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Liteng Zha, Praprut Songchitruksa, and Kevin N. Balke


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16. Abstract

Crash-based safety evaluation is often hampered by randomness, lack of timeliness, and rarity of crash occurrences. This is particularly the case for technology-driven safety improvement projects that are frequently updated or replaced by newer ones before it is possible to gather adequate crash data for a reliable and defensible before-after evaluation. Surrogate safety data are commonly used as an alternative to crash data; however, its current practice is still resource intensive and subject to human errors. The advent of connected vehicle technology allows vehicles to communicate with each other and infrastructure wirelessly. This platform also offers the opportunity for automated and continuous tracking of vehicle trajectories and signal status at the facilities in real time. These types of data can potentially be extracted and used to detect the deficiencies in the safety performance of the facility operation.

This project examines the viability of long-term monitoring of connected vehicle data for safety performance evaluation. As limited saturation of onboard equipment (OBE) is expected in the near-term evolution, the study focuses on a connected vehicle application that can process data elements from OBEs via vehicle-to-infrastructure communications using standard message sets. To accomplish the objective, a signalized intersection test bed was created in VISSIM while the wireless communications capability and the application were implemented using Car-to-Everything Application Programming Interface. The evaluation results indicated that the application can effectively detect changes in safety performance at full market penetration. Sensitivity analysis showed that at least 40 percent penetration rate is desirable for reliable safety deficiency detection under light to moderate traffic volume conditions. The observation period can be extended to compensate for low sample size under low OBE market penetrations. The required observation periods vary with the types of safety indicators being collected and the levels of OBE saturation.



17. Key Words

Connected Vehicles, Traffic Simulation, Safety Evaluation, Surrogate Safety Measures, Wireless Communications, Traffic Conflicts, Market Penetration


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


Liteng Zha
Graduate Research Assistant

Praprut Songchitruksa, Ph.D., P.E.
Associate Research Engineer

Kevin N. Balke, Ph.D., P.E.
Research Engineer



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## DISCLAIMER



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# EXECUTIVE SUMMARY


Safety performance at signalized intersections is an outcome of complex interactions among several contributing factors such as signal operations, geometric design, drivers' behavior, and vehicular performance. Crash-based safety evaluation is known to be hampered by randomness, lack of timeliness, and rarity of crash occurrences. Surrogate safety evaluation is commonly used as an alternative to a crash-based approach; however, its current practice is still resource intensive and subject to human errors. The advent of connected vehicle technology allows vehicles to communicate with each other and infrastructure wirelessly. This platform also offers the opportunity for automated and continuous tracking of vehicle trajectories and signal status at the facilities in real time. These types of data can potentially be extracted and used to detect the deficiencies in the safety performance of the facility operation.

This study proposes a novel connected application whereby vehicle-to-infrastructure communications (V2I) data at signalized intersections are monitored and extracted for the purpose of safety performance evaluation. The application is expected to reside within the roadside equipment (RSE) environment and does not require high market penetration of onboard equipment (OBE). This study focuses on the through movements at signalized intersections due to their relatively well-defined vehicle trajectories. The OBE's temporary identification was used to track individual vehicles. It is assumed that the temporary IDs of the OBEs remain the same throughout its communication with the RSE.

In the proposed framework, the eligible safety measures must have causal relationships with rear-end and right-angle crashes and can be extracted from existing V2I communication standard message sets. The selected safety measures were categorized into single-OBE measures (e.g., rates of vehicles trapped in the dilemma zone) and dual-OBE measures (e.g., time-to-collision) based on the number of OBEs required for computation of safety measures.

To evaluate the effectiveness of the application, the researchers developed a simulation test bed using VISSIM. The test bed uses the Car-to-Everything (C2X) Application Programming Interface (API) to model V2I wireless communications and implement the proposed application at the signalized intersection. The baseline scenario features an optimal signal timing parameters and dilemma zone detectors given the operating characteristics of the intersection. In the comparison scenarios, several suboptimal designs were intentionally introduced to the test bed to evaluate the effectiveness of the proposed framework in detecting any safety deficiency. These comparison scenarios include shortened yellow time and removal of dilemma zone protection. The evaluation also includes the sensitivity analysis of the detection of traffic volume patterns, the levels of OBE market penetration, and the duration of the observation periods. The evaluation results reveal the following:

- The application can effectively and rapidly detect the changes in safety measures at signalized intersections using V2I data under full market penetration of OBEs. The application can detect the migration of crash patterns such as the shift from rear-end to right-angle crashes when the inter-green period was shortened.
- The sample size of target safety measures generally increases with the traffic volume levels. Under light to moderate traffic conditions ($v/c < 0.5$), at least 40 percent market

penetration is desired for monitoring of dual-OBE measures. Single-OBE measures have relatively lower requirement at 20 percent market penetration.

- In some cases where desirable OBE market penetration levels cannot be achieved, a longer observation period can be used to compensate for the need of a higher penetration rate. Longer observation period translates to an increase in opportunity for collecting safety measures. Researchers measured the reliability of a safety measure using a coefficient of variation (CV) value. A CV can be reduced if the market penetration and/or observation period is increased. However, there is a diminishing return effect as the observation period increases. This implies that one unit of reduction at relatively low CV conditions would require a much longer observation time to achieve the same level of reduction at high CV conditions.
- Desirable observation periods vary with the types of safety measures to be collected. Safety measures that are less frequent and require dual OBEs will require longer observation periods to be effective. Longer observation time is required for collecting sufficient sample size. The crossing conflicts require the longest observation period to be reliably detected among all the examined safety measures.

The proposed safety performance monitoring application can be integrated into any connected-vehicle instrumented signalized intersections. High-resolution vehicle trajectory, signal status, and intersection geometric data can also be automatically captured within standard message sets to provide continuous safety monitoring. As connected vehicle adoption evolves in the near future, interested states or cities can implement the monitoring 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.

# 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 their early stages and mostly developed as stand-alone add-on systems instead of integrated intelligent transportation systems (ITS) solutions.

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; they may also take control of the signal controller to mitigate crash risks. Many of these safety applications require vehicle-to-vehicle (V2V) communications and high saturation of onboard 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 a safety performance monitoring capability. This study investigated the capability to mine vehicle movement, intersection description, and signal status data available at the RSE for 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 can be potentially mined for information to indicate the safety performance of the signal operation.

## 1.2 RESEARCH TASKS

This study proposed and evaluated a framework for continuously monitoring the safety performance of signalized intersections via V2I communications. The researchers conducted the following tasks to achieve this goal:

- Defined useful safety measures that can comprehensively represent the safety performance of the signalized intersection operation.
- Designed specific algorithms to derive the proposed safety measures by integrating and synchronizing the recorded vehicles' kinematics data, geometric data of intersection, and signal phases.

- Developed the simulation test bed that can operate at both optimal and degraded safety performance.
- Evaluated and compared the measurement effectiveness of detecting intersection operation safety deficiency between simulation scenarios.
- Investigated the effect of market penetration on effectiveness of the framework through sensitivity analysis.
- Examined 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 that may complicate the procedures for processing safety measures of interest. To simplify the development, researchers assumed that the temporary IDs of the OBEs remain the same throughout its communication with the RSE in this study. The proof-of-concept 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 chapters:

- Chapter 1 presents a brief overview, research objectives, and scope of this study.
- Chapter 2 summarizes the related literature in connected vehicle technology, safety applications, and surrogate safety measures.
- Chapter 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.
- Chapter 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.
- Chapter 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 and the required observation period for the framework to be successful.
- Chapter 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 or driver warnings have gone through concept development to field demonstrations via V2V and V2I communications. However, none of the applications developed to date have used connected vehicle data for long-term safety performance monitoring. While numerous studies have examined surrogate safety measures for safety performance assessment at signalized intersections, the 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 chapter provides a literature review related to recent research on connected vehicle frameworks, existing safety applications, and surrogate safety studies at signalized intersections.

## 2.1 CONNECTED VEHICLE TECHNOLOGY

### 2.1.1 Background

The history of connected vehicles can be traced back to 2003 when the U.S. Department of Transportation 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 V2V and 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 and environment. The real-time data captured in the connected vehicle framework provides valuable information for transportation managers to optimize the performance of transportation. Travelers 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 since IntelliDrive[SM] had been trademarked before its wireless communications application in the ITS. Despite the name change, its vision and focus remain the same (*2*).

### 2.1.2 Elements of Connected Vehicle

The connected vehicle framework relies on three critical elements, which are OBE, RSE, and back-office servers (*3*).

- OBE consists of devices embedded in the vehicle that support DSRC with nearby vehicles and 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 consists of roadside devices that support DSRC with nearby OBE-equipped vehicles within the communications distance, other RSEs, and 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 is a particular channel for connected vehicle applications. Liu et al. summarized the history background of the 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), and 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 that use 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 was 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 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 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. |

## 2.2 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.

### 2.2.1 Prototype Test Bed

Initially two prototype test beds were developed in the U.S., one in Michigan and the other in California (*7; 8*). The test bed in Michigan includes 57 RSEs and 25 vehicles equipped with OBEs. The test bed covers a 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, including Virginia, Florida, Arizona, and New York, are also building their test beds for connected vehicles (*10*).

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

### 2.2.2 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 example, VISSIM with NCTUns or PARAMICS with NS-2 to build a connected vehicle simulation test bed (*8; 12*). However, additional interfaces have to be added to connect both simulators 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, which integrates both the traffic simulator and wireless communications simulator in one module, sounds more appealing (*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.

## 2.3 CONNECTED VEHICLE SAFETY APPLICATIONS

The report from Wassim et al. showed the percentage of crashes that could be addressed by a 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 percent 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, and intersection collision warning. This counts for 26 percent of total crashes. A combination of V2I and V2V would address 81 percent of the total crashes.

### 2.3.1 Safety Application via V2V Communications

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

### 2.3.2 Safety Application via 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; thus also advancing the deployment of V2V. 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*).

### 2.3.3 Issues Related to V2V and V2I Safety Applications

#### *2.3.3.1 Communications Delay and Communications Success Rate*

Communications delay and communications success rate are critical elements for building robust V2V and V2I communications systems. Potential factors that 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 a 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 the P2P condition, which lead to a reduction on communications delay.

*2.3.3.2 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, 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*).

## 2.4 SURROGATE SAFETY MEASUREMENTS AT SIGNALIZED INTERSECTIONS

The 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 are more frequent than crashes. Rear-end and right-angle crashes are typically the most common 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.

### 2.4.1 Traffic Conflict Technique

The definition of conflict is "*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 traditionally relies on post-processing of video recordings, which involves human subjectivity in extracting conflict data and is criticized for a prohibitive cost for data reduction efforts. Some analysts have resorted to the use of surrogate safety data 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 the 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, lower PET, or higher DR values indicates a 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 the higher value of the listed indicators, the higher energy the collision would have. This indicates a 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 Table 20 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 their applicable conditions.

### 2.4.2 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 and clearing distances ( $X_s$ and $X_c$ , respectively) of a vehicle are calculated using the following equations to determine the location of dilemma zone.

$$X_c = v_0\tau + \frac{1}{2}a_1^*(\tau-\delta)^2 - (w+L) \qquad (0)$$

$$X_s = v_0\delta + \frac{{v_0}^2}{2a_2^*} \qquad (0)$$

where
$\tau$ = Yellow duration (*sec*).
$\delta$ = 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/s²*) (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, and 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 percent to 90 percent 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. 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 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*).

## 2.5 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., $15^{th}$ –$85^{th}$ 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 a 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 a 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**Error! Reference source not found.**, and more details can be found in the Traffic Signal Operation Handbook (*35*).

