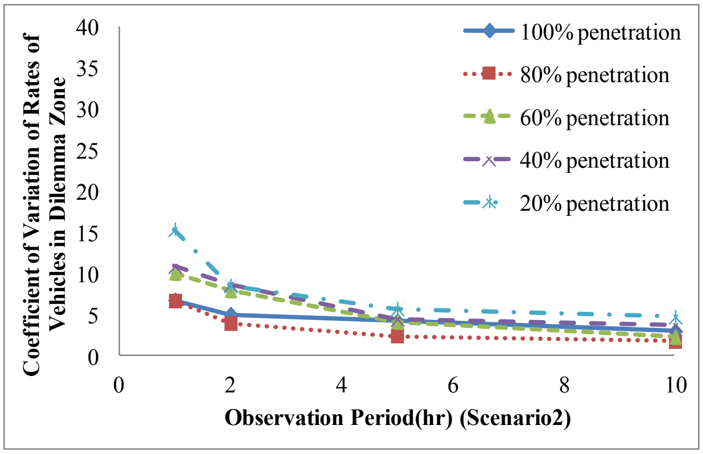
Figure 18: CV of Rear-End Conflict Rates versus Observation Period at Medium-to-High Volume.



(a) Baseline at Low Volume Level

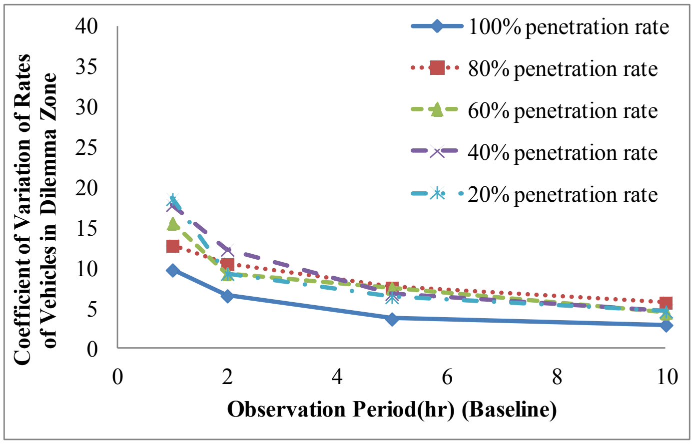


(b) Scenario 1 at Low Volume Level

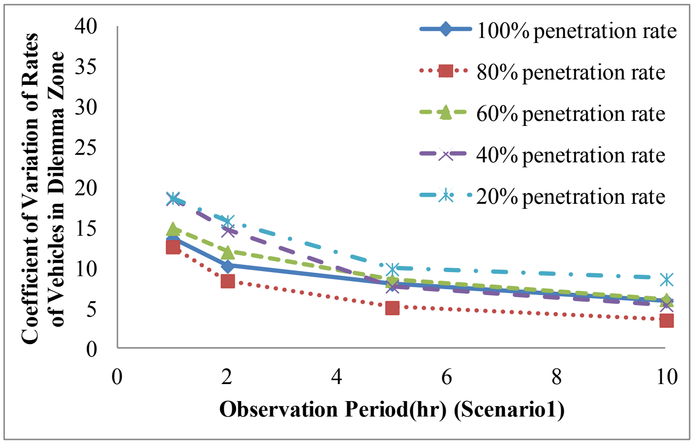


(c) Scenario 2 at Low Volume Level

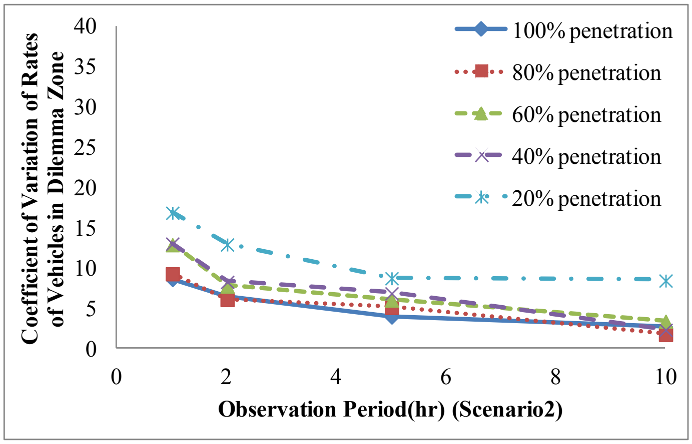
Figure 19: CV of Rates of Vehicles Trapped in DZ versus Observation Period at Low Volume Level.



