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Developing and Simulating a Communication Plan for Mitigation of Secondary Crashes: Leveraging Connected Vehicle Technologies

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DEVELOPING AND SIMULATING A COMMUNICATION PLAN FOR MITIGATION OF SECONDARY CRASHES: LEVERAGING CONNECTED VEHICLE TECHNOLOGIES

By

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THESIS CERTIFICATE OF APPROVAL

The thesis of Denis Elia Monyo is approved:

Dr. Thobias Sando, Thesis Advisor and Committee Chairperson	Date
Dr. Priyanka Alluri, Committee Member	Date
Dr. Ramin Shabanpour, Committee Member	Date

DEDICATION

I would like to dedicate this thesis to my Father and Mother, Elia and Judith Monyo.

And my whole family.

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4G	Fourth-Generation
5G	Fifth-Generation
AEB	Autonomous Emergency Braking
API	Application Programming Interface
AV	Autonomous Vehicle
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
BSM	Basic Safety Messages
BSW	Blind Spot Warning
CCTV	Closed Circuit Television
CDBA	Continuous Driving Behavior Adjustment
CMS	Changeable Message Sign
COM	Component Object Model
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
DMS	Dynamic Message Sign
DOT	Department of Transportation
DSRC	Dedicated Short Range Communication
EEBL	Emergency Electronic Brake Lights
FCC	Federal Communication Commission
FCW	Forward Collison Warning

FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FTO	Florida Traffic Online
GHz	GigaHertz
GPS	Global Positioning Systems
HAR	Highway Advisory Radio
HCM	Highway Capacity Manual
Hz	Hertz
ICM	Integrated Corridor Management
ID	Identification
ILB	Inner Lane Blocked
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation systems
LCA	Lane Change Assist
MHz	MegaHertz
MPR	Market Penetration Rate
OBU	On-Board Unit
OLB	Outer Lane Blocked
PET	Post Encroachment Time
PI	Primary Incident
RBC	Ring Barrier Controller
RSE	Road Side Equipment

RSU	Road Side Unit
SC	Secondary Crash
SMS	Short Message Service
SSAM	Surrogate Safety Assessment Model
TIM	Traffic Incident Management
TMC	Traffic Management Center
TTC	Time-to-Collision
US	United States
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad hoc Network
VBS	Visual Basic Scripting
VSL	Variable Speed Limit
Wi-Fi	Wireless Fidelity

ABSTRACT

The Federal Highway Administration (FHWA) has identified secondary crashes (SCs) on United States (US) highways as one of the core transportation issues that needs to be addressed. These crashes contribute to increased property damage, injuries, and fatalities and a decline in traffic flow conditions on freeways and adjacent arterials. The purpose of this study was to 1) propose a communication plan that leverages connected vehicle (CV) technologies to increase awareness to road users to target the mitigation of SCs, and 2) to evaluate the potential benefits of the proposed communication plan with CV technologies in alleviating SCs.

This study used VISSIM microscopic software to model a freeway road segment on Florida's Turnpike system and Lyons Road, a parallel arterial. The software was used to replicate the proposed communication plan and CV applications to issue advisories, such as speed, lane-change, or detour advisory to drivers during an incident. A safety evaluation was performed using the Surrogate Safety Assessment Model (SSAM) software by importing trajectory files from VISSIM to analyze generated traffic conflicts. The change in the number of simulated conflicts was used to evaluate the mitigation of SCs.

The results showed significant safety benefits using the proposed communication plan with CV technologies. A conflict reduction of up to 98% was observed with full penetration of CVs at low traffic volume. Statistical analysis indicated that different penetration rates of CVs were required to achieve significant safety benefits depending on the analyzed scenario, i.e., traffic volume, number of lanes closed, side of the road the lane is closed, and dissemination of detour advisory.

Keywords: Secondary Crashes, Safety Surrogate Measures, Connected Vehicles, Conflicts

CHAPTER 1 INTRODUCTION

1.1 Background

Traffic incidents are common occurrences on US freeways and create unsafe situations, putting lives at risk and impacting traffic operations. These incidents include crashes, vehicle breakdown, disabled vehicles, and spilled cargo or debris falling on travel lanes, and are a significant cause of non-recurrent congestion on freeways. According to the Federal Highway Administration (FHWA), these incidents contribute to 25 percent of congestion conditions (Federal Highway Administration [FHWA], 2015). The majority of incidents on freeways have considerable effects on operations, which often results in single or multiple lane closures for an extended period. Traffic congestion on freeways could last for a period of approximately 30 minutes to 2 hours due to lane closure incidents (Owens et al., 2010). Furthermore, these incidents may trigger the occurrence of secondary crashes. Researchers have reported that approximately more than 15 percent of primary incidents result in secondary crashes (Karlaftis et al., 1999; Asad Khattak et al., 2009). Although secondary crashes are fewer than primary incidents, their spatial-temporal effects may be more severe.

Although scholars have described secondary crashes (SCs) differently, a secondary crash can simply be defined as any accident that is an outcome of a prior incident within the same vicinity. SCs are considered to occur within the scene of the primary incident, along the queue upstream of the incident, or along the queue downstream of traffic in the opposite travelway (Kitali et al., 2018; Wang et al., 2016). Some SCs present more serious safety concerns than their primary incidents. Approximately 18 percent of freeways fatalities in the US are due to secondary crashes (Owens et al., 2010). Overall, these significant safety concerns lead to injuries and fatalities of travelers and responders as they offer assistance to primary incidents. The FHWA has identified secondary crashes on US roadways as one of the core transportation issues that needs to be addressed (Owens et al., 2010). Effective communication among various response agencies and road users can facilitate the reduction of SCs.

Enhancing communication capabilities on roadways is achieved by providing drivers with real-time information regarding downstream traffic conditions. Real-time incident information is transferred in two major phases: 1) detection and verification; and 2) traveler and responder information, also known as information dissemination (Federal Highway Adiministation [FHWA], 2010). Timely incident related information improves safety for travelers and responders at the scene of the incident and reduces the potential of SCs. When necessary, advisory messages may prompt travelers to take alternate routes based on prevailing traffic conditions and avoid being trapped by incident-induced congestion. Over the years, transportation agencies have used different methods, such as probe vehicles, sensors, and surveillance cameras, for incident detection. Other methods, such as Dynamic Message Signs (DMS), Highway Advisory Radio (HAR), traveler information websites, and 5-1-1 systems, are used to disseminate incident information to travelers (Federal Highway Adiministation [FHWA], 2010; Motamed & Machemehl, 2014; Pearce & Subramaniam, 1998). Currently, due to advancements in communications technologies, emerging technologies, such as connected vehicles (CVs) and smartphone applications, have shown the potential to improve transportation safety by enabling rapid real-time communication.

CV technology facilitates a real-time exchange of traffic operation and safety information among vehicle to vehicle, vehicle to infrastructure, and vehicle to road users' devices. The real-time information offered by CVs can quickly and accurately determine the prompt status of vehicles and the environment, which helps drivers to react immediately and accordingly to the traffic conditions. Thus, the increase of situational awareness provides the potential for reducing SCs. Due to its vast potential, the US Department of Transportation (USDOT) invested over $48 million in research on CVs in New York, Tampa-Florida, and Wyoming to deploy CVs on strategic roadways (Songchitruksa et al., 2016). Because CVs are not fully implemented yet, synthetic approaches, such as microsimulation models, which are cost-effective, are a viable method for analyzing the CV environments and their impact on transportation facilities (Hadi et al., 2007; Papadoulis et al., 2019; Rahman et al., 2018). However, mainstream traffic simulation tools are unable to model traffic crashes. Surrogate measures are normally used to assess safety characteristics under the CV environment, including occurrences of SCs (Paikari et al., 2014; Rahman et al., 2018; Yang et al., 2017).

The majority of previous studies on SCs have focused on identifying the characteristics of secondary crashes and determining factors associated with the probability of their occurrence. Little has been done on examining the potential of the CV technologies in mitigating SCs, and a communication plan to alleviate secondary crashes is not well developed in literature. Due to the advantages of CV technologies, it is essential to explore their benefits in mitigating SCs. This study investigates the potential of CV technologies in reducing SCs on freeways.

1.2 Study Objective

In light of the benefits offered by connected vehicles, the safety concerns associated with secondary crashes, and the need for an effective communication plan during the entire duration of an incident, this study has the following objectives:

<u>Main objective</u>

- To quantify potential benefits of CV technologies, at varying market penetration rates, in mitigating secondary crashes.

Specific objectives

- To develop a communication plan to inform upstream drivers of potential secondary crashes and give advisory messages, such as the use of available alternate routes, reduce speed, or change lanes.
- To develop a microscopic simulation model to demonstrate traffic flow characteristics under the CV environment.
- To conduct sensitivity analysis based on the communication plan developed by creating several scenarios, including varying market penetration of CVs, the number of lane closures, and introducing a detour in the system.

1.3 Thesis Organization

The research begins with a comprehensive review of previous studies on matters that relate to this study. In this context, Chapter 2 provides a synthesis of past studies related to secondary incident identification, the effects of blocking a single or multiple lanes, connected vehicle technologies, the use of detour strategies on freeways, traffic simulation, and surrogate safety measures in traffic safety analyses. Development of a communication plan to mitigate the occurrence of SCs is described in Chapter 3. Chapter 4 presents a conceptual framework of the research methodology, including a description of the study area, data sources, different analyzed scenarios, modeling procedures to implement the developed communication plan in microsimulation software, and proposes key analyses to answer the research objective. Chapter 5 presents the results and discusses the findings of the study. Finally, Chapter 6 concludes the study by summarizing the research findings and offers recommendations for future studies.

CHAPTER 2 LITERATURE REVIEW

A comprehensive literature review was conducted to summarize the broad concept of secondary crashes and the effect of incidents that result in lane blockage. Additionally, a review was performed of freeway detour strategies, connected vehicle technologies, traffic simulation, and the use of surrogate safety measures for traffic safety analyses. A summary of literature review findings is also presented, along with how these findings guided the research methodology of this thesis.

2.1 Secondary Crashes

SCs occur within the spatial and temporal influence area of the primary incident (PI). SCs can occur at the scene of the primary incident, within the queue upstream of the primary incident, or within the queue in the opposite direction of the primary incident, due to a traffic condition known as rubbernecking (Kitali et al., 2018).

2.1.1 Approaches used to identify SCs

Previous studies have strived to quantify SCs as the effect of primary incidents. However, these efforts have not been successful due to the complexity of identifying SCs (Pigman et al., 2011). Various approaches have been used to identify SCs, and can be categorized into four groups: (a) static spatial-temporal range-based; (b) queuing theory-based; (c) speed contour map-based; and (d) shockwave-based approaches (Yang et al., 2018).

Early studies have identified SCs based on defined spatial-temporal thresholds in relation to a prior incident (Asad Khattak et al., 2009; Moore et al., 2004; Tian et al., 2016). Some studies considered the effects of the primary incident on the opposite traffic, while others examined only the influence on the upstream traffic. One Florida study considered the effect on upstream traffic and established three spatial-temporal thresholds to identify SCs on interstate highways: (a) 2 miles, 2 hours; (b) 2 miles, clearance time + 15 minutes; and (c) 2 miles, clearance time + 30 minutes (Tian et al., 2016). Different thresholds resulted in a different number of identified SCs. It was shown that the use of 2 miles and 2 hour thresholds identified twice the number of SCs than other thresholds. Due to subjectivity in defining the spatiotemporal thresholds, methods, such as dynamic, and data-driven approaches were used to identify SCs. The dynamic method marks the end of the varying queue throughout the entire incident. One study used a dynamic progression threshold approach and found that the static and dynamic methods can differ by 30% in identifying SCs (Sun & Chilukuri, 2010).