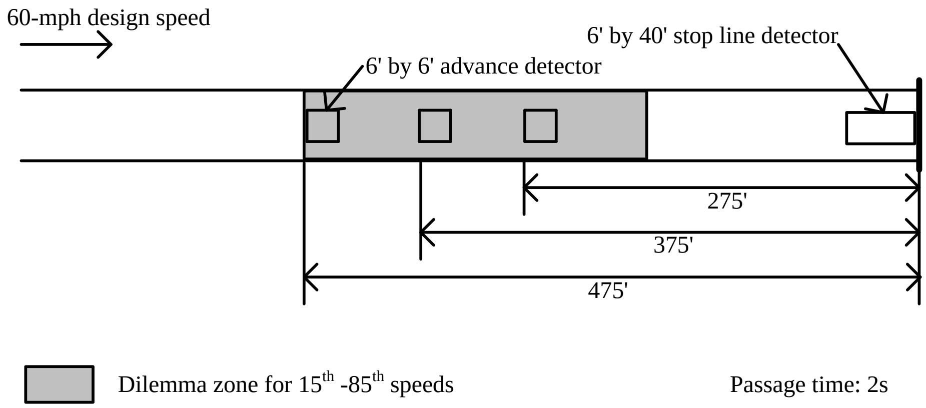



**Figure 1. Multiple Advance Detector System.**

**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 |

The operation for the stop line detector (if it exists) is in a deactivated mode, 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.

Although commonly used in real-world practice, mainly two limitations are associated with the multiple advance detector system. First, it can only provide dilemma zone protection for a portion of the vehicles. Protection will be given to 70 percent of the vehicles if the system is designed for the $15^{th}$–$85^{th}$ speed range. Green extension may not be provided to vehicles trapped in dilemma zone traveling faster than the $85^{th}$ percentile speed, since they are yet to reach the most upstream detector while the phase may gap out before the vehicles with speeds lower than $15^{th}$ percentile speed reaching the nearest detectors downstream. Second, 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 an 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 a certain proper moment before max-out (*29; 31*). These green termination systems have been demonstrated to improve the both efficiency and safety for signalized intersection operations.

# 3 SAFETY 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 chapter first proposed the safety indicators that are related to rear-end and right-angle crashes for quantifying the safety performance at signalized intersections. Then, researchers 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, this chapter explains 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 the information of that single equipped vehicle (current speed and distance to the stop bar) is needed. Number of vehicles 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 TTC, which serves as the threshold of traffic conflict. 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. The 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 defines the vehicles being trapped in the dilemma zone as the speed and location of vehicles available from BSMs that 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 risks and is often used to define the risk related to signal operation at high-speed signalized intersections (*30*). Since the 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 a 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 a deceleration rate updated to the maximum one. This process continues until the moment the deceleration rate drops below the threshold. Literature has confirmed the use 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 the resulting crash could be more severe. 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 does not trigger a MaxD-based event. This preliminary investigation of MaxD events in a simulation also showed mixed results as a potential indicator for unsafe scenarios. Therefore, it is excluded from 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 that signifies the collision risk of the conflict event.

For crossing conflict, 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 a higher probability of crash. Zero or negative PETs indicate real crash occurrences. In contrast, projected measures such as TTCs cannot be computed and are 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, researchers used TTC to measure the severity of the conflict events (both rear-end and crossing conflicts), and PETs were also computed for crossing conflicts. Smaller TTCs and PETs indicate more proximity of a conflict event to a crash and therefore can serve as a measurement of risk of getting involved in a crash.

To complete the framework for the safety evaluation, researchers initially considered speed related and deceleration related indicators for measuring the magnitude of the resulting crashes. Researchers used DeltaS as the speed related severity indicator. Two deceleration related indicators considered in this study were MaxD and RBR. Their definitions are given as follows:

- DeltaS: Difference in vehicle speeds at the moment when minimum TTC is observed (*22*).
- MaxD: Maximum deceleration of the second vehicle, recorded as the minimum instantaneous acceleration rate observed during the conflict (*22*).
- 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 what was 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, the preliminary examination showed 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. 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 prevented researchers 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, researchers 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 TTC.
  - Frequency of crossing conflicts based on 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, researchers defined the following severity indicators along with the dual-OBE measures to provide a comprehensive safety evaluation of signalized intersection operations:

- Minimum TTC.
- PET (only for crossing conflicts).
- 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.

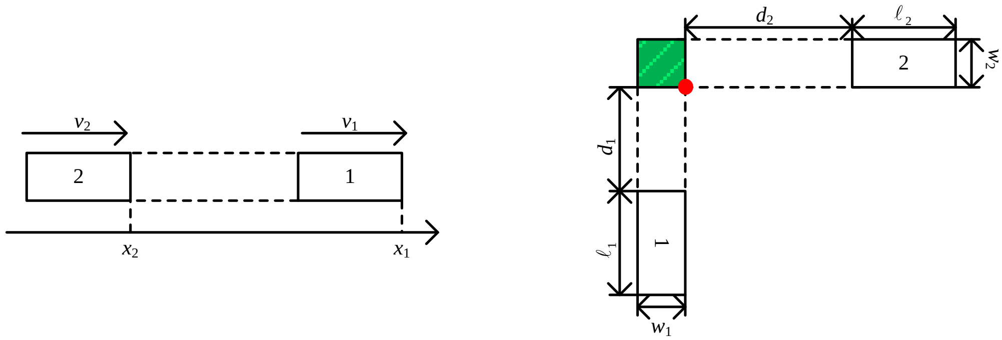
## 3.2 COMPUTATION FOR TTC AND PET

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 the definition of TTC is the same for both rear-end and crossing conflicts, 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, researchers treated it as a rear-end conflict as long as two consecutive vehicles remained at the same movement at the moment minimum TTC is monitored.

Unlike rear-end conflict, crossing conflict can only occur at a certain fixed area. Researchers 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 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 available in the MAP data. Equations (0) and (0) 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*).

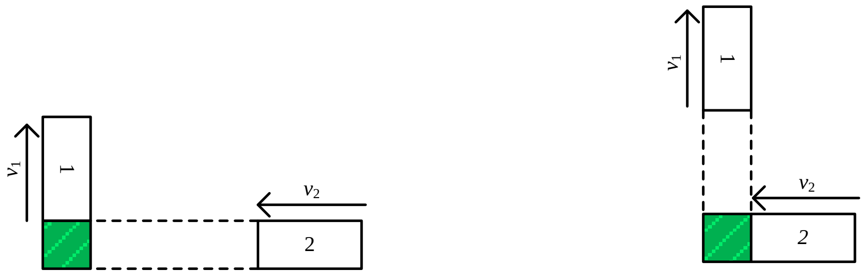
PET is exclusively computed for crossing conflict due to the well-defined conflict zone and conflict point. It is the elapsed time from the moment an encroaching vehicle leaves and an approaching vehicle arrives at the conflicting area. Calculation of PET is straightforward and given in Equation (0).




(a) Rear-End Conflict

(b) Crossing Conflict

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




(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. Computing of PET.**

$$\text{Rear-End TTC} = \frac{x_1 - x_2 - \ell_1}{v_2 - v_1}, if \ v_2 > v_1 \qquad (0)$$

$$\text{Crossing TTC} = \begin{cases} \dfrac{d_2}{v_2}, if \ \dfrac{d_1}{v_1} < \dfrac{d_2}{v_2} < \dfrac{d_1 + \ell_1 + w_2}{v_1} \\ \dfrac{d_1}{v_1}, if \ \dfrac{d_2}{v_2} < \dfrac{d_1}{v_1} < \dfrac{d_2 + \ell_2 + w_1}{v_2} \end{cases} \qquad (0)$$

$$PET = t_2 - t_1 \qquad (0)$$

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*.

$\ell_1$ = Length of vehicle 1, *ft*.

$\ell_2$ = 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. Researchers 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, researchers first categorized these raw data into customized databases. Then, the task of extracting safety indicators became mining the corresponding databases.

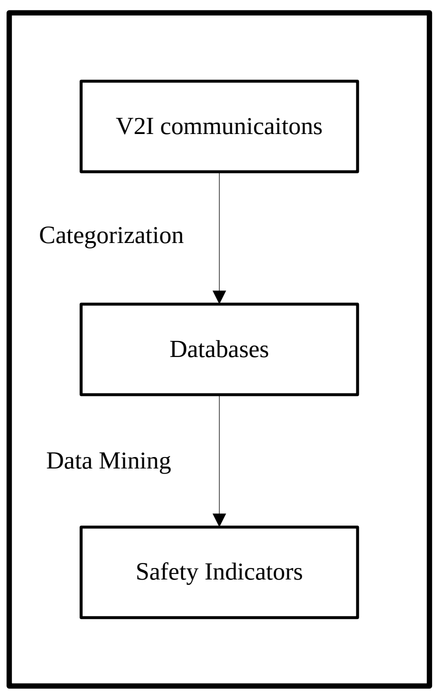



**Figure 4. Algorithm Logic.**

### 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.

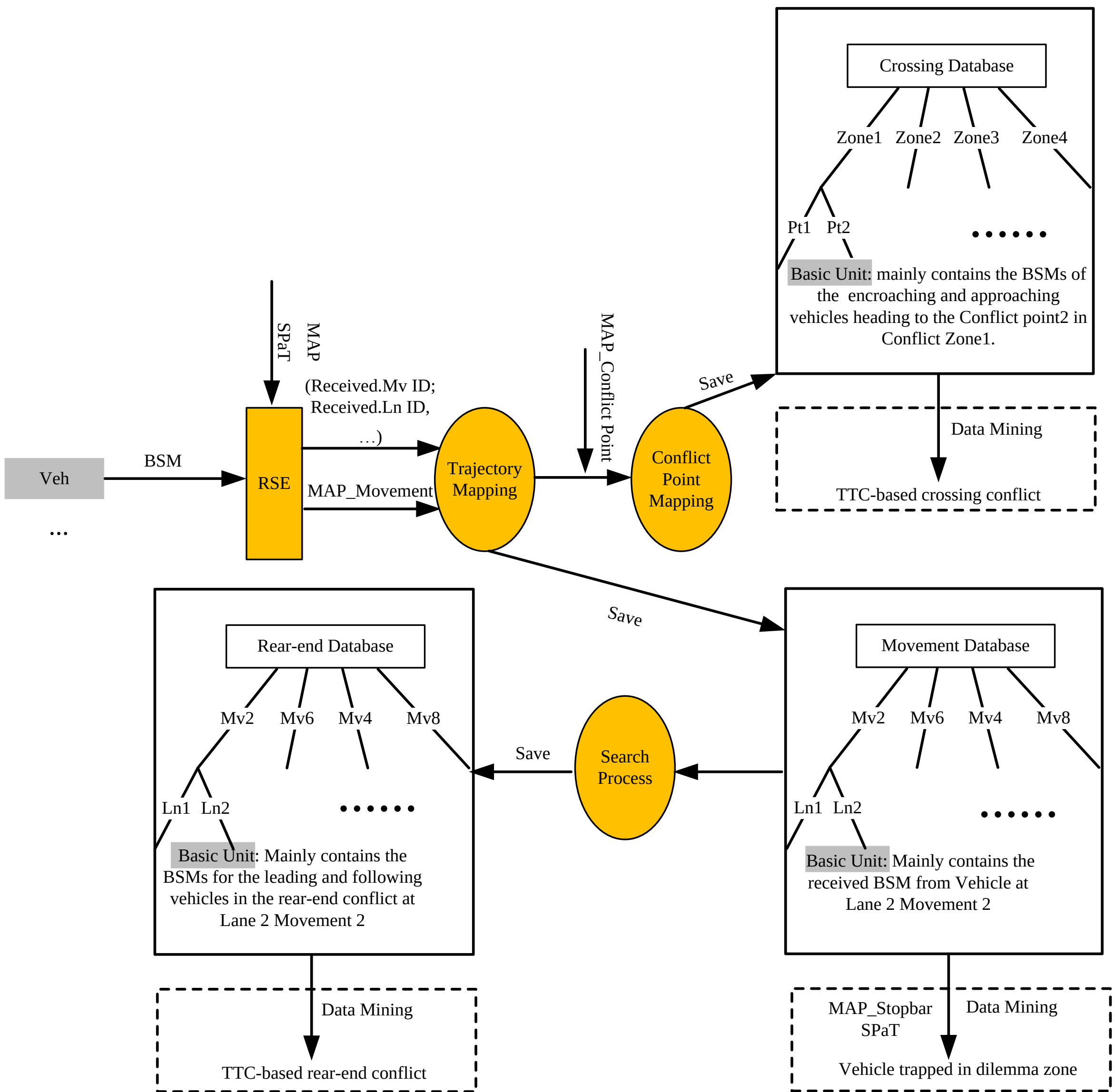



**Figure 5. Overview of Algorithm for Extracting Safety Indicators.**

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 intervals in real-world applications of connected vehicles. To simply the process of extracting and evaluating safety indicators, researchers assumed that the temporary ID of the OBE will not change during its communication with the RSE.