(a) Baseline at Medium-to-High Volume Level

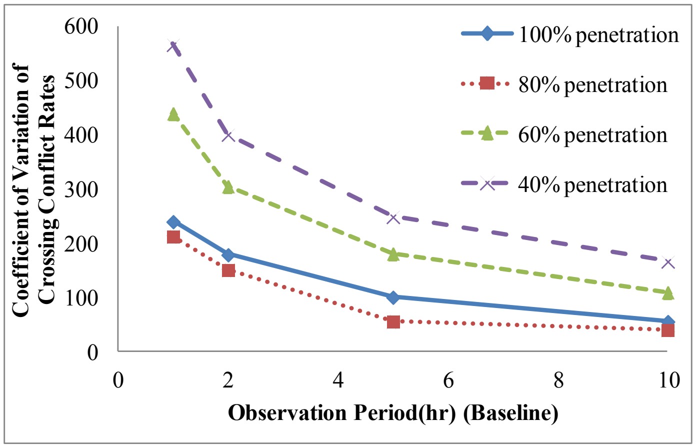


(b) Scenario 1 at Medium-to-High Volume Level

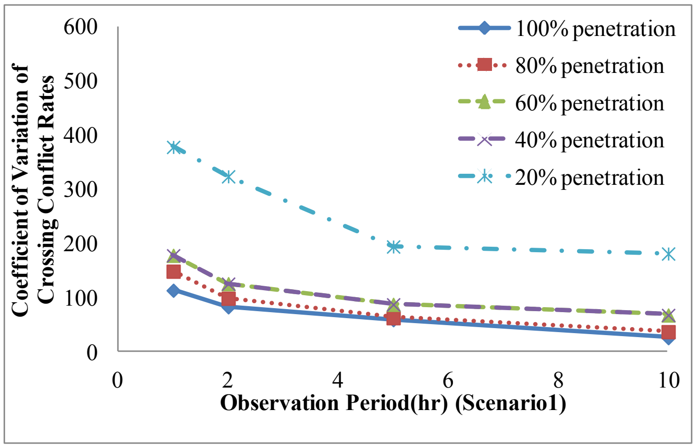


(c) Scenario 2 at Medium-to-High Volume Level

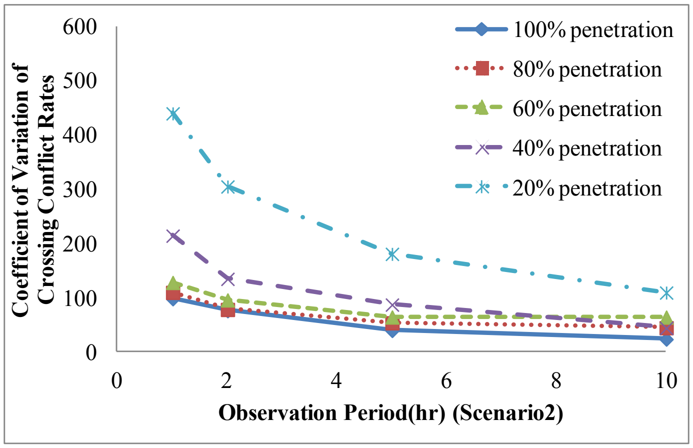
Figure 20: CV of Rates of Vehicles Trapped in DZ versus Observation Period at Medium-to-High Volume Level.