2.1.2 Factors contributing to the occurrence of SCs

Previous studies indicated various factors that influence the occurrence of SCs (A. Khattak et al., 2012; Asad Khattak et al., 2009; Vlahogianni et al., 2012; Zhan et al., 2009). In many of these studies, the incident duration was mentioned as a common factor influencing the likelihood of SCs. The likelihood for a SC to occur increases by 2.8% for each minute that the primary incident is not cleared (Owens et al., 2010). One study found that the primary incident duration and SC occurrence are statically interdependent (Asad Khattak et al., 2009). Other factors, such as the number of blocked lanes, travel speed, hourly volume, rainfall, and type of vehicle, were found to be significant in influencing the risk of SCs (Vlahogianni et al., 2012). Additionally, Zhan et al. (2009) identified four factors that influence the odds of SCs: primary incident type, time of day, primary incident lane blockage duration, and the direction of traffic.

2.1.3 Countermeasures for reducing SCs

To effectively mitigate the risk of SC occurrences, information about primary incidents must be communicated to upstream drivers in a timely manner (Kitali et al., 2018). Traffic Incident Management (TIM) agencies use advance warning messages to alert drivers about downstream incidents (Yang et al., 2018). Conventionally, the advance warning messages are posted along the roadside by incident response agencies, such as highway patrol and freeway service patrols. Responders can be hindered by incident-induced congestion (Yang et al., 2017, 2018), leading to potential delays in posting advance warning messages, and hence, increasing the likelihood of SC occurrence. Even in situations where TIM agencies use changeable message signs (CMS), variable message signs (VMS), or variable speed limit control (VSL), the time between the incident occurrences to the time when the message is posted may increase the likelihood of SCs. CV technologies have a potential of reducing the delay in relaying advance warning messages to upstream drivers by automating the incident detection process and instantly sending short message services (SMSs) to upstream drivers, while at the same time alerting TIM agencies.

2.2 Effects of Blocking Different Number of Lanes on Freeways

Traffic incidents on freeways may result in a temporary block of one or multiple lanes, depending on the type and severity of the incident. Incidents that block lanes or a shoulder deteriorate the performance of freeways operations, and are estimated to cause 30 to 50 percent of the congestion problems on urban roadways, affecting safety and causing environmental problems (A. Khattak et al., 2011). Incident-induced congestion can accelerate the potential of SCs occurrence.

A study by Pulugurtha & Balaram Mahanthi (2016) assessed the spatial and temporal effects due to crashes on freeways using a traffic simulation approach. The study considered the crash severity to influence the number of lanes blocked, i.e., injury crashes to block one lane and fatal crashes to block double lanes. Travel time variation was used as the measure of effectiveness, and results indicated that the blocking of two lanes has an effect under low, moderate, and high traffic volume conditions, whereas the blocking of a single lane has an effect only under moderate and high traffic volume conditions. The upstream distance, affected due to a blockage of two lanes, ranged from 1.5 miles to 7.5 miles, and varied from 0.5 miles to 7 miles for a single blocked lane, based on traffic volume and lane on which the crash occurred. Furthermore, irrespective of the side of the lane blockage(s), queue dissipation started 15 minutes after re-open to normal flow for light traffic. However, for higher traffic volumes and two lanes blocked, the dissipation was not observed during the analysis period (Pulugurtha & Balaram Mahanthi, 2016).

2.3 Use of Alternative Routes for Incident Management on Freeways

Diversion of traffic from the freeway to parallel arterials during the incident decreases the traffic volume approaching the incident location, which also reduces the incident-induced queues (Pulugurtha & Balaram Mahanthi, 2016). The FHWA listed reduction in SCs as one of the benefits of using alternative route plans on highways (Dunn Engineering Associates, 2006). Furthermore, in 2007, the USDOT embraced the Integrated Corridor Management (ICM) strategy, which aims at utilizing the underused capacities of parallel arterials by diverting traffic from freeways when necessary (Xiaoyue Liu et al., 2013). The strategy is accompanied by modifying traffic signal timing on detour routes and arterials. Diversion strategies have shown significant safety and mobility impacts for an incident duration of 30 minutes or longer, with blockages of more than one lane (Chou & Miller-Hooks, 2011).

Previous studies have shown that the diversion rate of only 10-15% of the traffic flow can produce optimal mobility benefits on highways, and higher diversion rates may further decrease the travel time on the main route (Liu et al., 2012; Park & Smith, 2012; Zhou, 2008). However, high diversion rates may also reduce performance on the alternate routes. Various Intelligent Transportation Systems (ITS), such as Dynamic Message Signs (DMSs), mobile devices, and CVs, can be used to inform drivers on when, why, and where to take a detour while traveling along the freeway.

2.4 Connected Vehicle (CV) Technologies

2.4.1 Overview

CVs are vehicles equipped with technologies that facilitate wireless communication and data exchange among vehicles and between vehicles and the environment to improve mobility, enhance safety, and minimize adverse environmental impacts. This process is achieved through the communication between vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicles to mobile devices. Three main components enhance the connected environment:

- On-Board Unit (OBU) that stays in CVs to facilitate the exchange of information,
- Road-Side Unit (RSU) located adjacent to the road which acts as a broadcaster and receiver to CVs within its range, and
- Back-office Server, which connects Road-Side Equipment (RSE), and also observes the traffic network (Songchitruksa et al., 2016).

Information conveyed in the CV environment falls under safety, mobility, and environmental applications (Krechmer et al., 2017). This information includes speed, location, direction of travel, emissions, the roadway, and traffic conditions. Unlike traditional vehicles, CVs allow drivers to receive information within their communication range in real- time, which increases situational awareness on roadways. Advancement in technologies continue to bring the CV era close to becoming a reality, and it is expected that the market penetration of CVs on roadways will rapidly increase with time (Papadoulis et al., 2019). Due to the potential benefits of CVs, the USDOT and other agencies have invested in various studies related to connected vehicles and their applications (Songchitruksa et al., 2016).

2.4.2 Traffic safety benefits

Information shared within the CV environment enables drivers to possess a 360-degree awareness of real-time traffic conditions, a much broader range than they can easily see while driving. Regardless of the varying driving capabilities of drivers to perceive traffic operations, in a CV environment, they are not limited by blocked sight, uncertain road geometry, blind spots, and inclement weather. This is because the CV can collect information in its range of communication and identify critical traffic safety and operation information. Therefore, with CV, the driving task becomes less demanding by reducing a driver's cognitive burden (H. Liu, 2016). Under this circumstance, drivers are expected to react more quickly and appropriately in the traffic stream, with behaviors that are more predictable to other motorists (H. Liu, 2016; Yan et al., 2015). Additionally, CV applications can operate even under inclement weather, unlike other ITS technologies, such as DMS. Overall, this would significantly enhance traffic safety by reducing the number of crashes while improving mobility and environmental performance (Yan et al., 2015).

Various CV-based safety systems have been developed to potentially influence driver behavior on freeways. These systems include the blind spot/lane change warning system, emergency electronic brake lights (EEBL) warning system, and forward-collision warning (FCW) (H. Liu, 2016). The EEBL systems equip a vehicle to disseminate a self-generated emergency brake event to surrounding vehicles. In receiving the event information, the onboard device in the receiving vehicle determines its relevance. If the event poses a potential risk to the subject driver, it will warn the driver to avoid the crash. This system is useful, especially when the driver's line of sight is obscured by other vehicles or inclement weather (Iteris, 2015). The FCW safety system is designed to assist the driver in evading rear-end collisions with the front vehicle by driver notification or warning messages (CAMP, 2005). The most common criteria used to release the warning message is a threshold following distance. Alternatively, time headway and time-to-collision thresholds are also used to define warning timings (H. Liu, 2016). The warning messages are released whenever the defined threshold is met, which reduces the risk of rear-end crashes by reducing reaction time and increasing the deceleration rate (Yan et al., 2015). These CV-based systems can help mitigate the occurrence of SCs since they broadcast early warnings to drivers on the potential risk of a crash.

2.4.3 Communication technologies that enable the CV environment

Unlike other traditional ITS technologies, CV technologies are enhanced through wireless communication. Various wireless communication technologies, such as radio connectivity, dedicated short-range communications (DSRC), Wi-Fi, infrared, radar, Bluetooth, and fourth-generation (4G) and fifth-generation (5G) connectivity, facilitate CV communications (Krechmer et al., 2017). The usefulness of one communication technology over the other is highly dependent on the targeted purpose within the CV environment. The two main characteristics that differentiate these technologies are coverage range and latency. The coverage range reflects how far the signal can propagate, while latency shows the time difference between the start of transmission and when transmission content is received. The coexistence for low latency and long-range capabilities in one communication technology is impractical; therefore, the choice or compromise should be considered based on the targeted application.

In October 1999, the Federal Communication Commission (FCC) allocated 75MHz of radio spectrum in the 5.850-5.925 GHz band for a variety of DSRC uses in ITS applications (Federal Communications Commission [FCC], 1999). These applications include traffic light control, traffic monitoring, travelers' alerts, automatic toll collection, traffic congestion detection, emergency vehicle signal preemption of traffic lights, and electronic inspection of moving trucks through data transmissions with roadside inspection facilities. The DSRC is targeted for low latency; therefore, used for short-range communications. It is particularly useful for time-sensitive applications, such as the V2V collision avoidance system, because it has a low latency of 100 microseconds and an ideal range of 300m (Bettisworth et al., 2015). DSRC is more suitable than many other communication technologies for transportation safety applications because it has a designated licensed bandwidth, fast network acquisition, low communication latency, high reliability in all weather, interoperability, and security (Zeng et al., 2012). However, despite these advantages, the DSRC protocol has a major drawback – low scalability; thus, it fails to give the required time-probability characteristics when traveling in dense traffic (Xu et al., 2017).

In 2015, a report by USDOT to Congress identified DSRC as a communication technology that can support applications that offer a path to a safer and more efficient surface transportation system for America (Bettisworth et al., 2015). The report highlighted California, Michigan, New York, Florida, Arizona, and Northern Virginia as states that were already using DSRC technology at that time. It also described the potential use of other technologies, including cellular, satellite, radio, fiber, and Wi-Fi, for applications, such as mobility and logistics, and traveler and road weather information, which do not require extremely low latency.

In December 2019, the FCC released a notice of proposed rulemaking (FCC 19-129) proposing changes to the 5.9GHz band rules to repurpose the use of 75MHz of mid-band spectrum in the 5.9GHz band. The proposed changes included keeping the upper 30MHz portion of the band for transportation and vehicle safety purposes, and repurposing the lower 45MHz for unlicensed operations. In the same report, the FCC claimed that the use of the 5.9GHz for transportation purposes has not lived up its potentials. Moreover, it mentioned that vehicle manufacturers have started to use new technologies, such as cellular to everything (C-V2X), particularly 5G, which also may support CV safety applications. Despite the motivation for the changes, to ensure that the spectrum supports its highest and best use, the FCC received objections from different transportation institutions, such as ITE and State DOTs, regarding the FCC's intention to repurpose the use of the safety spectrum.

2.5 Traffic Simulation and Surrogate Safety Measures in Traffic Safety Analysis

2.5.1 Traffic simulation

In recent years, traffic simulation has been used to facilitate better planning, designing, and analysis of various transportation systems, such as freeways, intersections, and arterials. Traffic simulation refers to mathematical modeling of transportation systems through computer software applications. The advantage of traffic simulations is to analyze complex models that are too difficult to achieve using analytical or numerical treatments. The simulations method is used to not only experiment on different mobility and safety scenarios, but also to provide the visualization of present and future/proposed scenarios.