Figure 5 shows an overview of the algorithm of building these databases. 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 the vehicle trapped in the 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 toward 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, researchers 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. Figure 6 shows the detailed algorithm flowchart for extraction. 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 (0). Vehicles' location, length, and speed could be obtained from the basic unit of the Rear-End Database. Figure 7 depicts the detailed algorithm for extracting safety indicators at rear-end conflict. 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.

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 (0). 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.

Unlike three databases that 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.

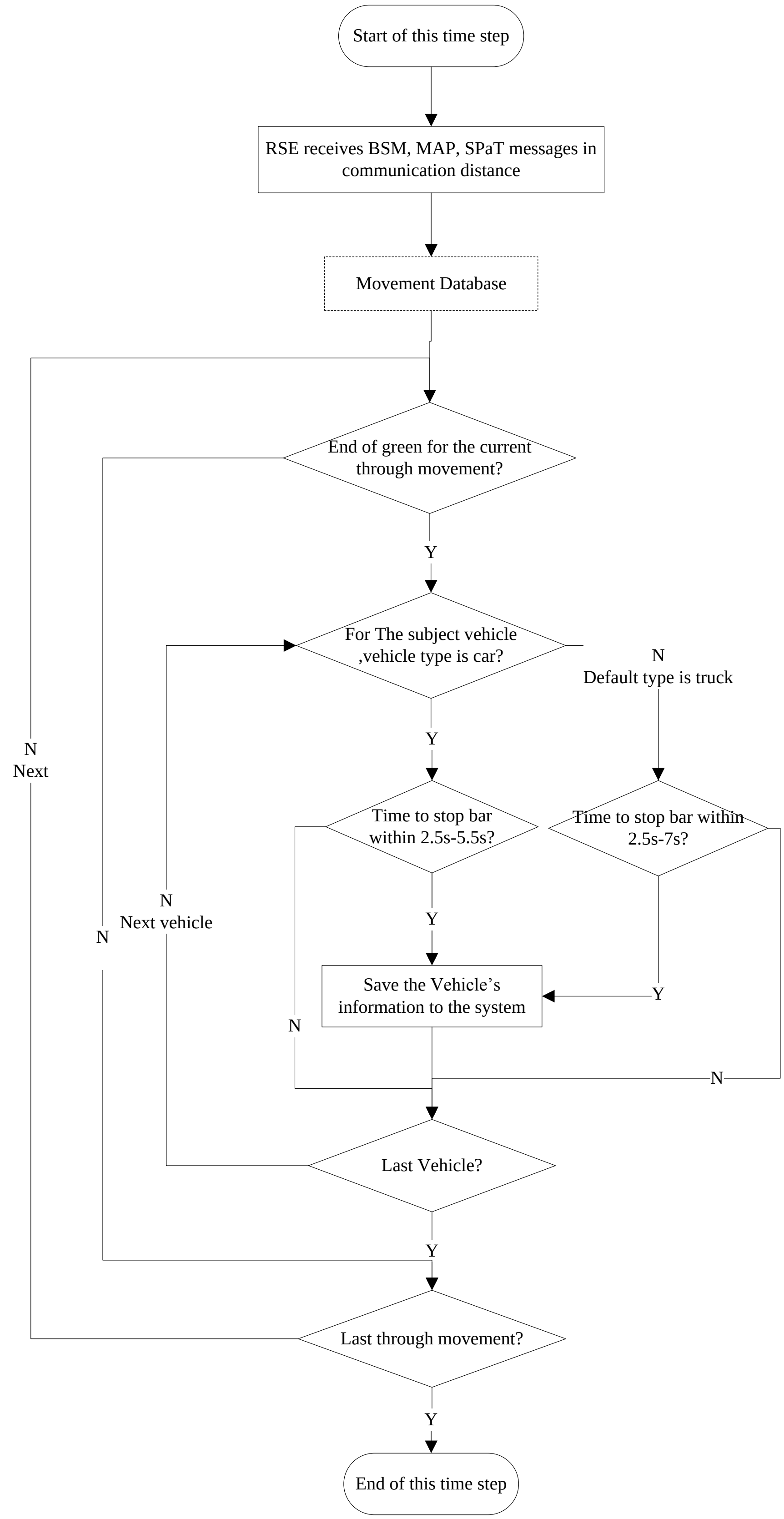



**Figure 6. Algorithm for Extracting Vehicles Trapped in Dilemma Zone.**

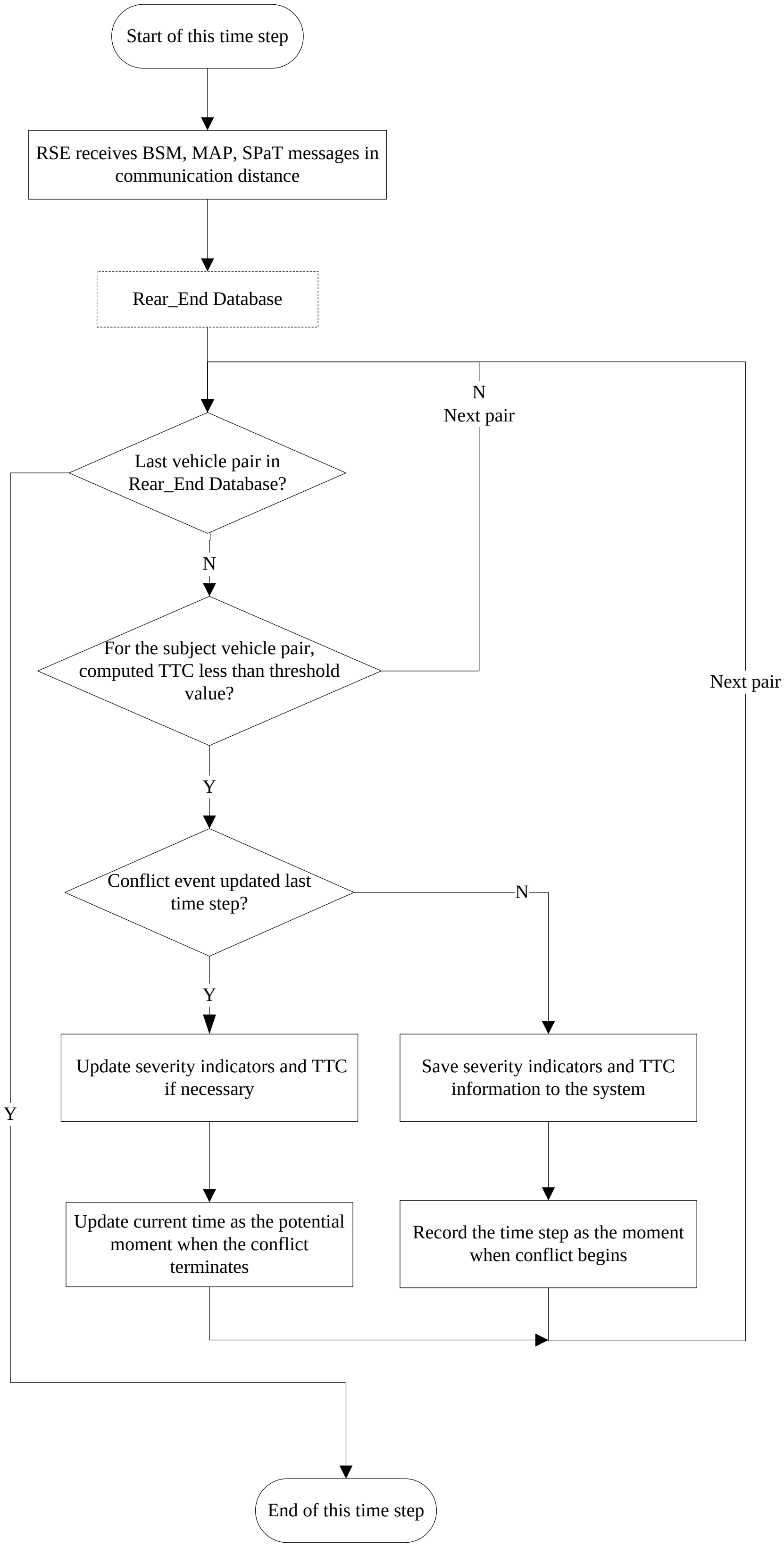



**Figure 7. Algorithm for Extracting Rear-End Conflict.**

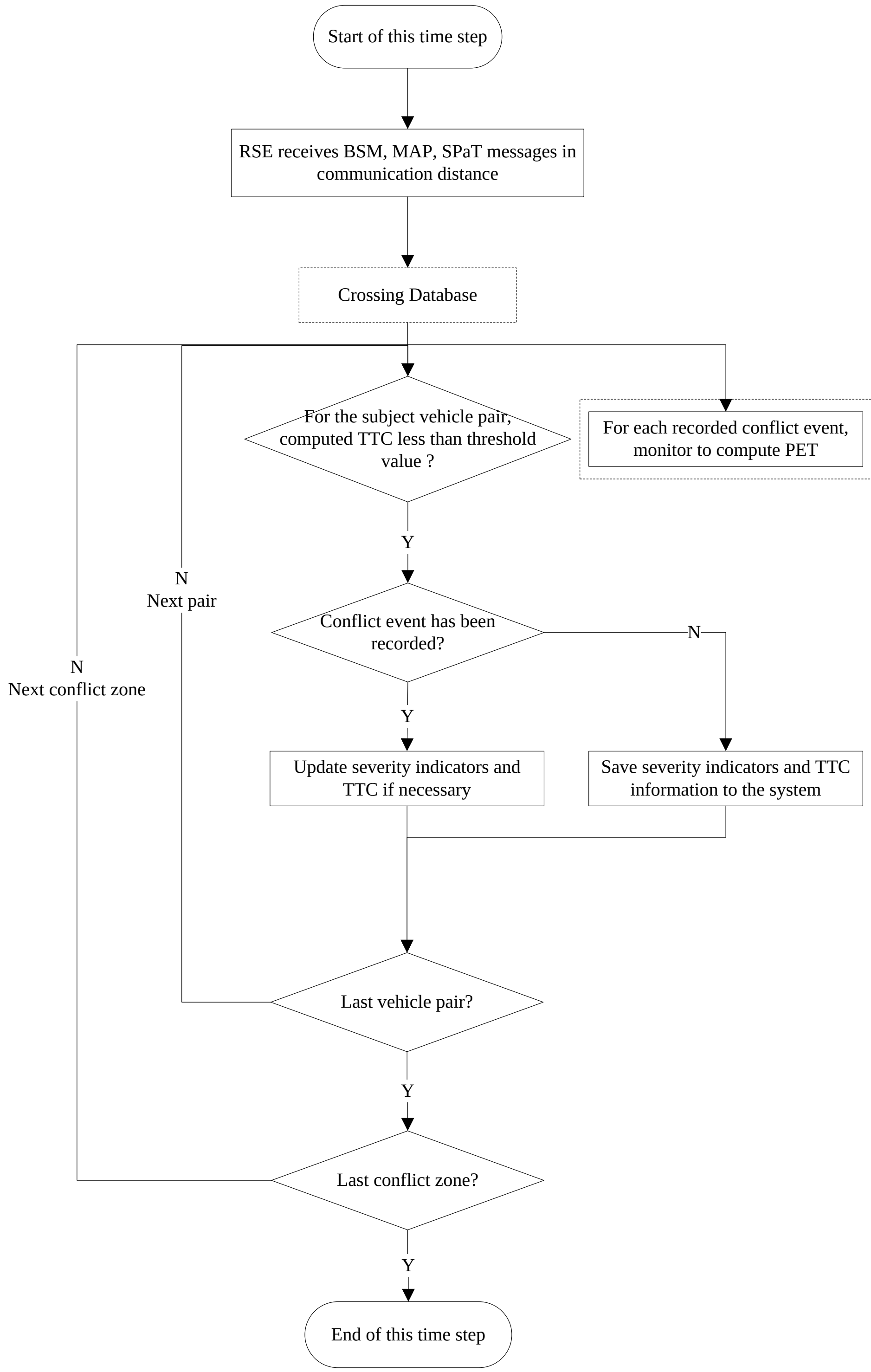



**Figure 8. Algorithm for Extracting Crossing Conflict.**

# 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 uses VISSIM microscopic simulation because of the researchers' extensive experience with the software. First, researchers developed a signalized intersection test bed in VISSIM designed with optimal signal timings and proper dilemma zone protection. Then, researchers 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. Last, researchers changed the distribution of volume input of one scenario to investigate whether the spatial distribution of the safety measures could sensitively reflect this variation.

In a real-world application, market penetration rate and observation period are likely to affect the performance of the proposed framework. 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

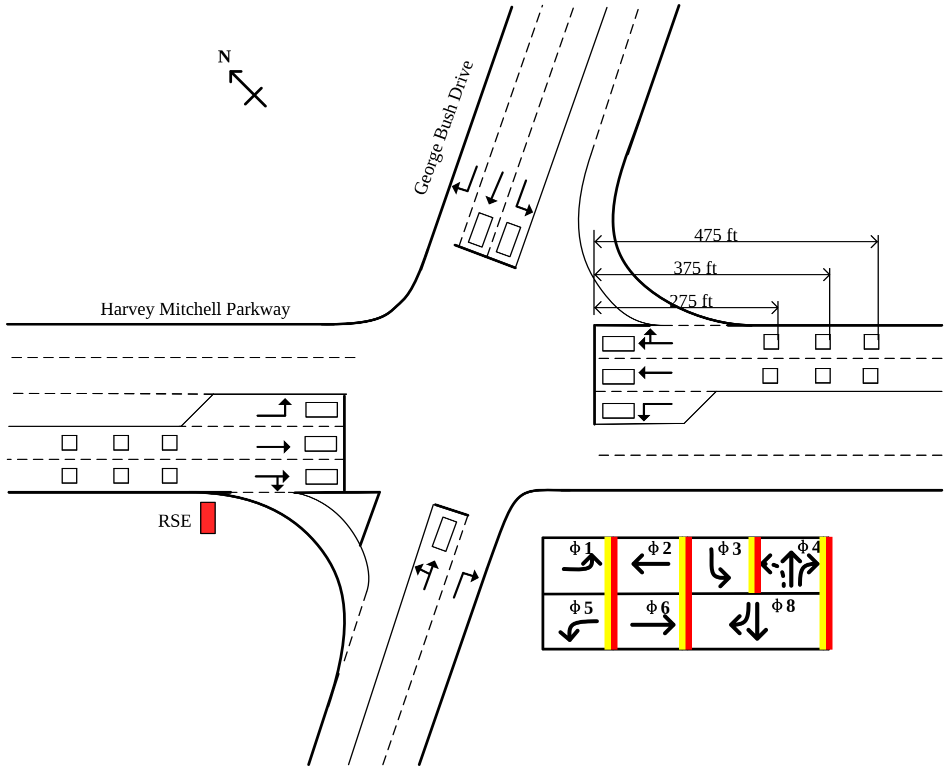
### 4.1.1 V2I Communications Simulation

The vehicle-to-infrastructure wireless communications were developed using VISSIM Car-to-Everything (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 the traffic flow module VISSIM and packet transmission module VCOM (*37*).

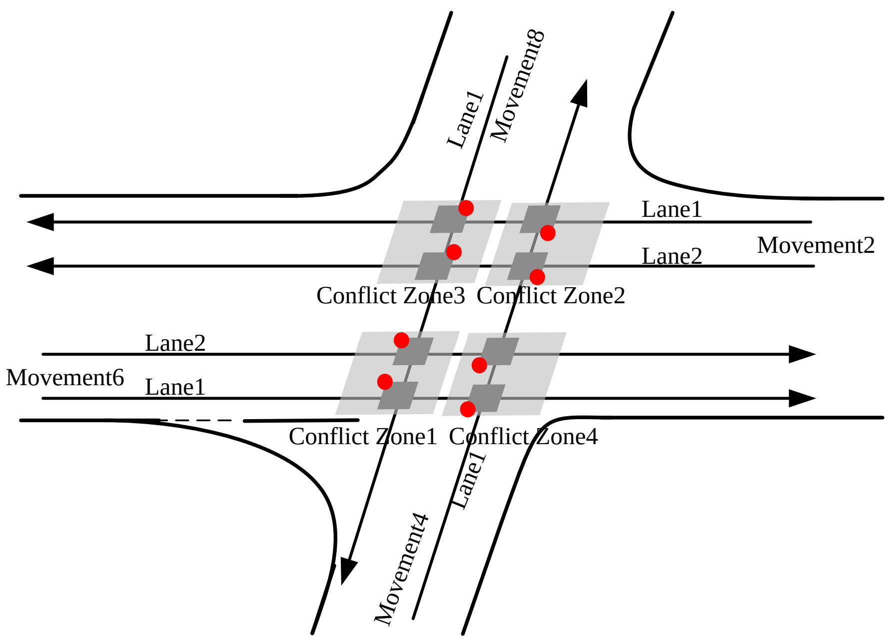
The codes required for C2X were written in Python. Simulation time step was set as 0.1 simulation seconds, which is equivalent to the frequency of 10 Hz for BSM transmission. The C2X module already integrates the wireless communication model, enabling the effect of communication delay and the wireless 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

Figure 9a shows the intersection layout and phase sequence. The studied intersection is located at George Bush Drive and Harvey Mitchell Parkway in College Station, Texas. Figure 9b 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.




(a) Intersection Layout and Signal Phasing.




(b) Conflict Observation Regions.

**Figure 9. Signalized Intersection Test Bed.**

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*). Researchers 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.

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

- Safety measures are extracted within the center intersection area and segments 650 ft from the stop bar for each approach to better reflect the effect of signalized intersection operations, although the 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. The last scenario changed the distribution of the volume input based on one suboptimal scenario. 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

Table 3 shows the volume levels, 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. Parameters for Baseline Scenario.**

| **Traffic Volume** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase Number | 1 | 2 | | 3 | 4 | | | 5 | 6 | | 8 | |
| Lane Type | LT | TH | RT | LT | LT | TH | RT | LT | TH | RT | TH | RT |
| Volume (*veh/hr*)[1] | 60 | 480 | 60 | 30 | 6 | 285 | 9 | 60 | 480 | 60 | 240 | 30 |
| **Signal Timing Setting** | | | | | | | | | | | | |
| Minimum Green (*s*) | 5 | 5 | | 5 | 5 | | | 5 | 5 | | 5 | |
| Maximum Green (*s*) | 20 | 50 | | 15 | 40 | | | 20 | 50 | | 60 | |
| Yellow Time (*s*)[2] | 4.3 | 5 | | 3.6 | 4.7 | | | 4.3 | 5 | | 4.7 | |
| All Red (*s*)[3] | 1.6 | 1.4 | | 1.5 | 1.6 | | | 1.5 | 1.5 | | 1.6 | |