(a) Baseline at Low Volume Level

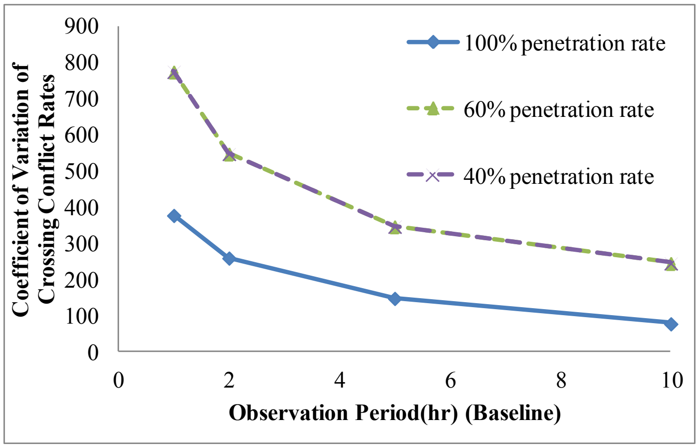


(b) Scenario 1 at Low Volume Level

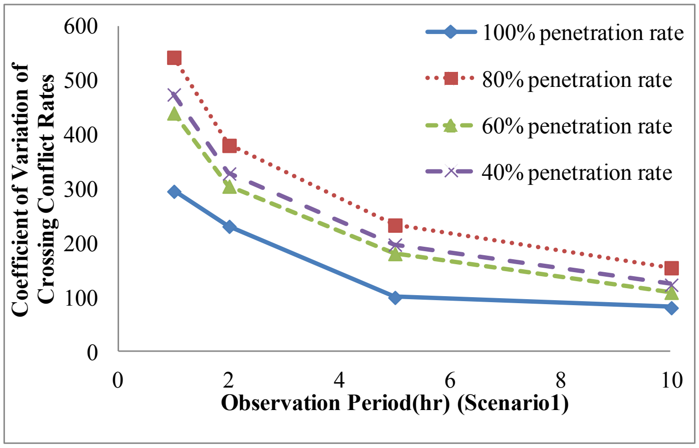


(c) Scenario 2 at Low Volume Level

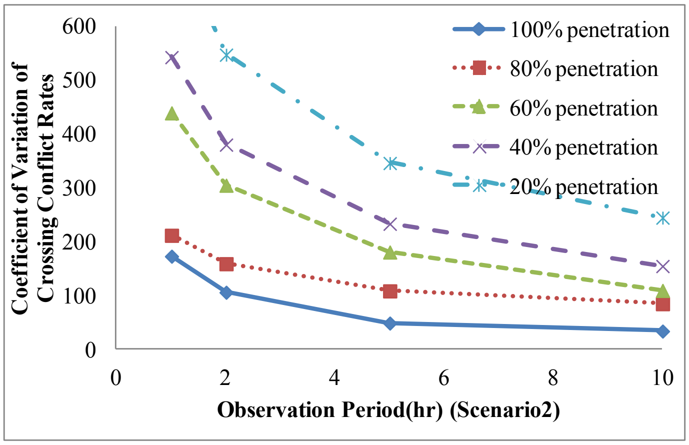
Figure 21: CV of Crossing Conflict Rates versus Observation Period at Low Volume Level.



(a) Baseline at Medium-to-High Volume Level



(b) Scenario 1 at Medium-to-High Volume Level



(c) Scenario 2 at Medium-to-High Volume Level

Figure 22: CV of Crossing Conflict Rates versus Observation Period at Medium-to-High Level.

To illustrate the effects of observation periods, we compared the equivalent observation time for rates of the safety measures at different penetration levels to achieve the same variability as those obtained from one-hour observation at the full penetration level. The tendency of the equivalent observation period for low volume group and medium-to-high volume group is presented in Table 21 and Table 22 respectively.

Table 21: Equivalent Observation Periods for Varying Penetration Levels for Low Volume Group.

Equivalent Observation Period[1] for Rear-End Conflict Rate (*hr*)					
	100%	80%	60%	40%	20%
Baseline	1.0	1.6	6.3	4.5	7.2
Scenario 1	1.0	1.8	3.6	6.7	13.6
Scenario 2	1.0	1.7	3.7	9.6	11.3
Average	1.0	1.7	4.5	6.9	10.7
Equivalent Observation Period for Rate of Vehicles Trapped in Dilemma Zone (*hr*)					
	100%	80%	60%	40%	20%
Baseline	1.0	1.0	1.3	1.9	5.0
Scenario 1	1.0	1.6	3.0	3.8	4.8
Scenario 2	1.0	1.0	3.0	3.4	3.9
Average	1.0	1.2	2.4	3.0	4.6
Equivalent Observation Period for Crossing Conflict Rate (*hr*)					
	100%	80%	60%	40%	20%
Baseline	1.0	1.0	3.6	5.5	N/A
Scenario 1	1.0	1.7	3.0	24.3	36.1
Scenario 2	1.0	1.4	1.9	4.3	10.8
Average	1.0	1.4	2.8	11.4	23.5

Notes: Equivalent observation period is obtained through linear interpolation.

Table 22: Equivalent Observation Periods for Varying Penetration Levels for Medium-to-High Volume Group.