Traffic simulation models fall under three main categories: macroscopic, microscopic, and mesoscopic simulation (Hadi et al., 2007). Macroscopic simulation considers the deterministic relationship of flow, speed, and density of the traffic stream. Microscopic simulation models individual vehicles, based on car-following and lane-changing theories. Mesoscopic simulation involves macroscopic and microscopic simulation properties, using an individual vehicle as a unit of flow while macroscopic models guide the movement**.**

Microsimulation models monitor individual vehicle movements on a second or sub-second time basis, making it suitable for analyzing various traffic safety and mobility scenarios. Microscopic traffic simulation has been used to determine surrogate safety performance measures based on high-risk vehicle interactions in various traffic and road conditions (Shahdah et al., 2015). There is a wide range of traffic simulation software on the market that differ in capacities and functionalities, such as VISSIM, PARAMICS, Integration, and TransModeler (Pell et al., 2017).

Traffic safety and operational analysis of emerging technologies, such as CV and Autonomous Vehicle (AV), cannot be fully explored in reality testbeds. This is because of the higher costs and associated risks of testbed environments. However, traffic microsimulation software and their extensions (e.g., COM-API in VISSIM) provide simplifications by indirect stimulation of sensors and wireless vehicle communication, which enables large scale analysis (Papadoulis et al., 2019).

2.5.2 Surrogate Safety Measures in Traffic Safety Analysis

Observational models, such as Empirical Bayes (EB), use historical crash data to assess traffic safety improvements after adopting a particular countermeasure. These methods are restricted to only systems that possess historical crash data and are not useful for analyzing systems that have not yet been implemented. Additionally, low reporting rates for less severe crashes and unreported near-misses tend to disregard portions of essential information concerning unsafe situations on a particular facility (Shahdah et al., 2015). Traffic conflict analysis gives an alternative approach to observational models in situations where crash data are limited or when evaluating the potential safety benefits of certain modifications before their implementation, e.g., CV deployment (Shahdah et al., 2015).

Traffic conflict analysis uses microsimulation and surrogate safety measures with predicted high-risk vehicle interactions. A traffic conflict is recorded when the interaction exceeds the thresholds of established risk tolerance. A conflict is described as an observable situation in which two or more road users approach each other in time and space to the extent that there is a risk of collision if their movements remain unchanged (Gettman & Head, 2003). Various surrogate safety indicators provide the temporal and spatial proximity aspects of unsafe interactions.

A research project sponsored by the FHWA proposed time to collision (TTC), post-encroachment time (PET), deceleration rate, maximum speed, and speed differential as the best surrogate safety measures for traffic simulation models (Gettman & Head, 2003). These surrogate measures support evaluations of different traffic engineering alternatives, such as unconstructed facilities and strategies that have not yet been used. Among other surrogate measures, TTC is the most well-known time-based safety indicator. TTC is defined as the time remaining before two vehicles collide, assuming both maintain their course and speed (Saffarzadeh et al., 2013; Shahdah et al., 2015). The TTC threshold defines the potential conflict range as 1.5 to 4.0 seconds, and is effective for rear-end, head-on, and weaving conflicts (Mahmud et al., 2019). PET is the second commonly used surrogate measure, and is more efficient for intersection conflicts with a critical value of up to five seconds (Mahmud et al., 2019). PET refers to the time interval between two instances when the first vehicle leaves a conflict point, and when the second vehicle enters it (Sen et al., 2007).

2.5.3 Studies on CV that used microsimulation and surrogate safety measures

A number of studies have used the microscopic simulation approach in assessing the effects of CVs in operations and safety (Paikari et al., 2014; Rahman et al., 2018; Yang et al., 2017). VISSIM and PARAMICS are the two main microscopic traffic models used in previous studies. One Florida study employed VISSIM to evaluate the effectiveness of CV technologies in reduced visibility conditions (Rahman et al., 2018). The study derived three surrogate measures of safety from VISSIM for the evaluation: the standard deviation of speed, the standard deviation of headway, and the rear-end crash risk index (RCRI). The results indicated that CVs provide significant safety benefits in reduced visibility when the market penetration rate (MPR) is 30% or greater. Another study by Fyfe and Sayed (2017) exported vehicle trajectories from VISSIM to SSAM to analyze the safety benefits of CVs at a signalized intersection and obtained a 40% reduction in the frequency of rear-end conflicts. Yang et al. (2017) used PARAMICS and TTC as a surrogate safety measure to examine the impact of CV technology (V2V) on mitigating SCs. The study reported a reduction in SCs as the CV MPR increased. Moreover, even at a relatively low MPR (e.g., 5%), CVs can better inform and potentially reduce SCs. The study considered the interaction between convectional vehicles and surrounding vehicles to adjust their driving behavior after observing roadside information, such as CMS and VSL. Another PARAMICS study used an Overall Risk Change Index (ORCI) as a primary measure of safety for rear-end and lane-change conflicts, and found higher safety and mobility benefits on freeways under the CV environment (Paikari et al., 2014).

2.6 Summary of Literature Review

Previous studies have shown that, although SCs are fewer in number than primary incidents, SCs can result in severe spatial-temporal effects. Safety is a critical effect of SCs, which affects both motorists and incident responders. Thus, SCs have been identified as a core transportation issue on US roadways that should be addressed.

Various factors, such as incident duration, travel speed, number of blocked lanes, and hourly volume, affect the likelihood of SC occurrence. The primary incident's type and severity might result in either single or multiple lane blockage, which results in incident-induced queues that trigger the occurrence of SCs. In order to mitigate the risk of SCs, driver awareness of a primary incident should be enhanced. Conventionally, TIMs direct advance incident warnings to be posted on roadside CMS or VSL signs using incident response agencies. Incident-induced congestion can hinder responders from quickly posting the warnings.

Emerging technologies in ITS have the potential to enable drivers to possess a 360-degree awareness of real-time traffic conditions, a much broader range than they can easily see while driving. Through V2V and V2I wireless connectivity, vehicles can share their real-time status among themselves and the infrastructure. This information includes speed, location, travel direction, emissions, and road and traffic conditions. The information can be processed and issue real-time advisory warnings to motorists whenever there is an incident on roadways. Therefore, the driving task becomes less demanding by reducing the drivers' cognitive burden through CV applications, such as FCW, speed advisory, detour advisory, and lane-changing assisting systems. Overall, this would significantly enhance traffic safety by reducing the number of crashes, including SCs, while improving mobility and environmental performance.

Microscopic traffic simulation can be used to analyze different proposed transportation strategies, including applications of connected vehicle technologies. It can be used to assess the safety, mobility, and environmental benefit of CVs before their actual deployment. In regards to safety benefits, traffic conflict analysis using microsimulation and surrogate safety measures is so far a suitable means to assess the safety benefits of CV applications, such as the mitigation of SCs.

CHAPTER 3 COMMUNICATION PLAN TO MITIGATE SCs.

This chapter presents a communication plan developed to convey incident-related information to travelers on freeways, with the aim of reducing SCs using ITS technologies, such as CVs. The plan depicts key stakeholders, technologies, and necessary infrastructure elements, such as DMS, RSU, and CCTV. Furthermore, the plan shows the sequence to convey messages among infrastructures, TIM agencies, and road users, under different scenarios.

According to FHWA, TIM consists of five planned and coordinated multi-disciplinary processes: detection and verification, traveler information, response, scene management, and quick incident clearing to restore normal traffic conditions. An effective TIM system improves the safety of first responders and motorists while reducing the impact and duration of the incident. In 2005, FHWA highlighted secondary incidents as a critical performance measure for TIM (Owens et al., 2010). From the same report, it is considered that the fewer the number of SCs, the more effective the TIM was applied at a precise location. A proper and efficient communication plan that disseminates information about the prior incident to road users potentially reduces the risk of SCs. In this study, a developed communication plan consists of two broad processes: 1) incident detection, which includes verification of the identified incident, and 2) processing and disseminating appropriate information to travelers and responders.

Over the years, the process of identifying incidents and managing traffic conditions at the incident scenes was mainly performed by freeway service patrols (Karlaftis et al., 1999). These individuals help to warn upstream traffic, remove debris and disabled vehicles from the travelway, and divert upstream traffic to allow for emergence responders to access the incident scene. Emerging ITS technologies offer significant improvements in detection capabilities and information dissemination than can be provided solely by freeway service patrols. CV technology, in particular, enables vehicles to communicate among themselves and with the environment, which extends their line-of-sight by increasing awareness of situations on the roadways (Harding et al., 2014).

Since each incident is different, the order of transferring traffic incident-related information to motorists depends on various factors such as type and severity of the incident, prevailing traffic condition, and among others. ITS technologies provide effective coordination and communication among agencies under TIM, which facilitate prompt incident detection, fast dissemination of incident-related information as well as quick clearance of incident scene, hence result in a reduction of SCs (Federal Highway Administration [FWHA], 2000). Transportation agencies such as Traffic Management Centers (TMCs), emergency responders, and maintenance field staff serve as a critical role in TIM. TMCs play a huge role in incident detection, verification, as well as serves as a hub for the collection and dissemination of incident information (Owens et al., 2010).

3.1 Stages in a Communication Plan

This section describes an effective process for developing a communication plan to mitigate SCs. The plan describes the stages used in detecting primary incidents and mitigating SCs. Figure 3-1 shows the sequence in the TIM timeline aimed at reducing SCs. This timeline is a modified version of incident management timeline by the FHWA. It shows steps/events, tools, and agencies involved, from detecting an incident to its clearance. Since the target of the proposed plan is to mitigate SCs, the focus is on events within the timeline that influence the occurrence of SCs. To achieve this, the plan was narrowed down into four major stages that make use of ITS. Figure 3-2 presents a flow chart that discusses the following four stages: Detection, Verification and Classification, Processing of Information and Advisory Messages, and Information Dissemination. Depending on the type of technology used, some of these stages may overlap.

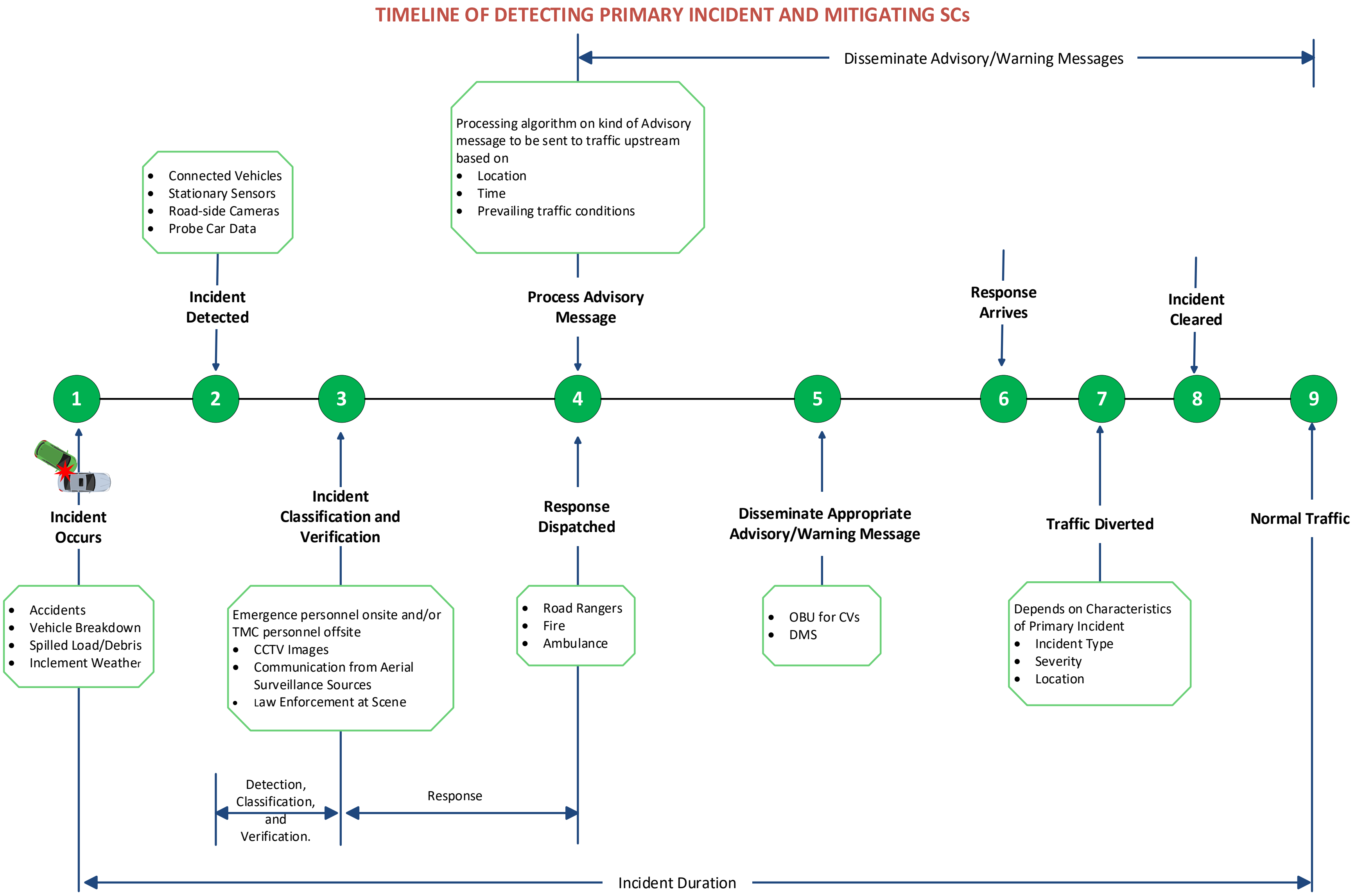

Figure 3-1 Timeline of detecting primary incident and mitigating SCs.