| **Detector Setting** | | | | | | | | | | | | |
| Advance Detector | No | Yes | | No | Yes | | | No | Yes | | Yes | |
| Stop Bar Detector[4] | Yes | Yes | | Yes | Yes | | | Yes | Yes | | Yes | |
| Passage Time (*s*) | 2 | 2 | | 2 | 2 | | | 2 | 2 | | 2 | |

Notes:

1. Vehicle composition is 90% cars and 10% trucks.
2. 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.
3. 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).
4. 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 (*32; 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.

### 4.2.4 Simulation Scenario 3: Unbalanced Flow Input

This scenario modifies the volume pattern in Scenario 2 from balanced to unbalanced traffic flow patterns. This scenario will be used to determine if the patterns of detected safety indicators are sensitive to changes in volume patterns. Modified volume input for each movement is provided in Table 4**Error! Reference source not found.**. Basically, 30 percent increase and decrease of traffic volume is seen at Movements 1 and 6 and Movements 2 and 5, respectively. Traffic volume from Movement 8 increases to 270 veh/hr while that from Movement 4 reduces to 180 veh/hr.

**Table 4. Traffic Volume Input for Scenario 2 and Scenario 3.**

| Phase Number | 1 | 2 | | 3 | 4 | | | 5 | 6 | | 8 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lane Type | LT | TH | RT | LT | LT | TH | RT | LT | TH | RT | TH | RT |
| **Traffic Volume (Scenario 2)** | | | | | | | | | | | | |
| Volume (*veh/hr*)[1] | 60 | 480 | 60 | 30 | 6 | 285 | 9 | 60 | 480 | 60 | 240 | 30 |
| **Traffic Volume (Scenario 3)** | | | | | | | | | | | | |
| Volume (*veh/hr*)[1] | 78 | 336 | 42 | 60 | 30 | 180 | 30 | 42 | 624 | 78 | 270 | 30 |

Notes: Vehicle composition is 90% cars and 10% trucks.

## 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.

### 4.3.1 Validation of the Safety Performance Monitoring Framework

This analysis determined if the collected data from connected vehicles can be used to detect changes in safety performance based on the proposed safety indicators. The ground truth analysis was based on 100 percent 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 expectations (i.e., the modified operation should be less safe and the collected safety indicators should reflect those changes with statistical significance). In addition, the researchers also analyzed the spatial distribution of the safety measures in Scenarios 2 and 3 (balanced versus unbalanced volume patterns). It is anticipated that the unbalanced volume patterns would produce spatial variations of detected measures. Conflict zones that are associated with relatively higher conflicting volumes should experience higher rates of detected safety measures.

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 a 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

This analysis evaluated 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 examined the relationship between the rates of the safety measures and penetration rate. Market penetration rate was decreased from 100 percent to 20 percent with a 20 percent decreasing interval. The results at 100 percent 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 percent penetration level indicates the safety measure becomes invalid at this penetration level. In other words, a higher penetration rate is required for the effectiveness of this measure.

### 4.3.3 Effect of Observation Period

This analysis examined the effect of observation periods on effective implementation of the framework. Particularly, researchers investigated the required observation period for specific safety indicators to be effective and the feasibility of extending observation period at a lower penetration level to obtain sufficient data. First, researchers 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 a lower penetration level to achieve the same variability as the 100 percent penetration condition. The feasibility of extending the observation period at a low penetration rate to collect sufficient data is demonstrated if the equivalent observation period increases at a decreasing penetration rate. Second, for each observation period, researchers computed the average variation over all penetration levels and compared the different safety measures to see whether they were at the same level of variation. Measures with larger variation require longer observation periods to be effective.