Equivalent Observation Period[1] for Rear-End Conflict Rate (*hr*)					
	100%	80%	60%	40%	20%
Baseline	1.0	1.7	4.8	4.5	9.7
Scenario 1	1.0	1.8	2.8	6.7	13.1
Scenario 2	1.0	1.3	3.9	3.9	61.2
Average	1.0	1.6	3.8	5.0	28.0
Equivalent Observation Period for Rate of Vehicles Trapped in Dilemma Zone (*hr*)					
	100%	80%	60%	40%	20%
Baseline	1.0	2.8	1.8	3.4	1.9
Scenario 1	1.0	0.8	1.4	2.4	3.0
Scenario 2	1.0	1.2	1.8	1.9	7.9
Average	1.0	1.6	1.7	2.6	4.3
Equivalent Observation Period for Crossing Conflict Rate (*hr*)					
	100%	80%	60%	40%	20%
Baseline	1.0	N/A	4.5	4.5	N/A
Scenario 1	1.0	3.7	2.2	2.8	N/A
Scenario 2	1.0	1.7	5.5	8.8	18.5
Average	1.0	2.7	4.1	5.4	18.5

Notes: Equivalent observation period is obtained through linear interpolation.

CV decreases with either the increase of observation period or market penetration rate in most cases. The increase of either the two can generate larger sample size and thus reduce the variation in the collected safety measures. Therefore, longer observation period can potentially be used to compensate for the need to collect sufficient data at lower penetration level. This is particularly important during the initial deployment of connected vehicle technology when the OBE market penetration is low.

From Table 21, for example, one-hour observation for the rear-end conflict at full penetration rate equals to approximately 1.7 hours of observation at 80% penetration level based on the measured CV. This equivalent observation period increases to 4.5 hours, 6.9 hours and 10.7 hours at 60%, 40% and 20% of penetration level, respectively. Analysis of the other two safety measures yielded similar tendency. Over all safety measures, 10 hours' observation at 40% penetration level can generally guarantee the same level of accuracy as 1 hour's observation at full market penetration.

In addition, there is a diminishing return effect on the decrease in CV as observation periods increase. For example, consider CVs of the rear-end conflict rate at 40% penetration for the low volume group (Figure 17 (b)). The increase of observation period from 1 hour to 5 hours reduces the CV by 32 units (52 to 20) while the further increase from 5 hours to 10 hours will further reduce the CV by only 6 units (20 to 14). This implies an exponential need of observation effort as we attempt to further reduce the variability in collected safety measures.

The results from medium-to-high volume group, as is indicated in Table 22, also demonstrated the requirement for longer observation period at lower penetration levels as well as the diminishment of return effect of increasing observation period.

5.3.2. Analysis of Observation Periods for Different Safety Measures

To investigate the requirement of each type of safety measures on the observation period, we computed the average CV values over all penetration levels for each observation period. Larger CV value indicates more observation period is required to mitigate the variability of the safety measures. The results are listed in Table 23 and for low volume level and medium-to-high volume level, respectively.

The scales of CV were found to vary for different measures. Single-OBE measures on average have smaller CVs than dual-OBE measures. For dual-OBE measures, CVs for crossing conflict rates are consistently larger than those for rear-end conflict rates. From Table 23, CVs for rear-end conflict rates are approximately more than twice larger than those for rates of vehicles trapped in the dilemma zone while CVs for crossing conflict rate are more than six times larger than those for rear-end conflicts. The results for the medium-to high volume (in Table 24) give similar tendency. Therefore, crossing conflicts would require the longest observation period to be effective while vehicles trapped in dilemma zone would require the shortest period to achieve the same level of variability.

This characteristic can be explained by the random nature of the safety measures as well as the presence of opportunities to compute the safety measures from the V2I communications data sets. Chances for vehicles trapped in the dilemma zone occur regularly at the end of green. The collection of a vehicle trapped in dilemma zone only requires the information of only single vehicle, which is relatively easier to capture. The computation of rear-end conflicts requires information of two consecutive OBE-equipped vehicles from the same movement and thus harder to detect. The detection of crossing conflict relies on monitoring two conflicting vehicles heading to the same conflicting point. This could only occur at certain "risky moment" when both vehicles choose to proceed during the transition of the signal interval and thus is the rarest case among the three.

It is also worth mentioning that the increase of volume does not necessarily guarantee smaller CV value of the collected safety measures. A cross comparison between Table 23 and Table 24 shows that although the medium-to-high volume group has relatively smaller CVs for rear-end conflicts, the scale of CV for vehicles trapped in dilemma zone is approximately the same for the two volume levels. Larger CVs were even observed for crossing conflict at the medium-to-high volume.