For instance, a CV can identify the incident and simultaneously verify the information, while sending the incident-related information to upstream CVs. The following subsections discuss each stage of the proposed communication plan in detail.

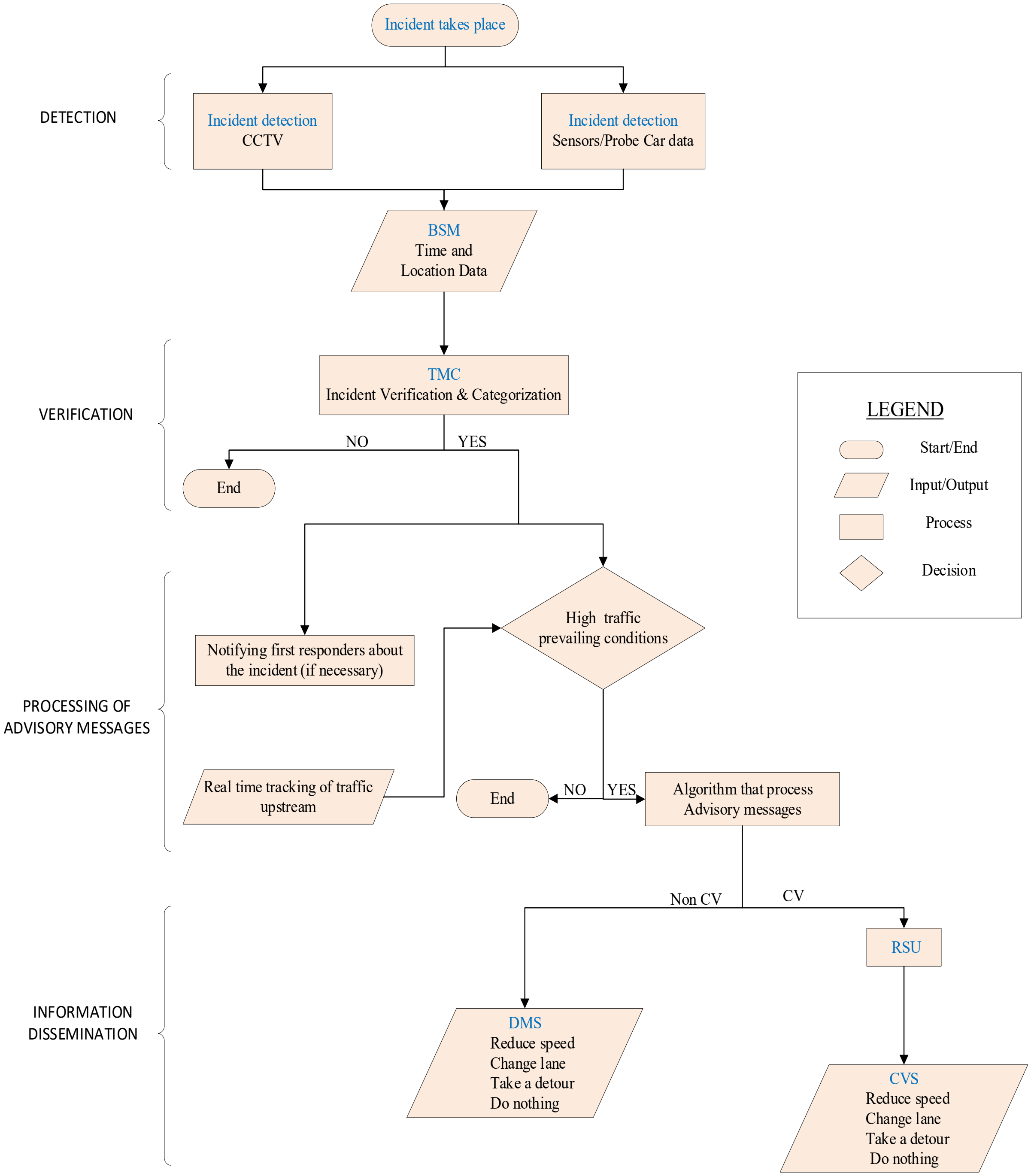

Figure 3-2 Flow chart of incident detection and mitigation of SCs.

3.1.1 Detection

Detection is the first stage in a communication plan and is also the first step in managing an incident. Detection is determining that an incident or an abnormal traffic condition has occurred. Quick detection enables quick execution of other stages in a communication plan, which in turn reduces the overall incident impact. Various techniques with different capabilities have been used for incident detection, which can be grouped into the following three categories (Federal Highway Administration [FHWA], 2010; Federal Highway Administration [FWHA], 2000):

- Motorists reports: motorists aid call boxes and cell phone calls from motorists,
- Reports by professionals: service and police patrols, aerial surveillance and department of transportation, and
- Electronics and ITS techniques: closed-circuit television (CCTV), electronic traffic measuring with incident detection algorithms, and emerging CV technology.

The proposed communication plan is primarily focused on ITS detection techniques due to their overall benefits (Neudorff et al., 2003). Additionally, the plan compliments other detection means such as motorist and professional reports.

Probe car data

Vehicles can serve as moving sensors (or probes) through the use of vehicle-locating technologies (Neudorff et al., 2003). These vehicles provide traffic information over the roadways they traverse, which is transferred to a central computer system where it can be used to detect an incident. Transferred information includes: car ID, position coordinates, acceleration, speeds, travel times, and origin and destination of vehicles within the system, all acquired in every second (Hyodo et al., 2017).

Vehicle locating technologies used by probe vehicles include Automatic Vehicle Identification (AVI) and Automatic Vehicle Location (AVL) (Xiaobo Liu et al., 2012; Neudorff et al., 2003). In the proposed communication plan, probe vehicles will use the AVL technology. This technology allows the identification and tracking of vehicle locations as they travel along the roadways. Control centers' software use probe vehicle reports to monitor the acceleration, travel speeds, and travel times to identify the occurrence of incidents (Neudorff et al., 2003). Detection software has algorithms that compare different metrics to detect an incident, such as acceleration and deceleration of the individual vehicle, the statistical difference in the mean section travel time, changes in vehicle speed in the space-time dimension, and abnormal car movements with pre-established thresholds (Asakura et al., 2015). Global Positioning Systems (GPS) is one of the technologies used in AVL for locating vehicles, and is also used to derive other traffic metrics.

GPS is a global navigation system that uses a network of satellites to provide users with positioning, navigation, and timing services. These satellites are free-of-charge to any device capable of decoding the satellite signals. GPS works under any weather conditions, anywhere in the world, 24 hours a day.

Video Image Processing

ITS systems, such as inductive loop detectors, video image processing, and probe car data use two techniques to detect an incident (Federal Highway Administration [FWHA], 2000). One of the techniques to detect an incident is where an operator observes an ITS graphical output and pinpoints unusual traffic conditions that might indicate the occurrence of an incident. The key warnings used to indicate an incident are immediate speed drops and a significant increase in traffic congestion. In the second technique, computer software that uses an incident detection algorithm is applied to pinpoint incidents by comparing traffic detection output from ITS systems to normal traffic conditions. The software provides an alert that identifies the location of the incident whenever there are specified abnormalities or significant variations from normal traffic conditions. Once either of the two methods has identified the incident, the operator is tasked to verify the incident.

3.1.2 Verification

Incident verification is the process of validating that an incident has occurred, identifying the precise location and other incident-related information (Martin et al., 2011; Neudorff et al., 2003). This process is usually performed by the TMC personnel, who communicate the verified incident-related information to incident responders and travelers. Efficient incident verification reduces the time required to dispatch responders and disseminate appropriate information to travelers (Federal Highway Administration [FWHA], 2000). Operators at the TMC may use various methods to verify incidents, including dispatched field units to the incident site, satellites, cellular calls, and CCTV cameras. In this proposed communication plan, the incident verification process focuses on the CCTV method.

Closed-Circuit Television (CCTV)

CCTV systems have been used for many years to monitor freeway operations remotely. These systems allow TMC operators to visually verify incidents detected in real-time. According to FWHA (2000), CCTV systems are more efficient in incident verification and monitoring traffic conditions than detecting incidents scenes. For better monitoring of traffic conditions on roadways, these cameras are positioned high enough and close to each other to provide continuous coverage (Federal Highway Administration [FWHA], 2000).

The availability of CCTV enables TMC operators to access the cameras closest to the identified incident location and perform an initial evaluation of the incident severity. This assessment determines the primary resources needed at the scene and the information dispatched to upstream traffic. Sharing CCTV images electronically between multiple agencies with different expertise can provide aid in verifying and evaluating incidents quickly. Modern CCTV systems are signaled by incident detection algorithms to automatically switch the display to the detected incident locations, and also give an alert to the operator (Neudorff et al., 2003; The U.S. Department of Homeland Security, 2013).

3.1.3 Processing of information and advisory messages

The processing of data for advisory messages begins after the incident verification process. This information is useful to warn and guide the upstream road users on current downstream traffic conditions. In the proposed communication plan, processing of information and advisory messages sent to upstream traffic is based on the following factors:

- Type and severity of the primary incident,
- Location of the driver relative to the incident location,
- Prevailing traffic conditions, and
- Presence and traffic conditions of possible alternative routes.

Information processing allows upstream drivers to receive different messages relevant to their respective positions relative to the incident scene. The purpose of these messages is to warn and give safety advisory messages, such as the use of available alternative routes, reduce speed, or change lanes. This information not only increases awareness to drivers, but also suggests the best action to take to reduce the chances of SCs, which in turn improves the overall safety on the freeway (Chou & Miller-Hooks, 2011; Xiaoyue Liu et al., 2013).

Speed Advisory Messages

A smooth reduction in speed of the upstream traffic decreases hard-braking, as well as rapid deceleration conditions, which can prevent the occurrence of SCs. Based on the factors mentioned above, the processing stage of the proposed communication plan advises different speeds to vehicles upstream. The rate of drivers to observe the advised speed, as well as improved performance of the network, have been reported when advisory speeds are only slightly lowered from posted speeds, compared to higher reductions (Riggins et al., 2016). Various ways and platforms, such as CVs and DMSs, are used to disseminate speed advisory messages to road users.