# 5 SIMULATION RESULTS AND DISCUSSIONS

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

## 5.1 DETECTING CHANGES IN SAFETY PERFORMANCE

This analysis determined if the collected data from connected vehicles can be used to detect changes in safety performance. Safety performance is measured by the risk of crashes. The analysis was based on 100 percent 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 expectations. Indicators addressing potential crash severities were 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, preliminary tests indicated that the 1.5 s threshold is likely to capture a 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 percent percentile of the collected TTC value (1.24 s) 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 summarizes the frequencies of observed safety indicators, number of vehicles, and number of cycles from the 60-hour simulation period. The operation settings for Scenario 2 and Scenario 3 were the same except for the distribution of traffic input. Both scenarios have similar simulation results on the aggregate level. Scenario 2 and Scenario 3 have 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 increased the number of cycles given the same simulation period. For Scenarios 2 and 3, 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 four scenarios are very close since the total volume in the simulation was set the same.

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 cycles and objective volume were used to normalized the frequencies of vehicles trapped in the dilemma zone and crossing conflicts (*39*). Researchers 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. Researchers assume that the OBE's temporary ID will not change within its communications with RSE, and the collected OBE volume is equal to the volume of equipped vehicles.

Researchers 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*). The comparison test is appropriate even when the sample size is relative small. The equation for the test is written as:

$$Z = \frac{(\frac{A+0.5}{E_A} - \frac{B-0.5}{E_B})}{\sqrt{\frac{A+B}{(E_A+E_B)E_A} + \frac{A+B}{(E_A+E_B)E_B}}} \qquad (0)$$

where

A = Total count in the after period.
B = Total count in the before period.
$E_A$ = Exposure in the after period.
$E_B$ = exposure in the before period.

The difference is considered statistically significant at 95 percent confidence level if *z* value is not within [−1.96, 1.96].

**Table 5. Summary of Simulation Results.**

| **Measures** | **Baseline** | **Scenario 1** | **Scenario 2** | **Scenario 3** |
|---|---|---|---|---|
| TTC-Based Rear-End Conflicts | 2487 | 1850 | 2074 | 2053 |
| Number of Vehicles Trapped in Dilemma Zone | 2674 | 3196 | 10,406 | 9619 |
| TTC-Based Crossing Conflicts | 9 | 62 | 82 | 77 |
| Total Number of Vehicles | 96,659 | 96,671 | 96,718 | 94,771 |
| Number of Cycles | 4020 | 4980 | 6407 | 6342 |
| Simulation Duration (*hours*) | 60 | 60 | 60 | 60 |

*5.1.2.1 Comparing Rates of Safety Measures between Baseline and Scenario 1*

Table 6 gives the results of the statistical test of the differences. The rate of vehicles trapped in the dilemma zone slightly decreases by 4 percent. This result is expected because no change was made to the dilemma zone protection. This change is not statistically significant at the 95 percent confidence level.

The changes in the two conflict types observed were found to be significant at the 95 percent 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. Crossing conflicts are typically rare and can require a long duration of observation to gather sufficient sample size. A 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, preventing the increase of traffic conflicts.

Further examination of the detailed outputs reveals that over 80 percent of the TTC-based rear-end conflicts 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. 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 6. Statistical Comparison of Safety Measures (100 Percent 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 $\sum Count \Big/ \left( \frac{\sum veh \times \sum Cycle}{10000 \times \sum Simulation\ Hour} \right)$, 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.

*5.1.2.2 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 and the differences between the two scenarios were statistically significant at the 95 percent confidence level. This result is anticipated since the green extension to dilemma-zone vehicles at the end of green is no longer available. Twelve percent and 3 percent increases of rear-end and crossing conflict rates were respectively observed in Scenario 2, which is likely attributed to the increasing number of vehicles trapped in dilemma zone. Results of the statistical test showed that only the increase in rear-end conflict is significant while that of crossing conflict is not.

### 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 7 summarizes the statistics of those indicators.

**Table 7. Summary of Indicators for Conflict Measures (100 Percent 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.

For the rear-end conflicts, Scenario 2 has the smallest average value of TTC, 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 all crossing conflicts, Scenario 1 has the smallest TTC and PET values while Scenario 2 has the largest DeltaS.

Researchers applied pooled t-test to examine the difference between the conflict-related severity indicators, since the standard deviations of each indicator for the test scenarios are similar. The equation for the statistical test is given below and test results are listed in Table 8. Confidence interval for t distribution relies on the degree of freedom (DF). The t distribution converges to standard normal distribution at high DF.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{X_1X_2} \times \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad (0)$$

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 $X_2$.

$Degree\ of\ Freedom = n_1 + n_2 - 2$.

*5.1.3.1 Comparing Mean Value of Safety Indicators between Baseline and Scenario 1*

No significant difference was found at the 95 percent 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 Scenario 1 had a significantly higher value, which means more severe resulting crashes. In other words, the baseline is likely to have more rear-end crashes though the severity for the potential crashes is less.

For crossing conflicts, the TTC and PET values in Baseline were demonstrated to be significantly higher than those in Scenario 1, 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.

The results also indicated more right-angle conflicts with less rear-end conflicts in Scenario 1. This may suggest a shift of crash patterns from rear-end to right-angle crashes when the yellow and all red intervals were reduced.

**Table 8. Statistical Comparisons of Safety Indicators for Conflicts (100 Percent OBEs).**

| Comparison 1: Baseline and Scenario 1 | | | | | | |
|---|---|---|---|---|---|---|
| **Indicators** | **Baseline** | **Scenario 1** | **%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** | **Scenario 1** | **Scenario 2** | **% 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 |

*5.1.3.2 Comparing Mean Value of Safety Indicators between Scenario 1 and Scenario 2*

For the rear-end conflict, a smaller mean of TTC value was observed in Scenario 2. In addition, Scenario 2 experiences significantly higher rear-end conflict rates. This increasing risk for rear-end crashes may be attributed to the removal of the advance detectors, 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 with smaller DeltaS values observed in Scenario 2. For crossing conflict, the difference in neither average TTC and PET nor DeltaS was found significant. Scenario 2 has shown a significantly higher crossing conflicts rate, which in this case indicates more right-angle crashes.

In summary, the elimination of the 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 Safety Measures

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 safety indicators from each through movement as the result of the varying traffic volume patterns. The analysis is based on Scenario 2 and Scenario 3 with the same geometric and operational settings except for different volume distribution.

*5.1.4.1 Analysis of Rear-End Conflict*

Figure 10 displays the distribution of the collected rear-end conflicts at movement level. The frequencies of rear-end conflicts in Scenario 2 from Movement 6 and 2 are about the same due to the same traffic input. More rear-end conflicts are found from Movement 4 than those from Movement 8. This mainly results from the slightly higher through input at Movement 4 and more interruption from the left-turning vehicles in the shared lane. Corresponding to the volume changes in Scenario 3, rear-end conflicts increase at Movement 6 and decrease at Movement 2. After the researchers increased traffic volume at Movement 8 and reduced that at Movement 4, rear-end conflicts varied accordingly.

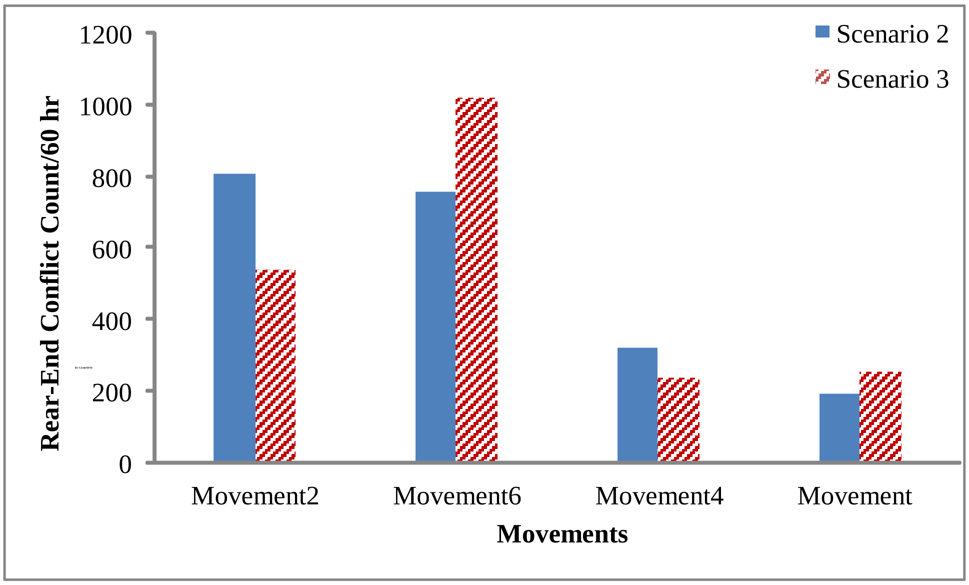



**Figure 10. Distribution of Rear-End Conflict at Movement Level.**

*5.1.4.2 Analysis of Vehicles Trapped in Dilemma Zone*

Figure 11 shows the distribution of the vehicles trapped in dilemma zone for Scenario 2 and Scenario 3 over the 60 simulation hours. In unsaturated traffic condition, number of vehicles trapped in dilemma zone is also closely associated to the traffic volume. The tendency in Figure 11 is similar to that in Figure 10, which reflects the changes from balanced flow input to unbalanced flow input.

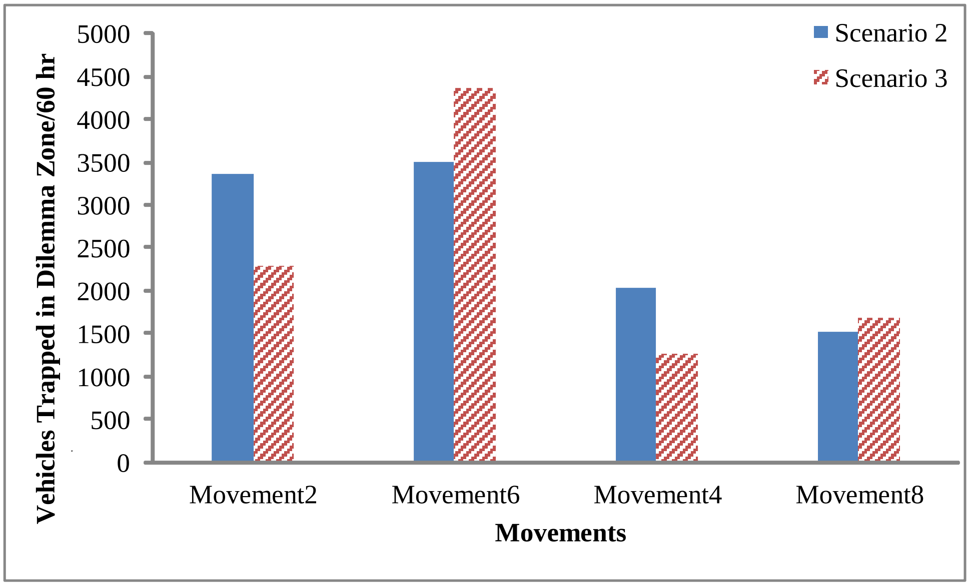



**Figure 11. Distribution of Vehicles Trapped in Dilemma Zone at Movement Level.**

*5.1.4.3 Analysis of Crossing Conflict*

The necessary component for a crossing conflict is a vehicle pair from two conflicting movements. This type of conflict often involves one vehicle running on red (due to some inappropriate geometric/operational settings) while another conflicting vehicle already gets a green indication. Figure 12 summarizes the detailed configuration, signal timing sequence for the simulation test bed and possible reasons for crossing conflicts at each conflict zone.