CV mainly relies on the size of the recorded safety measures. At the medium-to-high volume level, more rear-end conflicts were collected due to higher through traffic input as well as the resulting long queue during the red period. Abrupt deceleration, acceleration and even lane change can occur during the expanding and receding of the queue. However, the increase of through volume kept activating through green and thus reduced the number of cycles. In fact, more vehicles were observed trapped in dilemma zone in Scenario 2 under the low volume condition, as is displayed in Table 5. As for crossing conflict, the increasing left-turning volume activated the left-turning phase more frequently which blocked two conflicting through phases. Thus, fewer crossing conflicts were detected at higher volume level.

Table 23: Average CV for Different Observation Periods for Low Volume Level.

CV for Rear-End Conflict Rate				
	1 (*hr*)	**2 (*hr*)**	**5 (*hr*)**	**10 (*hr*)**
Baseline	32.7	23.7	13.1	8.0
Scenario 1	41.8	31.1	17.6	13.1
Scenario 2	41.0	29.7	17.1	11.1
Average	38.5	28.2	15.9	10.7
CV for Rate of Vehicles Trapped in Dilemma Zone				
	1 (*hr*)	**2 (*hr*)**	**5 (*hr*)**	**10 (*hr*)**
Baseline	21.6	14.4	7.7	5.6
Scenario 1	20.1	14.3	8.3	5.4
Scenario 2	10.0	6.8	4.2	3.1
Average	17.2	11.8	6.8	4.7
CV for Crossing Conflict Rate				
	1 (*hr*)	**2 (*hr*)**	**5 (*hr*)**	**10 (*hr*)**
Baseline	364.8	259.0	146.6	93.2
Scenario 1	211.8	166.6	113.8	92.8
Scenario 2	198.2	138.1	85.2	57.3
Average	258.2	187.9	115.2	81.1

Table 24: Average CV for Different Observation Periods for Medium-to-High Volume Level.

CV for Rear-End Conflict Rate				
	1 (*hr*)	**2 (*hr*)**	**5 (*hr*)**	**10 (*hr*)**
Baseline	21.7	16.0	9.2	6.4
Scenario 1	22.4	16.6	10.3	7.6
Scenario 2	23.0	17.0	10.4	8.2
Average	22.4	16.5	10.0	7.4
CV for Rate of Vehicles Trapped in Dilemma Zone				
	1 (*hr*)	**2 (*hr*)**	**5 (*hr*)**	**10 (*hr*)**
Baseline	14.9	9.6	6.4	4.5
Scenario 1	15.7	12.2	7.8	5.9
Scenario 2	12.1	8.3	6.1	3.7
Average	14.2	10.0	6.8	4.7
CV for Crossing Conflict Rate				
	1 (*hr*)	**2 (*hr*)**	**5 (*hr*)**	**10 (*hr*)**
Baseline	642.2	451.6	280.2	189.1
Scenario 1	438.4	311.5	178.0	117.3
Scenario 2	428.5	299.8	183.7	125.7
Average	503.0	354.3	214.0	144.0

5.3.3. Summary

This section investigated the effect of observation period for effective implementation of the proposed framework. The CV of the rates of safety measures was used to measure their variability with respect to different measures, observation periods, and market penetration rates. Larger CVs are less desirable as it signifies more variability in the data and thus indicates the need for more sample size in order to converge closer to true safety performance. The relationships between CV, market penetration and observation period were examined in details. Characteristics of different types of safety measures and their effect on the required observation period were also analyzed. The key findings include the following:

- Longer observation period could be used to compensate for the need for more sample size at lower market penetration rates. Over all safety measures, 10 hours' observation at 40% penetration level can guarantee the same level of accuracy as 1 hour's observation at full market penetration.
- There is a diminishing return effect with the increase in observation time. One unit gain in CV at low variability would require much longer observation time to achieve the same amount under high CV conditions.
- Safety indicators that occur less frequently and are more computationally intensive would require longer observation period to be effective.
- Higher traffic volume does not necessarily guarantee smaller CV value. The varying traffic volume may change the operational characteristics of the signalized intersection (e.g. reduced cycles, reduced skipping of left-turning phases), which can lead to fewer safety measures being collected at higher traffic volume.