Lane Change Advisory

An incident may result in lane(s) closure. The upstream traffic needs to be informed about the closure and also be advised to change to unblocked lanes. The distance from the incident location and the upstream lane change message varies depending on the method of broadcasting. DMS signs are fixed in position, hence advisory messages may be displayed well upstream of an incident. Unlike DMSs, CV technologies disseminate the advisory message to all vehicles in its range of communication. In both cases, the algorithm considers traffic conditions and incident characteristics to vary the message among vehicles upstream of the incident scene.

Alternate Route Advisory

The FHWA listed reduction in SCs as one of the benefits of using alternative route plans on highways (Dunn Engineering Associates, 2006). Furthermore, in 2007, the USDOT embraced the ICM strategy. This strategy aims at utilizing the underused capacity of parallel arterials by diverting traffic from the freeway when necessary (Xiaoyue Liu et al., 2013).

The developed communication plan considers the number of lane closure, the location of the incident scene relative to the starting point of the diversion opening, and an increase in travel time to advise upstream drivers to consider an alternative route. Diversion strategies have shown significant benefits in safety and mobility for incidents with durations of 30 minutes or longer, with more than one lane closure (Chou & Miller-Hooks, 2011).

In the proposed communication plan, travel time is used as a performance measure that triggers traffic diversion during incident duration. Vehicles are advised to consider a detour whenever the travel time on the main route becomes longer than using a detour. Previous studies show that diversion of only 10-15% of the traffic flow can produce optimal benefits, and higher diversion rates may further decrease travel time on the main route and overall network (Liu et al., 2012; Park & Smith, 2012; Zhou, 2008). However, high diversion rates may also reduce performance on the alternate routes. Therefore, diversion of traffic is advised so long as motorists do not experience longer travel times when using the alternate route. This is accomplished by tracking the diverting traffic on the alternate route. In the proposed communication plan, DMSs and CV on-board systems are the primary methods for disseminating detour messages, as discussed later in this chapter.

3.1.4 Information dissemination

Motorists depend on a wide variety of information to safely attain the control, guidance, and navigational aspects of driving tasks. Information may be provided in various ways, including static (pavement markings and regulatory, warning, and guide signs) and real-time information. The first three stages of the proposed communication plan generate an appropriate advisory and warning messages to different vehicles upstream of the incident location. The last stage is to broadcast the generated messages/information to upstream travelers (information dissemination). Broadcasting of incident-related information and advisory messages is performed to improve safety and travel conditions on the roadway by adjusting the motorist behavior (Neudorff et al., 2003). Dissemination of information to motorists can be accomplished using various methods, and may include:

- DMSs,
- Emerging technologies, such as CV, and
- Information sharing technologies, such as WAZE and 511 information services.

Regardless of the method used in broadcasting, in order to share information effectively, it must be timely, complete, accurate, and credible; otherwise, it will be ignored (Neudorff et al., 2003). Since the target of the proposed communication plan is to mitigate the occurrence of SCs, en route traveler information was employed. This provides motorists with real-time roadway incident information while traveling en route to their destination. Information is generally disseminated via roadside devices, or from devices equipped on the dashboard of the vehicle. Along the roadway, the plan utilizes DMSs and Highway Advisory Radio (HAR) messages, which display information, such as lane closure, congestion, weather conditions, advisory speed, or alternative routes. The connection from the control room in TMCs and DMSs enables updated information to be shared with motorists to reflect prevailing traffic conditions. The proposed communication plan also utilizes in-vehicle and personal mobile devices, as discussed below.

3.2 Connected Vehicles and Information Sharing Technologies

3.2.1 The Infrastructure used in the CV environment

Three main components which enhance the connected environment are:

- On-board Units (OBUs) that stay on in CVs to facilitate the exchange of information,
- Roadside Units (RSUs), located adjacent to the road and act as both a broadcaster and receiver to and from CVs within its range, and

A back-office server, which connects to the roadside equipment (RSE) and monitors the entire traffic network (Songchitruksa et al., 2016). The server receives requests to post in-vehicle messages

The communication plan to mitigate SCs under the CV environment consists of on-board equipment capable of acquiring, catching, formatting, and sending data from CVs, using DSRC, to roadside equipment from which probe data can be acquired for other CV applications. Unlike communication under a non-CV environment, connected environments have fewer stages from detection to information dissemination, as shown in Figure 3-3. This enables the connected environment to quickly broadcast safety messages and potentially mitigate SCs in real-time.

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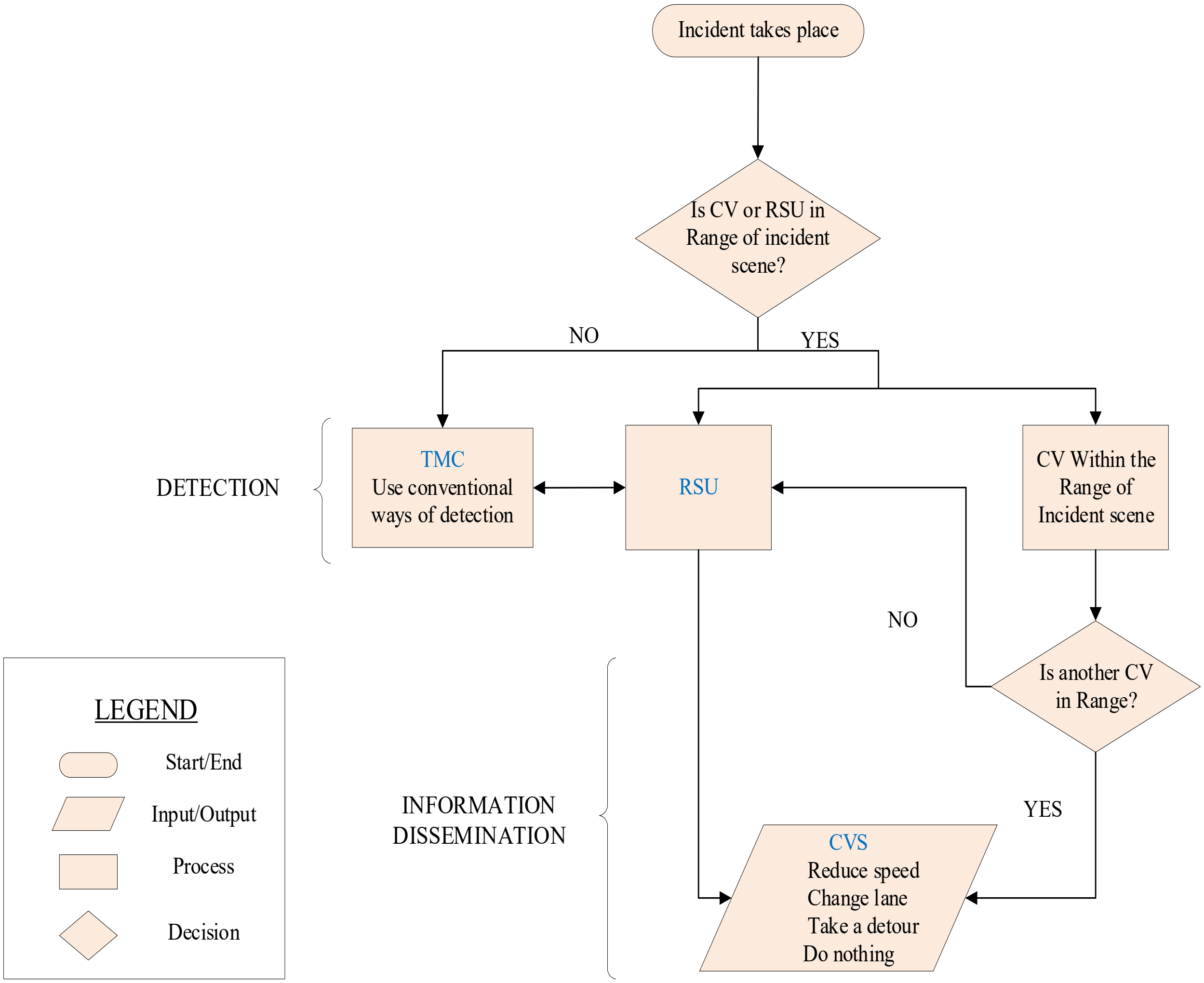

Figure 3-3 Flow chart of incident detection and mitigation of SCs under the CV environment

3.2.2 Incident detection using the CV technologies

Various communication technologies, such as DSRC, cellular communication, and the Vehicle Ad-hoc Network (VANET), enable on-board devices, mounted on CVs, to enhance V2V, V2X, and V2I communications. DSRC has been mentioned as an effective means of communication for traffic safety applications because it is fast, secure, reliable, and operates on a dedicated spectrum (Songchitruksa et al., 2016). A continuous exchange of real-time information, such as speed, position, acceleration/deceleration, and direction, among and between on-board units (OBUs) and roadside unit (RSUs), updates CVs about the status of other CVs. Changes in vehicle status, for instance, hard braking, stopped vehicles, and a significant reduction in speed, will notify CVs upstream about a possible incident occurrence at the downstream location. CVs in the network detect the abnormal vehicle status of other equipped vehicles by using CV applications listed in Table 3-1. In addition, vehicle status is shared as probe data from CVs to RSUs, whereby it can be used by other CV applications, such as incident detection, by comparing received vehicle status with the normal traffic flow.

Table 3-1: CV Applications Used for Incident Detection

No:	Need	CV application	Support
1	Need to reduce crashes between vehicles	Forward Crash Warning (FCW)	Warn drivers in case of an impending rear-end crash with another vehicle ahead in the same lane and direction of travel
2	Need to reduce crashes between vehicles	Emergency Electronics Brake Light (EEBL)	Notify drivers when a vehicle ahead generates an emergency brake event
3		Distress Notification	This application enables connected vehicles to communicate a distress status when the vehicle's sensors detect an event that might require assistance from others such as airbag deployment or when the vehicle's operator manually initiates a distress status.

3.2.3 Information dissemination using the CV technologies

The greatest challenge associated with the broadcasting of advance warning messages (i.e., speed advisory, lane change advisory, and detour/alternate route advisory) to inform upstream drivers of potential SC risks is to determine the location, time, and delivery method to alert motorists of the primary incident. The use of inter-vehicle communications, such as DSRC, Cellular, and VANET, allows CVs to exchange information and vehicle status with other devices in a connected environment, and hence, alleviate the challenge of broadcasting advance warning messages. DSRC is useful for time-sensitive applications, such as the V2V collision avoidance system, as it has a low latency of 200 microseconds and an ideal range of 1000 meters (Songchitruksa et al., 2016).

This allows vehicle status to be shared between CVs, which increases situational awareness within the 1000-meter vicinity of other equipped vehicles and several miles within the range of RSUs.

The developed communication plan has a connection between TMCs and RSUs; therefore, advisory messages processed at the TMCs can be shared to RSUs, and CV status can be collected by the RSUs for aggregation and provided to the TMCs as probe data. Advisory messages are generated by CV applications installed in equipped vehicles and RSUs. Vehicles that approach an RSU receive messages and decode them before passing the RSU (Badis et al., 2015). Currently, there are various CV applications that are used to increase situational awareness and enable crash prevention, safety, and mobility, as indicated in Table 3-2. Equipped vehicles receive advisory messages on the dashboard-mounted OBUs in the form of audio or visual messages, which alert drivers to act accordingly.

Table 3-2: CV Application Used to Increase Situational Awareness

No:	Need	CV application	Support
1	Need to manage speed in incident zones	Speed Compliance / incident Zone	Advise drivers to comply with the speed recommended to transverse or approach an incident location, thus reducing the potential of a SCs.
2	Need to reduce crashes between vehicles	Blind Spot Warning (BSW) + Lane Change Warning/Assist (LCA)	Warn the driver of the vehicle if the blind-spot zone is occupied by another vehicle traveling in the same direction during a lane change attempt and when it is not attempted
3	Need to inform drivers of serious incidents	Evacuation Notification	Provides notification that an area is to be avoided and why.
4		Infrastructure-to-Vehicle (I2V) Situational Awareness	This application enables relevant downstream road condition information including weather alerts, speed restrictions, vehicle restrictions, road conditions, incidents, parking, and road closures to be broadcast from an RSU and received by the connected vehicle.