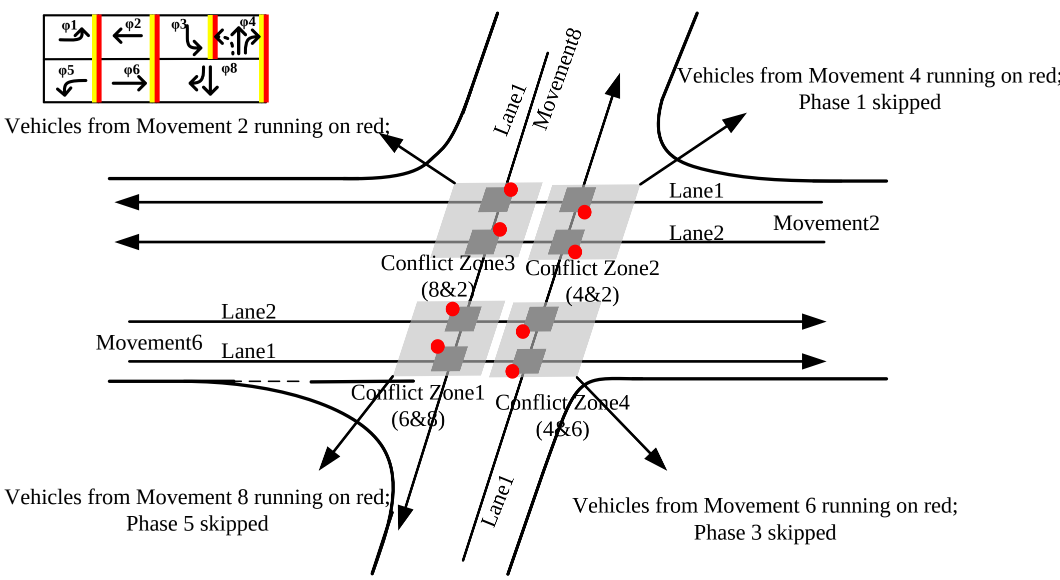



**Figure 12. Operational Situations for Crossing Conflicts.**

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 comes 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.

Figure 13 shows the distribution of crossing conflicts for Scenario 2 and Scenario 3. Generally, the majority of the conflicts are located in Conflict Zones 1 and 2. The light traffic condition in both scenarios 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 Zones 1 and 2. The likelihood of vehicles running on red increases without the presence of dilemma zone protection. The number of vehicles from Movements 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 Zones 3 and 4.

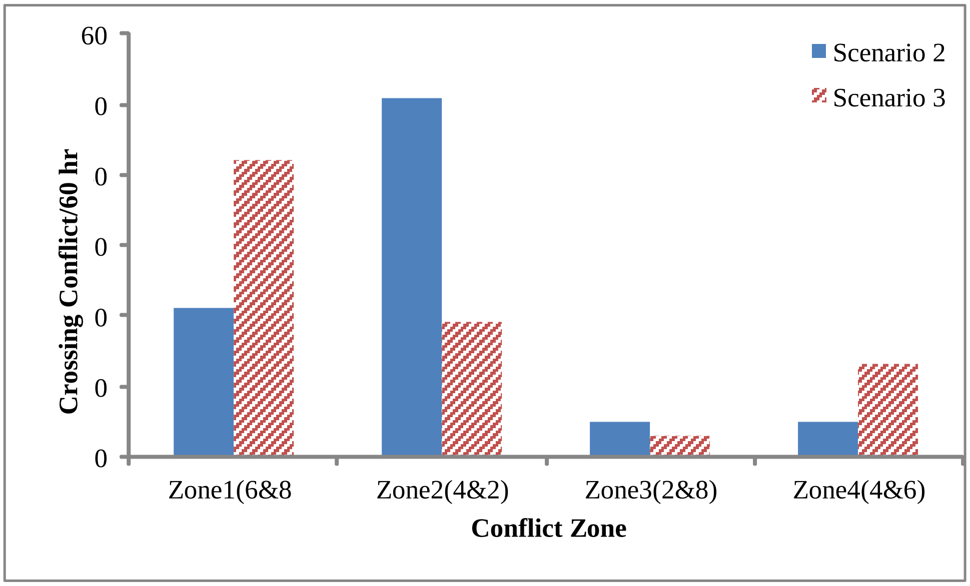



**Figure 13. Distribution of Crossing Conflicts.**

Increase of through input at Movements 6 and 8 definitely increases crossing conflicts at Conflict Zone 1 while the reduction of the through volume at Movement 2 and Movement 4 reduces the crossing conflicts at Conflict Zone 2. Given that both two lanes from Movement 2 saw a reduction of 30 percent of traffic volume while the increase of volume at the single lane from Movement 8 was only 12.5 percent, it is expected that Scenario 3 has slightly fewer crossing conflicts in Conflict Zone 3.

The obvious increase of crossing conflicts at Conflict Zone 4 in Scenario 3 seems unreasonable. Although the input volume for both two through lanes at Movement 6 increased by 30 percent, a reduction of nearly 37 percent was seen at Movement 4. Besides, the increase the opposing left-turning reduced the chances for skipping Phase 3. Note that two conflicting movements may not play the equal role in accounting for a crossing conflict. Vehicles from Movement 4 have at least the duration of Phase 6 to accumulate before the light turns green. Moreover, only the leading vehicle from that movement has the chance for a crossing conflict regardless of the approach volume. This offsets the loss of volume input at Movement 4 to some extent. In addition, the small sample size for Conflict Zones 3 and 4 is likely to bring noise. The researchers performed additional simulation runs of 60 hours with different random seeds (complete results are not shown here) and found that the increase of crossing conflicts in Scenario 3 at Conflict Zone 4 than Scenario 2 was not obvious (4 and 6 crossing conflicts were observed, respectively).

Generally, the spatial distribution of collected safety indicators corresponds well with changes in traffic volume. 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 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 safety measures were also analyzed as the result of the different traffic input patterns. It can be concluded that:

- The proposed framework can effectively monitor the safety performance of the signalized intersection. It can effectively detect a shift in crash pattern from rear-end crashes to right-angle crashes due to the shortened inter-green intervals. It can also detect the increase in both rear-end and right-angle crash risks due to the removal of advance detectors.
- There appears to be a trade-off between the patterns of crash frequency and crash severity. However, the mechanism for these changes was not clearly understood and will require further investigation effort.
- Spatial distribution of the safety measures within the intersection generally corresponds with the spatial patterns of traffic movement.

So far, analyses are based on 100 percent 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

This analysis evaluated 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 relationship between the rates of the safety indicators 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 percent, 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. Researchers 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.

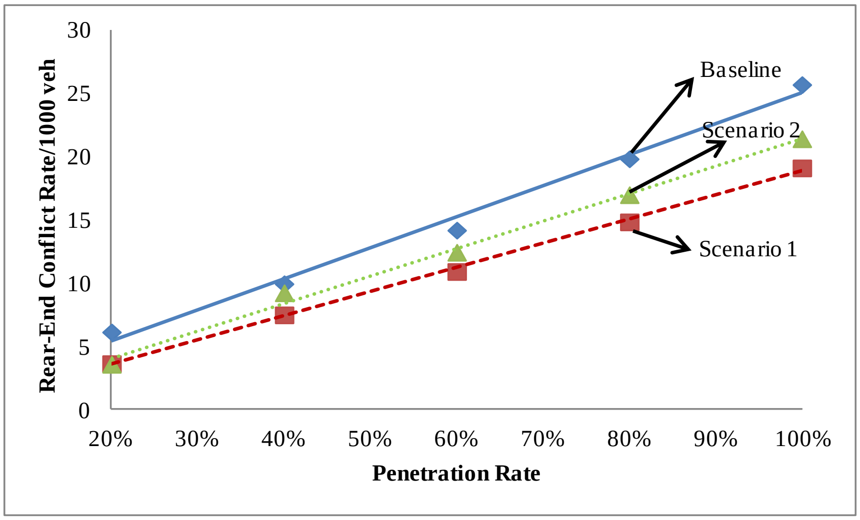
The relationship between the rates of the safety measures and market penetration rate was investigated for Baseline, Scenario 1, and Scenario 2. Market penetration rate was decreased from 100 percent to 20 percent at a 20 percent decrement. At each penetration level, the proposed Z test was iteratively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

### 5.2.1 Relationship between the Rates of Safety Measures and Penetration Rate

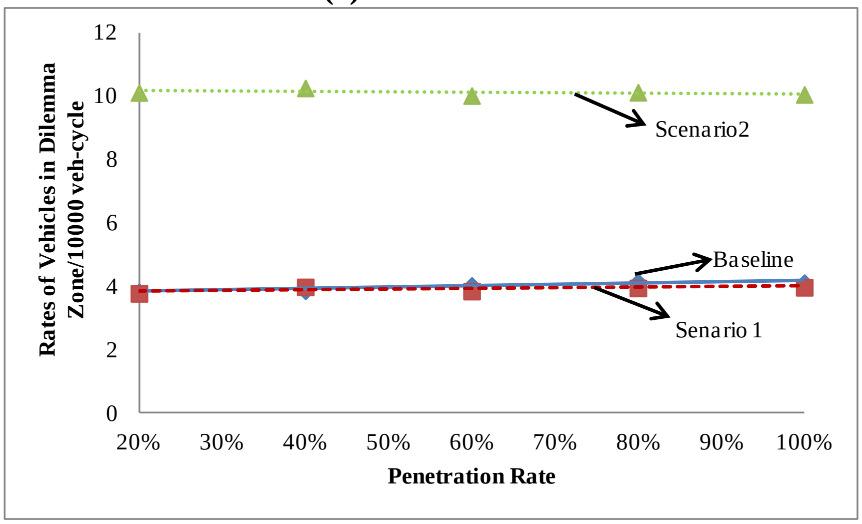
Figure 14 shows the relationship between the penetration rate and the mean rates of collected safety measures. Generally, the rate of single-OBE measure (rate of vehicles trapped in dilemma zone) seems to be stable at different penetration rate level. While the rates of dual-OBE measures (crossing and rear-end conflicts) decrease linearly as penetration rate decreases.

The computation for a single-OBE measure requires only one vehicle’s information. Although the framework captured fewer safety measures at a lower penetration rate, the total OBE volume collected also decreased at the same percentage. The calculated rate 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.

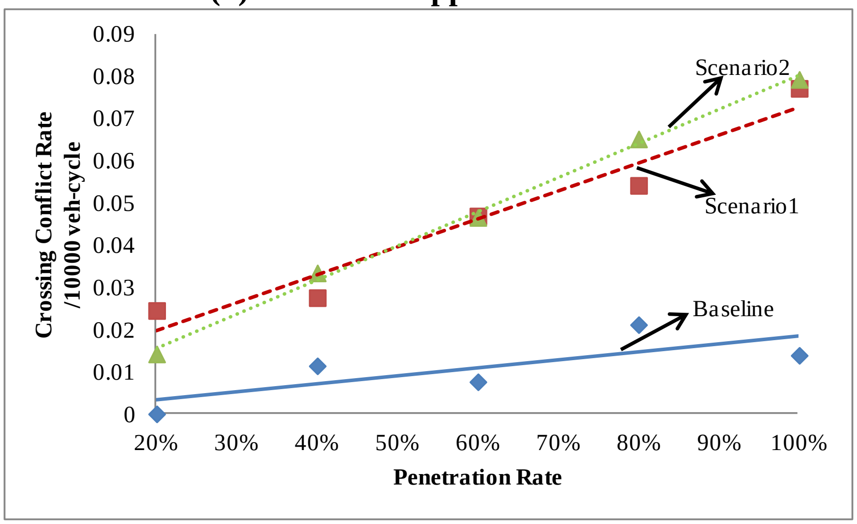
If the real traffic volume is used as the denominator for computing the rates, researchers could expect that single-OBE measures will decrease linearly and dual-OBE will decrease quadratically. In this case, the collected real traffic volume would approximately be constant, which means the rates are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




**(a) Rear-End Conflicts**




**(b) Vehicles Trapped in Dilemma Zone**




**(c) Crossing Conflicts**

**Figure 14: Penetration Rates versus Rates of Detected Safety Measures.**

### 5.2.2 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, researchers iteratively applied Equation (0) 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 9 through Table 12. The following describes the findings.