6. SUMMARY AND CONCLUSIONS

6.1. Overview

Safety performance at signalized intersections is an outcome of complex interactions among several contributing factors including signal operations, geometric design, drivers' behavior and vehicular performance. Traditional safety evaluation approaches fall within crash-based analysis and surrogate safety studies. However, the former is often criticized for the randomness, lack of timeliness, and rarity of crash occurrences while the latter requires labor-intensive back-office processing and manual review to collect surrogate safety data.

Connected vehicle technology allows vehicles to talk to each other and to infrastructure wirelessly using the dedicated short-range communications (DSRC). Since the introduction of the connected vehicle initiative, many safety applications have been developed which mainly focus on providing in-vehicle advisory and warning information based on the detected or predicted hazard event. However, some of these applications require high saturation rate of onboard equipment (OBE), which may not be feasible in the near future. To date, no application exists for monitoring long-term safety and detecting changes in safety performance.

The objective of this study is to propose and evaluate a framework for continuously monitoring the safety performance of signalized intersections via vehicle-to-infrastructure (V2I) communications. The proposed application would require only V2I communications, RSE, and some levels of OBE to be successful. This section documents the findings and conclusions from the study.

6.2. Summary

6.2.1. Framework Description

In the proposed safety performance monitoring framework, we first defined the safety indicators that are able to comprehensively quantify the safety performance at signalized intersections. Then, we developed algorithms to extract them in real time from the V2I communications data sets. The goal of the algorithm is to mine the data received at RSE by integrating and synchronizing vehicle kinematics (BSM), signal data (SPaT) and intersection geometric data (MAP) from the V2I communications data sets.

Safety measures were categorized into single-OBE measure and dual-OBE measures based on the number of OBE needs to be monitored. Careful examination of the candidate safety measures was made based on their availability from the V2I communication data sets and the causal relationship to crashes. We used vehicles trapped in dilemma zone as the single-OBE measure. The dual-OBE measures included rear-end conflict and crossing conflict. The selected safety indicators addressed both potential crash frequency and crash severity. Due to the easiness of positioning, we only focused on the vehicles from the through movements and accordingly the recorded safety measures mainly accounted for rear-end and right-angle crashes. The OBE's temporary ID was used for identifying vehicles and we assumed that this ID did not change within vehicle's communications with RSE.

6.2.2. Simulation Evaluation

To evaluate the effectiveness of the V2I safety performance monitoring framework, the researchers first built a simulation test bed in VISSIM which enabled V2I communications via C2X module. The test bed features a fully actuated isolated high-speed intersection. Based on the test bed, we developed a basic scenario with optimal safety design. Then, we revised it to suboptimal settings by reducing the inter-green interval and removing the advance detectors. Each scenario was tested under low traffic volume level and medium-to-high volume level. The effectiveness of the framework is determined if the extracted measures can sensitively detect the safety deficiency.

As full market penetration may not be available in the near future, we investigated the effect of the market penetration rate on the performance of the proposed framework. Lower penetration rate indicates fewer safety measures being extracted from V2I communications and thus the variation of the collected data increases. This evaluation first examined the relationship between rates of the safety measures and the penetration rate. Afterwards, the researchers compared the rates of measures between different scenarios at each decreasing penetration level. An inconsistency from the 100% penetration level indicates the safety measure becomes invalid at this penetration level.

Moreover, we also examined the effect of observation periods on effective implementation of the framework. Particularly, we are interested in if longer observation period would be able to offset the need for higher market penetration and the different required observation period for specific measures to be effective. Coefficient of variation (CV) was utilized to measure the variability of the data. Firstly, we investigated the relationship between the CV of the rate of the safety measures and observation period. The equivalent observation time was computed for lower penetration level to achieve the same variability as the 100% penetration condition. The feasibility of extending observation period at low penetration rate to collect sufficient data is demonstrated if the equivalent observation period increases at decreasing penetration rate. Secondly, for each observation period, we averaged the CV over all penetration levels and compared different safety measures to see whether they were at the same level of variation. Those with larger variation require longer observation period to be effective.