Speed advisory warnings are provided by the *speed compliance* CV application, whereby a driver receives a recommended speed when approaching an incident zone, based on prevailing traffic conditions. For incidents that result in a lane closure, lane changing of vehicles upstream is assisted by *Blind Spot Warning (BSW)* and *Lane Change Warning/Assist (LCA)* applications*,* which ensure safe lane changes and help to mitigate SCs as vehicles strive to avoid the blocked path. The *evacuation notification* application informs drivers about serious incidents downstream and also suggests a suitable alternative route/detour. Table 3-3 summarizes the different CV applications used in different scenarios to mitigate the occurrence of SCs.

Table 3-3: CV Application Used in Different Scenarios to Mitigate SCs

Scenario		Effect to traffic upstream	Detection Means	Data Input	CV Application	Objective of CV Application	Communication		Message	Form of massage Display	Post-Conditions
							V2I	V2V			
Lane Closure	Shoulder Blocking, One lane blocked, Two lanes blocked	Hard braking/ Following too close and external distraction	Approached Vehicle OBU	CV Data: BSM from Approaching vehicle OBU. GNSS: Time and Location data.	Forward Collision Warning	Provide a warning to vehicle operators when too close to a preceding vehicle given the speed differential.		Approaching vehicle broadcasts a BSM containing data elements that indicates its position and motion. Approached vehicle receives the BSM, processes it, and determines that a warning should be issued.	Receives a warning that a forward collision is imminent.	Warning audio/ visual output from host OBU to vehicle operator under certain conditions.	Approaching Vehicle safely comes to a stop at the back of the queue.
		Improper lane change	Leading Vehicle OBU	CV Data: BSM from Leading vehicle OBU. GNSS: Time and Location data.	Lane Change Warning/ Blind Spot Warning	Notify vehicle operators when another vehicle is located in their blind spot.		Leading Vehicle Broadcasts a BSM containing data elements that indicates its position and motion. Trailing Vehicle Receives the BSM, processes it, and determine that a warning should be issued.	Receives a warning that there is a vehicle in the blind spot	Warning audio/ visual output from host/ leading OBU to vehicle operator under certain conditions.	Increased awareness of surrounding vehicles in blind spot and provide warning for safe lane change.

Table 3-4: CV Application Used in Different Scenarios to Mitigate SCs (continued)

Scenario		Effect to traffic upstream	Detection Means	Data Input	CV Application	Objective of CV Application	Communication		Message	Form of massage Display	Post-Conditions
							V2I	V2V			
Inclement Weather	Low visibility/ fog / icy road/ Poor road condition	Speeding based on conditions. Loss of traction Loss of Control	Turnpike weather Sources		Spot Weather Impact Warning (SWIW)	Provides more localized information (i.e., at the segment level instead of area wide or region wide)	Whether impact is reported to TMC from the source then from TMC to RSU broadcast from a RSU and received by the connected host vehicles.				
	Precipitation/ Wind	Speeding based on conditions. Loss of traction Loss of Control	Turnpike weather stations.		Situational Awareness application	Improve responsiveness of traffic management response during adverse weather information (i.e., at the wide or region area)	assembles important travel information from back-office systems and communications that directly to drivers through both DSRC and satellite communications			Variable speed limits, warnings on DMS, and full or partial road closures.	
Disabled Vehicle/ Primary crash (e.g. Air bag deployment)		Lack of attention Improper lane change Hard braking	Vehicles sensors/ Manual initiation by vehicle operator	The DN will include the location, time of message, distress message explanation, and vehicle category.	Distress Notification (DN)	This application enables connected vehicles to communicate a distress status	Vehicle generate and send DN to nearest RSU RSU forwards DN on TMC for notification of system operators and first responders.	V2V relay of DN (when RSU if primarily not in range)	The DN will include the location, time of message, distress message explanation, and vehicle category.		
					Curve Speed Warning (CSW)	An application where alerts are provided to the driver approaching a curve at a speed that may be too high for safe travel.					

Table 3-5: CV Application Used in Different Scenarios to Mitigate SCs (continued)

Scenario		Effect to traffic upstream	Detection Means	Data Input	CV Application	Objective of CV Application	Communication		Message	Form of massage Display	Post-Conditions
							V2I	V2V			
Debris	Sudden Traffic Stop	Improper lane change/ Sudden Stop	Host Vehicle OBU	CV Data: BSM from remote OBU. GNSS: Location and motion data.	Emergency Electronic Brake Application	Provide a warning to vehicle operators when a downstream vehicle brakes in an emergency fashion.		V1 OBU- Broadcasts a BSM containing a data element that indicates that an emergency braking maneuver has occurred V Upstream OBU- Receive the BSM, process it, and determine that a warning should be issued.	Emergency brake light warning.	Warning audio/ visual output from host OBU to vehicle operator under certain conditions.	The detrimental effects of a backward propagating congestion wave is minimized.

CHAPTER 4 METHODOLOGY

This study developed and modified a VISSIM model, adopted to attain the study objectives. The model was used as a simulation testbed. Incident modeling and V2I communication, i.e., applying the developed communication plan, was modeled using the Car-to-everything (C2X) module in the VISSIM software through the COM API. This module simulates wireless communication and data exchange within the connected environment. Scripting was done by the Visual Basic Scripting (VBS) language.

Another critical stage of this methodology was a safety evaluation, which employed the SSAM software. Finally, a statistical analysis was conducted to assess the significance of CVs in mitigating SCs in the analyzed scenarios.

4.1 Study site

The selected study corridor is a 7.8-mile, 6-lane (3-lanes in each direction) road segment on Florida's Turnpike Mainline (SR-91). The freeway segment is in Broward County and crosses four roadways: Sample Road, Copans Road, Coconut Creek Road, and Atlantic Boulevard. Each interchange ranges from 1 to 2 miles apart, with access to the Turnpike at each interchange except the Copans Road crossing. This site was chosen over other segments along Florida's Turnpike due to its relatively high number of crashes in the years 2016- 2019, based on observations from the Signal Four Analytics database.

Furthermore, a 4.2-mile section of Lyons Road, with two lanes in each direction, was considered for detouring purposes, as shown in Figure 4-1. The detour route is expected to divert a portion of the Turnpike's mainline traffic, particularly during the incident duration. The diverted traffic exits on Coconut Creek Road before traveling along Lyons Road and returning to the Turnpike mainline via W Sample Road. Compared to other possible detour routes on the Turnpike corridor, the selected detour is one of the sections with the closest consecutive interchanges (about ~ two miles).

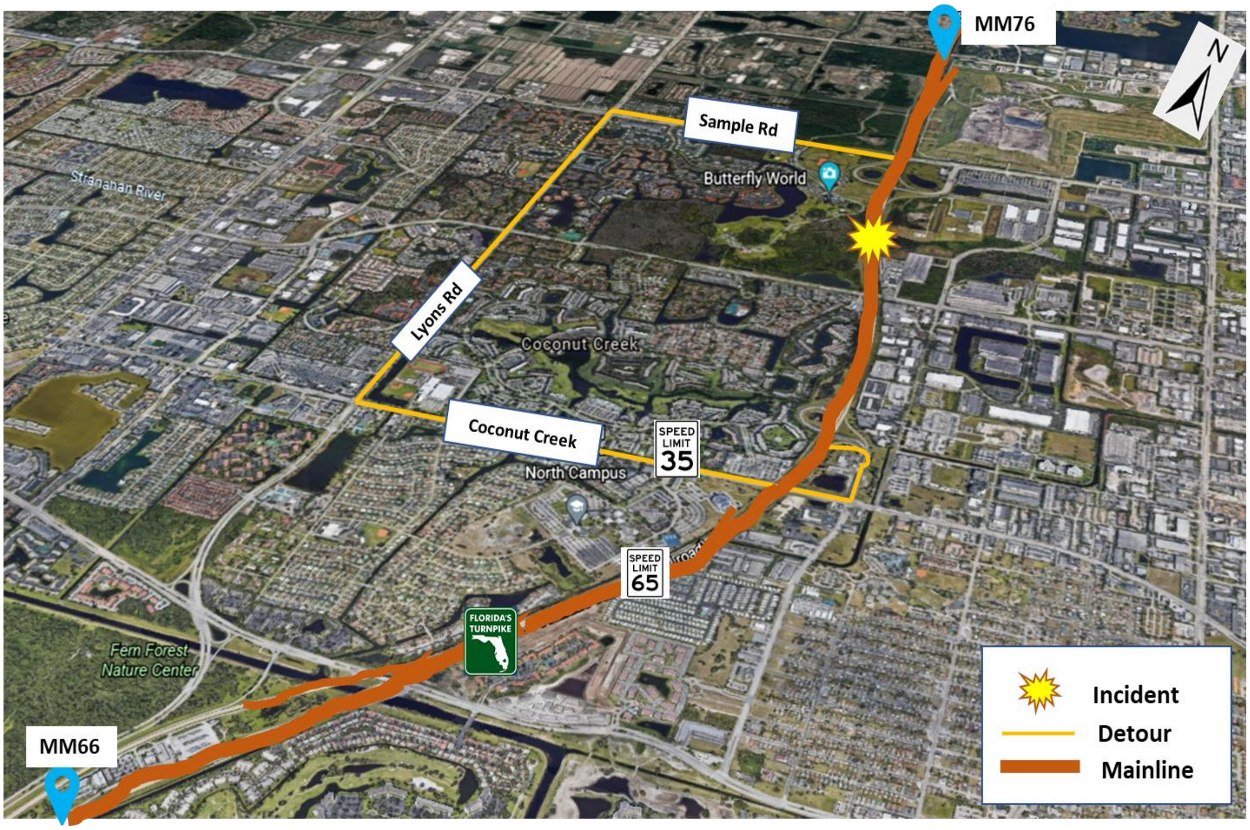

Figure 4-1 Study area

4.2 Model Network Development

VISSIM is a microscopic simulation software that evaluates the data of each vehicle data, based on car-following and lane-changing models. The software is capable of modeling complex traffic situations, such as CV communication, by indirect creation of sensors and wireless communication through the use of the component object model (COM). For these reasons, VISSIM 2020 software was used to model the traffic and road conditions and simulate the CV environment.

The VISSIM model used in this study was partly developed by the Florida Department of Transportation (FDOT) by merging the previously developed VISSIM models for the Sawgrass Expressway and Interstate 95 (I-95). To include the real-world queues, the model limits of the arterials were extended to a minimum of 0.5 miles outside the main construction project limits. It should be noted that the same model was used in previous work by Soloka (2019), which analyzed the potential safety benefits of CV technologies by considering blocking of an outside lane as the primary incident. This study extends the previous work by analyzing more scenarios, including blocking the inner lane, blocking the two outer lanes, and detouring strategies. Therefore, another VISSIM model for a detour was created and merged into the previous model to analyze the potential safety benefits of using detour strategies in the CV environment. The following subsections describe the merged VISSIM model used in this study.

4.2.1 Florida's Turnpike mainline

As shown by a rectangle in Figure 4-2, the segment of the location that experienced more crashes was clipped and modified from the parent Turnpike model used by Soloka (2019). The clipped segment was then used for further analysis.