First, the proposed framework could perform effectively in detecting the changes of safety performance when the penetration rate is above 40 percent. Generally, the power of statistical test decreases with decreasing penetration levels. At 40 percent or less OBEs, the difference in crossing conflict rates between Baseline and Scenario 1 was unable to detect at the 95 percent confidence level (p-value = 0.097). At 20 percent 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.

Second, 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 percent OBEs level could still give a Z statistic larger than 22, with the p-value far less than 0.01.

**Table 9. Statistical Comparison of Safety Measures (80 Percent 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 10. Statistical Comparison of Safety Measures (60 Percent 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 11. Statistical Comparison of Safety Measures (40 Percent OBEs).**

| Comparison 1: Baseline and Scenario 1 | | | | | | |
|---|---|---|---|---|---|---|
| **Measurements** | **Baseline** | **Scenario 1** | **Z**[3] | **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**[3] | **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 12. Statistical Comparison of Safety Measures (20 Percent OBEs).**

| Comparison 1: Baseline and Scenario 1 | | | | | | |
|---|---|---|---|---|---|---|
| **Measurements** | **Baseline** | **Scenario 1** | **Z[3]** | **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[3]** | **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.*

### 5.2.3 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. Researchers 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.
- Forty percent or more penetration rate would likely be needed to ensure effective application of the proposed safety performance monitoring.

Generally, researchers 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 to investigate if and how researchers 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

This analysis examined the effect of observation period on effective implementation of the proposed framework. Researchers examined the relationships between penetration rate, observation period, and the variability of the computed safety measures. Specifically, researchers investigated if a 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 the real world. Observation period was 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 2 days versus 10 days at 50 percent 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 2 hours of data collection. If the penetration rate increases to 100 percent, 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.

Researchers used 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 could provide more reliable analysis. The definition of CV is given as:

$$CV\% = 100 \times \frac{\sigma}{\mu} \qquad (0)$$

where
$\sigma$ = Standard deviation of the population, which is substituted by the standard deviation of the rate of the safety measure.
$\mu$ = Population mean, which is substituted by the mean of the rate of the safety measure.

Accordingly, researchers first investigated the relationship between the variation of rate of the safety measures and observation period for each scenario. Based on this, researchers estimated and compared equivalent observation time needed at lower penetration levels to achieve the same variability as the 100 percent penetration level. Then researchers 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 a longer observation period to be effective.

Considered observation periods ranged 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

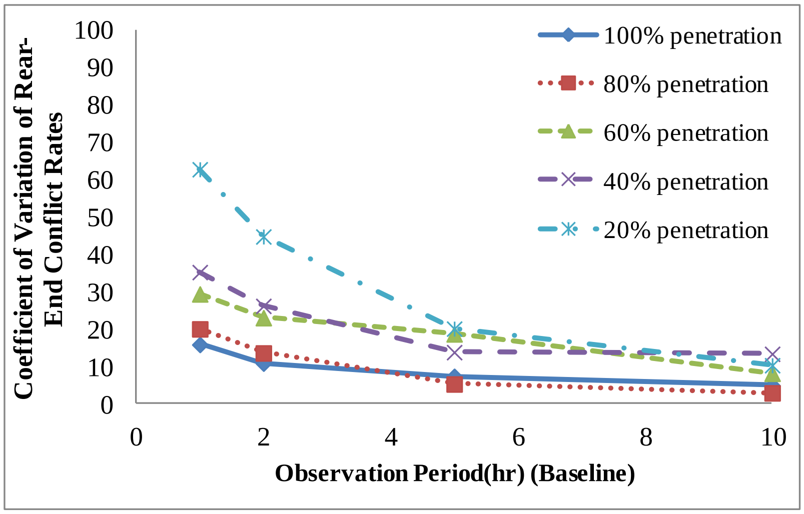
Figure 15 through Figure 17 demonstrate the relationship between CV and observation period for selected safety measures. Curves for different penetration levels are also shown in each figure. Note that the curve for crossing conflict rate at 20 percent penetration level is not available in Figure 17a as no crossing conflict was observed.

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 reduce the variation in the collected safety measures. Therefore, a 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.

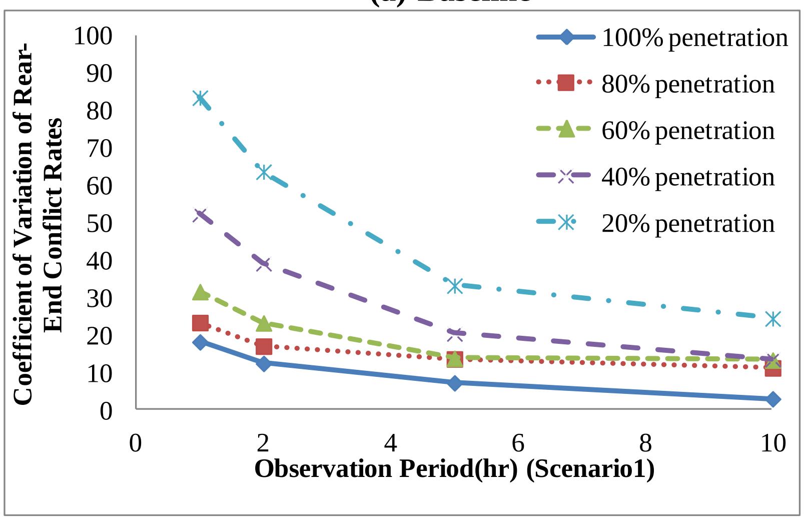
To illustrate the effects of observation periods, researchers compared the equivalent observation time for rates of the safety measures at different penetration levels to achieve the same variability as those obtained from a one-hour observation at the full penetration level. Table 13 presents the tendency of the equivalent observation period.

For rear-end conflict rate, one-hour observation at full penetration rate equals to approximately 1.7 hours of observation at 80 percent 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 percent, 40 percent, and 20 percent of penetration level, respectively. Analysis of the other two safety measures yielded similar tendency.

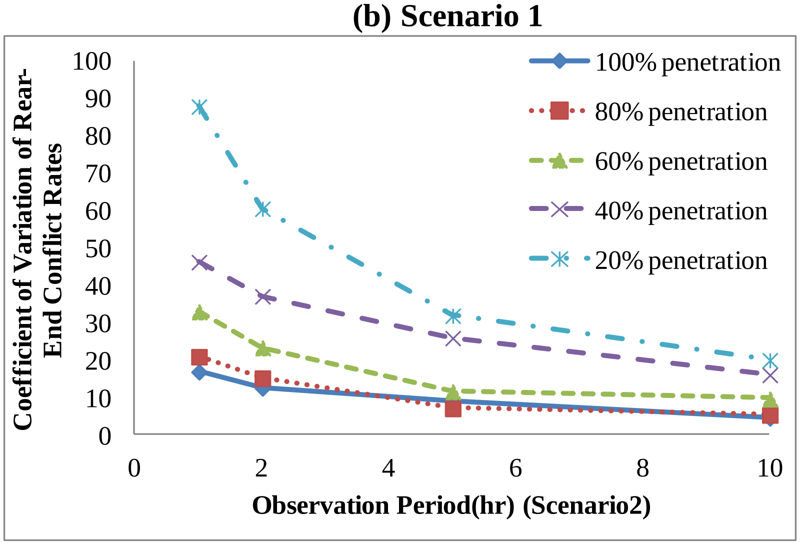
In addition, there is a diminishing return effect on the decrease in CV as observation periods increase. For example, consider CVs of the rear-end conflict rate at 40 percent penetration (Figure 15b). The increase of observation period from 1 hour to 5 hours reduces the CV by 32 percent (52 percent to 20 percent) while the further increase from 5 hours to 10 hours will further reduce the CV by only 6 percent (20 percent to 14 percent). This implies an exponential need of observation effort as researchers attempt to further reduce the variability in collected safety measures.




**(a) Baseline**

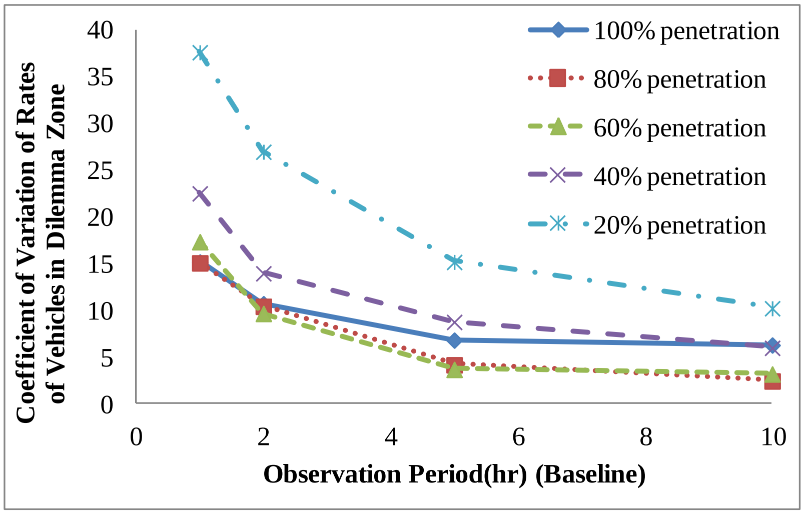



**(b) Scenario 1**

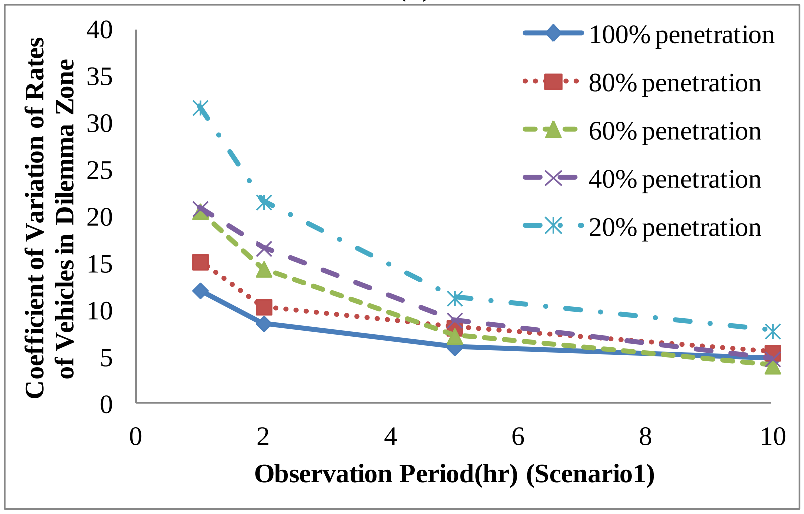



**(c) Scenario 2**

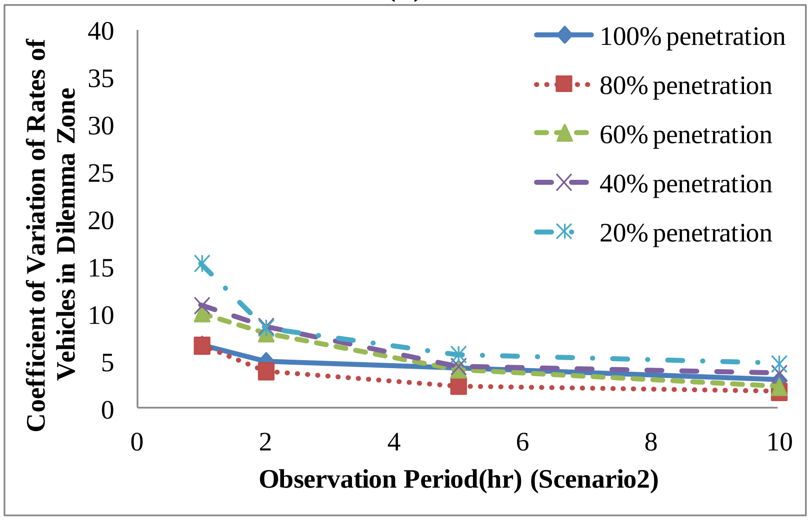
**Figure 15: CV of Rear-End Conflict Rates versus Observation Period.**