6.2.3. Conclusion

From this simulation study, it is showed that:

- The proposed application can effectively monitor safety performance at signalized intersections using V2I communications data. Both single-OBE and dual-OBE measures sensitively detected the safety deficiency in suboptimal scenarios. In the low volume group, it can effectively detect a shift in crash pattern from rear-end crashes to right-angle crashes due to reduced stop duration from shortened inter-green intervals. Besides, it can capture the mitigation of this shift in the medium-to-high volume group where stop duration is mainly determined by the long queue accumulated during the red time. It can also detect the increase in both rear-end and right-angle crash risks due to the removal of advance detectors. Related safety indicators demonstrated the potential of providing a comprehensive safety evaluation which can quantify crash frequency and severity.

- More than 40% and 60% of the market penetration rate is required for effective monitoring for the low volume group and the medium-to-high volume group respectively during the 60 simulation hours. As the decease of the market penetration rate, the rate of single-OBE measure stayed almost the same while the rate of dual-OBE measures decreased linearly. In fact, single-OBE measure still worked well even at the 20% penetration rate for both volume groups. For the dual-OBE measures, crossing conflict first became ineffective at 40% penetration rate while rear-end conflict lost it power of detection at 20% penetration rate in the low volume group. The corresponding penetration thresholds at the medium-to-high volume group for these two measures are 60% and 40%.
- Longer observation period can be used to compensate for the need of higher penetration rate. Considering that traffic volume in simulation is fixed, the extended hours of simulation may only reflect one hour's operation in real world. Observation period was extended by increasing the observation frequency of a studied period. Increase of either observation period or market penetration rate will generate larger sample size for a reliable analysis. However, the marginal effect of increasing observation time decreases. Much more observation effort is expected to further improve the accuracy of the detection.
- Higher traffic volume does not necessarily guarantee smaller CV value. CV mainly relies on the size of the recorded safety measures. The varying traffic volume changed the signal timing of the signalized intersection, which led to even fewer crossing conflicts and vehicles trapped in dilemma zone being collected at higher traffic volume.
- Observation period for different safety measures varies. At given penetration level, safety measures which occur less frequently and are more computationally intensive will require longer observation period to be effective. For all operation scenarios, crossing conflict needed the longest observation period to provide a reliable detection among the examined safety measures.

It is anticipated the safety performance monitoring framework can be integrated as a separate module hosted in the RSE. High-resolution vehicle kinematics, signal status as well as signalized intersection geometric data can also be automatically collected along with the proposed safety measures. All recorded data is supposed to be transmitted to the specified database in the back office server, which connects the RSEs in the local network. Evaluation of the safety performance of the signalized intersection can be conducted by post-analyzing the collected safety measures. With some level of penetration in the near future, states or cities of interest can implement the proposed application for several weeks or even days rather than have to wait for years to collect enough crash data for an in-depth safety performance evaluation at signalized intersections.

6.3. Limitations and Future Research

Simulation in VISSIM cannot model the driving behaviors changes under different traffic conditions which actually happen in real world operations. It is possible that drivers learn to be more careful to potential skipping of left-turning phase when they get familiar to the signalized intersection operations.

The key of the proposed framework is to define appropriate safety measures to quantify the safety performance of the signalized intersection. Safety measures which can appropriately quantify safety performance, require less computational effort and robust to market penetration are preferred. In this sense, single-OBE measures are more appealing and require further investigation. Variation of the speed, for instance, may be introduced to the measure the safety performance of the signalized intersection. The variation of speed for equipped vehicles could be computed for homogeneous segments of the different approaches at each time step. Larger variation may indicate degrading safety performance.

Considering this study is limited to through movements, we also plan to incorporate turning movements in the current framework. Safety performance of left-turning movement, for instance, is a focus for the safety studies of signalized intersection. The basic idea for safety performance monitoring at turning movements is the same except that additional rules need to be developed to accurately compute the relative distance/ direction of targeted vehicles (on the curve) from V2I communications data sets. Similarly in concept, the framework can also be easily expanded to other facilities such as freeway and work zones.

The integration of V2V communications will also be a task for future study. A complete state-of-art safety performance monitoring framework should include both V2I communications and V2V communications. V2V communications will be more efficient in extracting dual-OBE measures. The complicated matching and searching process of finding targeted vehicle pairs could then be substituted by communications directly between each vehicle pair.

Lastly, a highly integrated system which includes wireless transmission of advisory/warning information upon the detected hazard events should also be developed based on the proposed safety performance monitoring framework. Extensive researches will be conducted on when and how to send appropriate messages to effectively warn the drivers of potential crash risks. A systematic approach of selecting thresholds for different safety measures as well as analysis on the drivers' reaction to the warning information is of particular importance.

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