The morning peak period was from 6:30 AM to 9:30 AM, and the evening peak was from 4:00 PM to 7:00 PM. During the peak period, the AM and PM peak hours were 7:30 AM to 8:30 AM and 5:00 PM to 6:00 PM, respectively. Furthermore, a 30-minute seeding time was added to load the network with traffic to attain equilibrium between the number of vehicles entering and exiting the traffic flow. The total simulation time was marked as 6:00 AM to 9:30 AM and 3:30 PM to 7:00 PM. Notably, traffic volumes represented traffic conditions of three different one-hour periods, including the pre-peak hour, peak hour, and the post-peak hour. The volumes were given in 15-minute intervals with the percentages of passenger cars and heavy goods vehicles. Table 4-1 provides a breakdown of traffic volumes along the Turnpike Mainline and the ramp volumes on each on-ramp and off-ramp used in the clipped model. Additionally, Table 4-2 shows the hourly conversion factors for each 15-minute interval in the total simulation period. These factors were generated based on time-slicing factors obtained from the hourly traffic volume distribution recorded in the field.

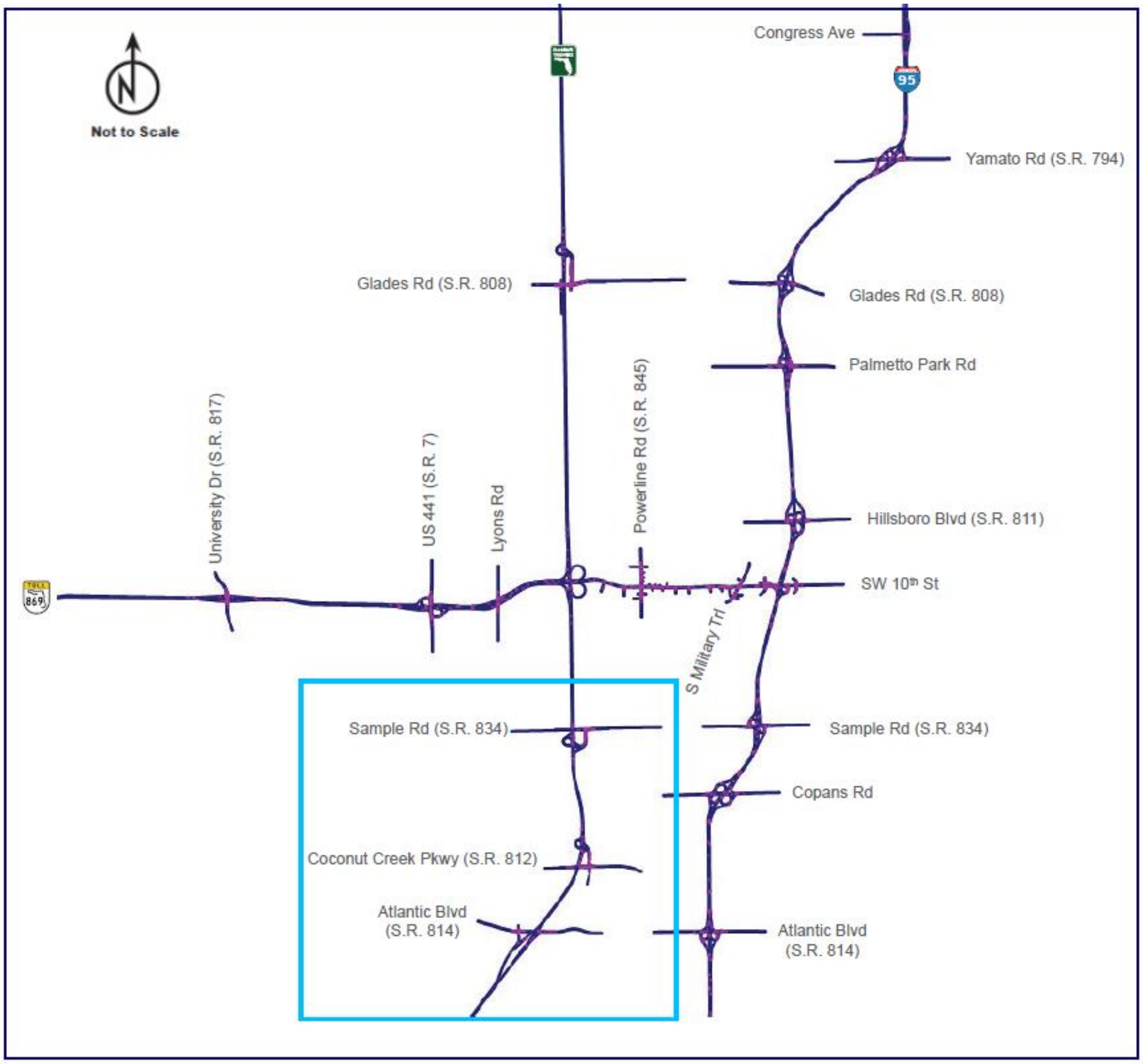

Figure 4-2 Turnpike VISSIM model.

Table 4-1: Main Simulation Model Traffic volumes

(a) AM Period			
Location	Demand Volume	Location	Demand Volume
Florida’s Turnpike Northbound		Florida’s Turnpike and Southbound	
Mainline before Atlantic Boulevard off-ramp	6,090	Mainline after on-ramp from Sawgrass Expressway	5,460
Mainline after Atlantic Boulevard off-ramp	4,860	Mainline after on-ramp from Sample Road	5,740
Mainline after on-ramp from Coconut Creek Road	4,810	Mainline after on-ramp from Coconut Creek Road	4,910
Mainline after on-ramp from Sample Road	4,160	Mainline after on-ramp from Atlantic Boulevard	5,840
Off-ramp to Atlantic Boulevard	1,230	On-ramp from Atlantic Boulevard	930
Off-ramp to Coconut Creek Parkway	710	Off-ramp to Coconut Creek Parkway	1,230
On-ramp from Coconut Creek Parkway	660	On-ramp from Coconut Creek Parkway	400
Off-ramp to Sample Road	1,200	Off-ramp to Sample Road	690
On-ramp from Sample Road	550	On-ramp from Sample Road	970
(b) PM Period			
Location	Demand Volume	Location	Demand Volume
Florida’s Turnpike Northbound		Florida’s Turnpike Southbound	
Mainline before Atlantic Boulevard off-ramp	5,720	Mainline after on-ramp from Sawgrass Expressway	3,980
Mainline after Atlantic Boulevard off-ramp	4,830	Mainline after on-ramp from Sample Road	4,610
Mainline after on-ramp from Coconut Creek Road	5,560	Mainline after on-ramp from Coconut Creek Road	4,660
Mainline after on-ramp from Sample Road	5,140	Mainline after on-ramp from Atlantic Boulevard	5,900
Off-ramp to Atlantic Boulevard	890	On-ramp from Atlantic Boulevard	1,240
Off-ramp to Coconut Creek Parkway	400	Off-ramp to Coconut Creek Parkway	620
On-ramp from Coconut Creek Parkway	1,130	On-ramp from Coconut Creek Parkway	670
Off-ramp to Sample Road	1,060	Off-ramp to Sample Road	400
On-ramp from Sample Road	640	On-ramp from Sample Road	1,030

Table 4-2: Hourly Volume Conversion Factors

	Simulation Time (Seconds)	AM Condition		PM Condition	
		15 minutes	Hourly	15 minutes	Hourly
Seed Time	0 - 900	9.38%	22.07%	22.08%	45.34%
	900 - 1800	12.69%		23.26%	
Pre-Peak Hour	1800 - 2700	16.57%	81.55%	22.37%	92.31%
	2700 - 3600	19.38%		22.92%	
	3600 - 4500	21.29%		23.20%	
	4500 - 5400	24.31%		23.82%	
Peak Hour	5400 - 6300	25.50%	100.00%	24.25%	100.00%
	6300 - 7200	25.32%		25.20%	
	7200 - 8100	24.74%		25.39%	
	8100 - 9000	24.44%		25.17%	
Post-Peak Hour	9000 - 9900	23.60%	87.19%	24.44%	92.82%
	9900 - 10800	22.38%		24.07%	
	10800 - 11700	20.74%		22.83%	
	11700 - 12600	20.47%		21.48%	

4.2.2 Lyons Road

A parallel arterial, Lyons Road, was included in the analysis to evaluate the benefits of detour strategies. Therefore, a VISSIM model was developed from the Turnpike exit on Coconut Creek Road and then connected to Lyons Road, and finally, to W Sample Road. The model replicated the existing road geometric conditions, desired speed, and priority rules along the detour. The traffic volumes were taken from the Florida Traffic Online (FTO) database for the AM and PM peaks. The traffic volume balance was considered between the volume obtained from FTO and those entering and exiting the Turnpike network, and then entered in 15-minute intervals, the same as in the Turnpike mainline model.

PTV Vistro 2020 software was used to obtain signal timings for major signalized intersections along the detour. The software exported Ring Barrier Controller (RBC) files with optimized signal timings for each intersection. The RBC files were imported into the VISSIM software to provide priority rules at signalized intersections along the considered detour. It was advantageous to use PTV Vistro for signal optimization due to its compatibility with PTV VISSIM.

4.3 Model Calibration and Validation Processes

The VISSIM model containing the Turnpike network was provided by the Florida Turnpike Enterprise, and the initial calibration and validation process is well documented in their VISSIM model calibration report. The report gives details of the model development and calibration processes for the existing 2016 AM and PM peak conditions for the SW 10th Street project in Broward County. Calibration targets, including capacity, traffic volume, travel time, speed, intersection delay, queue length, and visualization, were used as recommended by the FDOT *Traffic Analysis Handbook*. These targets were established based on average speed, vehicle flows, and queues to ensure the developed model replicates existing traffic conditions.

The model was calibrated by an iteration process of adjusting model parameters, including vehicle following and lane changing driver behavior, to replicate congestions, bottlenecks, traffic patterns, and observed driver behaviors. A comparison was made between existing volumes and modeled volumes at freeway segments, ramps, and intersections. This comparison aimed to check and adjust the model geometry and parameters for any unmet demand at entry links.

4.3.1 Model calibration parameters.

The calibration process resulted in parameters indicated in Tables 4-3 and 4-4. Table 4-3 presents the freeway calibration parameters, and Table 4-4 presents the calibration parameters for the arterials. As mentioned before, the model included an extended segment of arterials outside the main construction project limits to include the real-world queues. Therefore, the calibration parameters for arterials were adopted for the merged detour model. Fine adjustments were made to the detour model's calibration parameters after merging it into the Turnpike model.

Table 4-3: Model Freeway Calibration Parameters

Lane Change Parameters	**Default**	**Freeway Calibration Parameters**
Necessary Lane Change (Route)		
Maximum deceleration	-13.12 ft/s2 (Own) -9.84 ft/s2 (Trail)	-13.12 ft/s2 -9.84 ft/s2
-1 ft/s2 per distance	200 ft (Freeway)	200 ft
Accepted deceleration	-3.28 ft/s2 (Own) -1.64 ft/s2 (Trail)	-3.28 ft/s2 -1.64 ft/s2
Waiting time before diffusion	60 s	180
Min. headway (front/rear)	1.64 ft	0.98 and 1.51 ft
To Slower Lane if Collision Time Above (seconds)	0.00	0.00
Safety distance reduction factor	0.6	0.25 and 0.40

Note: Max. = Maximum; Min. = Minimum.

Table 4-4: Model Freeway Calibration Parameters (continued)

Lane Change Parameters		**Default**	**Freeway Calibration Parameters**
Necessary Lane Change (Route)			
Max. deceleration for cooperative braking		-9.84 ft/s2	-29.99 and -31.99 ft/s2
Overtake reduced speed areas		Uncheck	Checked
Advanced Merging		Checked	Checked
Cooperative lane change		Unchecked	Checked especially for freeway merge/diverge areas
If Checked	Max. Speed Difference	6.71 mph	6.71mph
	Max. Collision Time	10 sec	10 sec

Note: Max. = Maximum; Min. = Minimum.