**(a) Baseline**

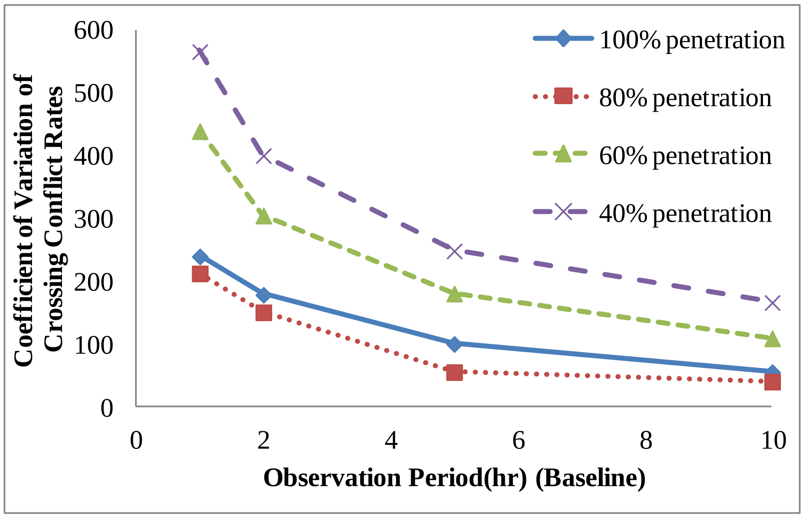



**(b) Scenario 1**

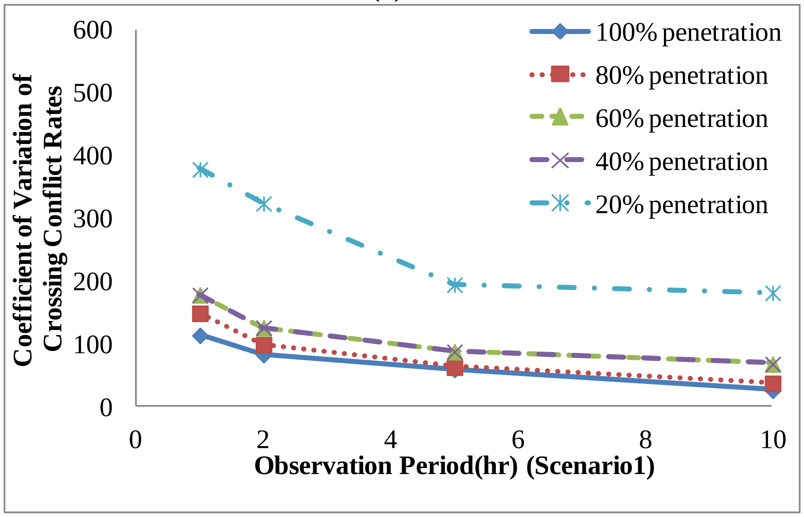



**(c) Scenario 2**

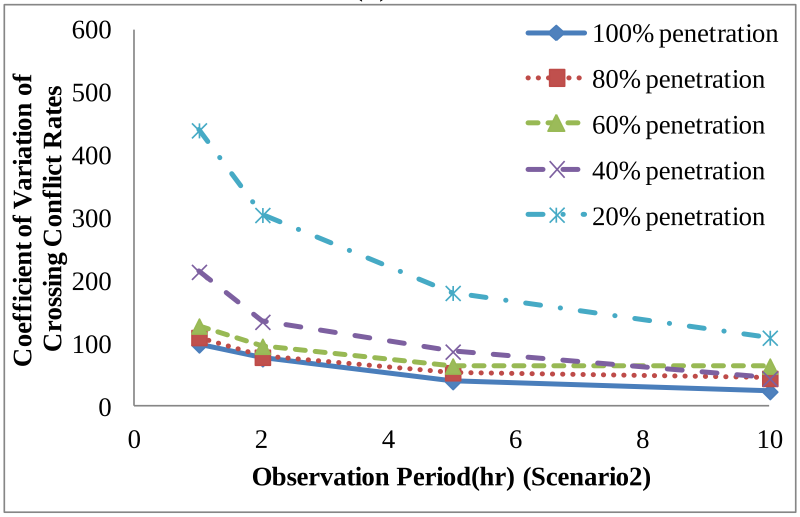
**Figure 16: CV of Rates of Vehicles Trapped in DZ versus Observation Period.**




(a) **Baseline**




(b) **Scenario 1**




(c) **Scenario 2**

**Figure 17: CV of Crossing Conflict Rates versus Observation Period.**

**Table 13: Equivalent Observation Periods for Varying Penetration Levels.**

| 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:

1. Equivalent observation period is obtained through linear interpolation.

### 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, researchers 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. Table 14 lists the results.

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. CVs for rear-end conflict rates are approximately more than twice as big 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. 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 and 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, which is 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 a certain risky moment when both vehicles choose to proceed during the transition of the signal interval and is the rarest case among the three.

**Table 14. Average CV for Different Observation Periods.**

| **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 |

### 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 they signify more variability in the data and 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 detail. 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.
- There is a diminishing return effect with the increase in observation time. One percent gain in CV at low variability would require a 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 a longer observation period to be effective.

# 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. Commonly used safety evaluation approaches rely on crash-based analyses. However, crash-based safety evaluation is often affected by the randomness, lack of timeliness, and rarity of crash occurrences. Alternative approaches to crash-based data use surrogate safety measures that are observable, more frequent than crashes, and possess causal relationship with crashes. Surrogate safety measures are not always desirable due to its inherent subjectivity of the data collection process and resource-intensive back-office processing.

Connected vehicle technology allows vehicles to talk to each other and to infrastructure wirelessly using a variety of communications technology such as DSRC and 4G LTE. With the advent of the connected vehicle initiative, several safety applications have been developed with the emphasis on providing in-vehicle advisory and warning information based on the detected or predicted hazardous events. However, some of these applications require high saturation rate of OBE, which may not be feasible in the near future. In addition, to the best of our knowledge, no applications exist for monitoring long-term safety and detecting changes in safety performance of transportation facilities to date.

This study proposed and evaluated a framework for continuously monitoring the safety performance of signalized intersections via V2I communications. The proposed application requires only V2I communications, RSE, and some levels of OBE for initial deployment. This chapter documents the findings and conclusions from this study.

## 6.2 SUMMARY

### 6.2.1 Framework Description

In the proposed safety performance monitoring framework, researchers identified and developed working definitions of the safety indicators that can comprehensively quantify safety performance at signalized intersections. Researchers 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 OBEs required to generate indicators of interest. Candidate safety measures were selected based on the ability to extract them from V2I communication data sets and their causal relationship with crashes. Researchers used vehicles trapped in dilemma zone as the single-OBE measure. The dual-OBE measures included rear-end and crossing conflicts. The selected safety indicators addressed both potential crash frequency and crash severity. In the scope of this study, researchers only focused on the vehicles from through movements due to their relatively well-defined vehicle trajectories. Then researchers extracted safety measures that potentially have linkage with rear-end and right-angle crashes. The OBE's temporary ID was used for identifying unique vehicles. It is assumed that these IDs remain unchanged during their communications with the RSE.

### 6.2.2 Simulation Evaluation

To evaluate the effectiveness of the proposed V2I safety performance monitoring framework, the researchers first built a simulation test bed in VISSIM that enabled V2I communications via C2X API. The developed test bed features a fully-actuated isolated high-speed signalized intersection. Based on the test bed, researchers developed an optimal scenario with proper signal timings and dilemma zone protection. Researchers intentionally introduced two suboptimal scenarios by reducing the inter-green interval and removing advance detectors that provide dilemma zone protection. Researchers also changed the volume input pattern from balanced to unbalanced traffic volume pattern based on one suboptimal scenario. The effectiveness of the framework is determined if the extracted measures can sensitively detect the safety deficiency and their spatial distribution at movement level reflects the changes in input volume.

As high market penetration of OBEs is not expected in the near future, researchers investigated the effect of the market penetration rate on the performance of the proposed framework. Lower penetration rate reduces the capability to extract safety indicators from V2I communications, increasing the level of uncertainty in the extracted indicators. This evaluation first examined the relationship between rates of the safety measures and the penetration rate. Afterward, the researchers compared the rates of measures between different scenarios at each decreasing penetration level. Inconsistent ranking of computed measures at lower penetration levels versus those of 100 percent penetration level (ground truth) indicates its inability to consistently depict the safety performance of the facilities.

Finally, researchers also examined the effect of observation period on effective implementation of the framework. Particularly, researchers investigated the required observation period for specific safety indicators to be effective and the feasibility of extending observation period at a lower penetration level to obtain sufficient data. First, researchers investigated the relationship between the variation of rate of the safety measures and observation period for each scenario. CV was used to measure the variability of the computed indicators. The equivalent observation time was computed for lower penetration level to achieve the same variability as the 100 percent 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. Second, for each observation period, researchers computed the average variation over all penetration levels and compared the different safety measures to see whether they were at the same level of variation. Measures with larger variation require a longer observation period to be effective.

### 6.2.3 Conclusions

The following conclusions can be drawn from this study:

- The proposed application can effectively monitor safety performance at signalized intersections using V2I communications data. Both single-OBE and dual-OBE measures can detect safety deficiencies in the suboptimal scenarios. Their spatial distribution also corresponded to varying traffic volume patterns. Related safety indicators demonstrated the potential of providing a comprehensive safety evaluation that can quantify crash frequency and severity.

- Under light to moderate traffic conditions, at least 40 percent market penetration rate is required for effective monitoring based on extended simulation period of 60 hours. As the market penetration rate decreases, the detection rate of single-OBE measures remains almost the same while the rate of dual-OBE measures decreased linearly. In fact, single-OBE measures still fare well even at the 20 percent penetration level. For dual-OBE measures, crossing conflicts became ineffective at 40 percent penetration rate while rear-end conflicts lost its detection power at 20 percent penetration rate.
- A longer observation period can be used to compensate the need for a higher penetration rate. Increase of either observation period or market penetration rate will generate a larger sample size to produce a more reliable analysis. However, there was a diminishing return effect on the reliability of extracted safety indicators as researchers increased the observation period. One percent reduction in CV at low variability would require a much longer observation time to achieve the same amount under high CV conditions.
- Desirable observation periods vary with the types of safety measures to be collected. At a given penetration level, safety measures that are less frequent and require dual-OBEs will require a longer observation period to be effective. For all simulated scenarios, crossing conflicts require the longest observation period to provide a reliable detection among all the examined safety measures.

## 6.3 FUTURE RESEARCH

The critical element of the proposed framework is to define appropriate safety measures that can be efficiently collected within connected vehicle platform, effectively used to quantify safety performance of signalized intersections, and are robust to low market penetration levels. In this sense, single-OBE measures may be more appealing and require further investigation. Variation of the speeds, for instance, may be considered an aggregate measure for 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.

This study is also currently limited to only through movements. Future work could incorporate turning movements in the current framework. For example, safety performance of left-turning movements can be added to the existing framework. 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.

Last, the integration of V2V communications for safety data mining could be another potential research issue. Researchers envision a state-of-art safety performance monitoring framework that can take advantage of both V2I and V2V communications data sets. V2V communications could potentially 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.

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