Table 4-5: Arterial Calibration Parameters

Lane Change Parameters		**Default**	**Arterial Calibration Parameters**
Necessary Lane Change (Route)			
Maximum deceleration		-13.12 ft/s2 (Own) -9.84 ft/s2 (Trail)	-13.12 ft/s2 -9.84 ft/s2
-1 ft/s2 per distance		100 ft (Arterial)	100 ft
Accepted deceleration		-3.28 ft/s2 (Own) -3.28 ft/s2 (Trail)	-3.28 ft/s2 -3.28 ft/s2
Waiting time before diffusion		60 s	180
Min. headway (front/rear)		1.64 ft	1.51 ft
To Slower Lane if Collision Time Above (seconds)		0.00	0.00
Safety distance reduction factor		0.6	0.25, 0.40, 0.50
Max. deceleration for cooperative braking		-9.84 ft/s2	-29.99 and -31.99 ft/s2
Overtake reduced speed areas		Uncheck	Checked
Advanced Merging		Checked	Checked
Cooperative lane change		Unchecked	Checked
If Checked	Max. Speed Difference	6.71 mph	6.71mph
	Max. Collision Time	10 sec	10 sec

Note: Max. = Maximum; Min. = Minimum.

4.4 Incident Modeling

Traffic microsimulation software allows the analyst to simulate incident blockages either directly or by using other events that have similar impacts on traffic operation at the incident location (Hadi et al., 2007). VISSIM simulation software does not have a specific built-in incident formation module. Therefore, various events are used to model incident blockages, such as parking events with specified dwell times (Xiaoyue Liu et al., 2013), signal heads, and adding a stopped vehicle at a specific link position (Chou & Miller-Hooks, 2011). However, the parking event approach has deficiencies. For instance, the incident start time depends on the vehicle's decision to enter the parking lot; hence, there is no control over the exact time of incident occurrence.

Instead of using the parking lot approach, the present study adopted a stopped vehicle approach to simulate incident blockages. This approach utilizes the *"AddVehicleAtLinkPosition"* function that exists within the COM interface. The function lets users add and remove a vehicle at a specific time at a chosen location (Chou & Miller-Hooks, 2011). In order to replicate an incident with this function, a vehicle is added with a speed of zero and stays at the incident location for the chosen incident active period. It is set to be removed when the incident is cleared. To simulate situations where two or more lanes are blocked, multiple vehicles with the same time of placement and removal can be added to adjacent lanes.

4.4.1 Incident duration

Exhibit 11-22 of the 2016 Highway Capacity Manual (HCM) provides mean distributions of freeway incidents by severity, as well as default incident duration parameters by incident type (Highway Capacity Manual [HCM], 2016). The present study adopted an incident duration of 30 minutes for both single and two lanes blockages. The chosen span was between the minimum and maximum duration for one lane and two lanes closed, as shown in Table 4-5.

Table 4-6: Incident Probabilities and Durations (HCM, 2016)

	Incident Severity Type				
Parameter	Shoulder Closed	1 Lane Closed	2 Lanes Closed	3 Lanes Closed	4+ Lanes Closed
Distribution (%)	75.4	19.6	3.1	1.9	0
Duration (mean)	34	34.6	53.6	67.9	67.9
Duration (std. dev.)	15.1	13.8	13.9	21.9	21.9
Duration (min.)	8.7	16	30.5	36	36
Duration (max.)	58	58.2	66.9	93.3	93.3

4.4.2 Analyzed scenarios

A lane blockage was considered as a primary incident that facilitates the creation of a SC environment. Various lane blockage scenarios were analyzed, such as one outer lane closed, one inner lane closed, and two outer lanes closed. The analysis also considered the effect of the time period, which reflects situations with different traffic volumes. Since full market penetration of CVs is not anticipated soon, a sensitivity analysis was performed using varying CV MPRs. A total of 90 scenarios were considered in the analysis, as described in Table 4-6.

Table 4-7: Different scenarios considered in this study

Scenario	Period	CV penetration
One outer lane blocked (AM)	Peak, Pre-peak, Post-peak	0%, 25%, 50%, 75%, and 100%
One outer lane blocked (PM)	Peak, Pre-peak, Post-peak	0%, 25%, 50%, 75%, and 100%
One inner lane blocked (AM)	Peak, Pre-peak, Post-peak	0%, 25%, 50%, 75%, and 100%
One inner lane blocked (PM)	Peak, Pre-peak, Post-peak	0%, 25%, 50%, 75%, and 100%
Two outer lanes blocked without detour (AM)	Peak, Pre-peak, Post-peak	0%, 25%, 50%, 75%, and 100%
Two outer lanes blocked with detour (AM)	Peak, Pre-peak, Post-peak	0%, 25%, 50%, 75%, and 100%

4.5 Secondary Crashes in Simulation Environment

Various models, such as the regression model, ordered logit model, probit model, logistic regression model, and Bayesian network model, have been developed and used to quantify SCs and their characteristics in the presence of historical traffic data (Federal Highway Administration [FHWA], 2020). The microsimulation approach has also been used to evaluate safety benefits of emerging technologies for the mitigation of SCs (Yang et al., 2017).

Despite being sophisticated, current microsimulation models do not simulate crashes and do not have any feature to assess the safety of different simulated traffic scenarios (Astarita & Giofré, 2020). The only alternative approach that has been introduced to evaluate the road traffic safety level is based on surrogate safety performance indicators. These indicators provide a causal or mechanistic basis for explaining complex time-dependent vehicle interactions that can compromise safety. In fact, safety evaluation using traffic conflicts or other surrogate safety measures derived on vehicle trajectories has been a booming research topic. According to the FHWA, the surrogate safety performance measures show the potential to provide a useful platform for identifying high-risk situations in the traffic stream and guiding cost-effective intervention strategies (Gettman et al., 2008).

Microsimulation and surrogate safety performances have been used to assess the impact of connected and autonomous vehicles on traffic safety (Paikari et al., 2014; Rahman et al., 2018; Yang et al., 2017). One study investigated the impact of V2V applications to mitigate SCs (Yang et al., 2017). The study captured vehicular conflicts as a proxy for secondary crash risk upstream of a primary crash site.

This study considered a lane blockage to represent a primary incident. The trajectory files for conflict analysis were filtered based on spatial-temporal relation with the modeled primary incident. That means the traffic conflicts obtained was directly influenced by the lane blockage. Therefore, the captured vehicular conflicts were used as a proxy for SCs risk upstream of the primary crash location. It is worth mentioning that the proposed communication plan and CV applications discussed in this study were targeted but not limited to the mitigation of SCs. The plan can improve the overall traffic safety on roadways since it increases situational awareness to motorists.

4.5.1 Limitation on SCs analysis in microscopic simulation environment

This study's primary focus is to mitigate SCs by using the proposed communication plan and CV applications. As was mentioned, vehicular conflicts were used as a proxy for the risk of SCs to occur. However, with the current state of the art, there is no direct linkage between simulated traffic conflicts and the number of possible SCs. Moreover, traffic conflicts are based on trajectories of a point representing the center of gravity of a vehicle (Young et al., 2014). Real vehicle dimensions and physical interactions at crashes are not commonly considered. This means that different types of vehicles, such as heavy vehicles, have not been specifically considered. Also, conflict indicators do not consider conflicts between moving vehicles and fixed roadside barriers and obstacles.

Certainly, driver mistakes generate many real crashes, and current microsimulation models have no way to simulate this. In a nutshell, the role of the human factor (error), the conflicts that are determined by non-intersecting trajectories (between vehicles and roadside objects and barriers), and the potential consequences of crashes have not been thoroughly investigated in traffic conflict simulation (Astarita & Giofré, 2020).

4.5.2 Behavior of convectional vehicles in the simulation environment

Despite CVs' promotion, it is anticipated that unequipped vehicles and CVs will operate together in mixed traffic environment over a relatively long period. Although CVs that received the safety message can optimize their driving behavior for safety, other non-equipped vehicles are still unaware of the crash condition. These non-equipped vehicles have to passively interact with each other as well as the informed CVs. They may adjust their car-following behavior and lane-changing behavior after perceiving and assessing other surrounding vehicles' status. These induced interactions and the adjusted behavior of CVs may change the overall safety performance of the traffic flow.

4.6 Employing the Developed Communication Plan in Microsimulation to Mitigate SCs

To mitigate the occurrence of SCs, the present study developed a communication plan discussed in Chapter 3 of this document. To the extent possible, the study used VB-scripting and the COM API interface in VISSIM to simulate the developed communication plan. This method enhances the CV environment and modeling of traffic behaviors and conditions during the simulation process. This section describes the procedures and techniques adopted to simulate the communication plan to alleviate SCs in freeways.

4.6.1 Incident occurrence

A number of events may act as a primary incident on freeways, as shown in Figure 3-1. These incidents may create conditions for the occurrence of SCs. In this study, a vehicle that blocks one or two lanes was used as a primary incident to create an environment for SCs. The incident modeling was performed in the COM interface, as discussed in Section 4.4.

4.6.2 The role of RSUs

TMCs monitor traffic flow in real-time by continuously collecting and assessing vehicle data, such as speed and position. This process is enhanced by various techniques, including probe car data, roadside cameras, and stationary sensors, which link to the TMCs. The role of these techniques in incident detection is well discussed in Section 3.1 of this document. In the connected environment, RSUs can collect and transmit various vehicle data from CVs in range. Thus, in this study, the modeling of RSU capabilities was considered in the COM environment to enable real-time data collection.

In the COM environment, the function "GetbyLocation" was used to return vehicle collection data within a 2-mile communication range. Vehicle attributes collected include vehicle ID, speed, desired speed, link ID, lane number, desired lane, location, coordinate front, and vehicle type. The collection of data followed a distance distribution that specifies probability of data loss. In this study, it was assumed that there was no data loss. Thus, all vehicle data within range were collected, and all CVs received information generated from the RSU in range. The "GetbyLocation" mimics RSU functions in the real world, which collects and communicates CV information within a range of two miles under DSRC communication technologies. All collected vehicle data were available for other processes in the COM, which enables the generation of advisory messages to be sent to CVs within range.

4.6.3 Incident detection

CV technology is one of the ITS incident detection methods used in the developed communication plan. In the COM environment, the RSU was modeled at the point close to the incident location. It was assumed that the RSU automatically detected an incident once occurred. A study by Sheikh et al. (2020) fully discusses the automatic incident detection mechanism using V2I communication. After incident detection and verification, vehicle data collected by the RSU was processed to generate an appropriate advisory message to upstream vehicles

4.6.4 Incident verification

Section 3.1 discusses various methods used to verify a detected incident. This process was simulated through the COM by tracking vehicle speed to detect any significant drop, thus, verifying incident occurrence. In VISSIM software, the desired speed distribution governs vehicle speed in the network. It defines the probability distribution of vehicle speed between the lower and upper bound. The VISSIM model contained data collection points close to the incident location, which operate as stationary sensors on freeways. The sensors collected vehicle data, speed in particular, at each simulation time step. After incident detection, the function *"SpeedAvgHarm"* was used to detect significant speed drop close to the incident location. The incident was verified when a speed drop was greater than or equal to 10 mph, and represented a significant difference between the upper and lower bound in the desired speed distribution. Notably, this method was used to verify an incident, but can also be used for incident detection.

4.6.5 Processing of information and advisory messages

Several operational assumptions were made in modeling the V2I communications to alleviate SCs. The adopted assumptions include:

- An incident was modeled in the northbound direction, and the safety analysis considered only northbound traffic.
- The communication plan was set to operate at 10 Hz. i.e., the vehicle data collection, processing of an appropriate advisory message, and dissemination of advisory messages were done on every 0.1 second, which has been used for Basic Safety Messages (BSM) (Kenney, 2011).

- The effective range of V2I communication was two miles, with the use of the DSRC mode.
- The study assumed no communication latency or information loss in V2I communication.
- Driver compliance with advisory messages was assumed to be 100%.

Figure 4-3 shows the algorithm used to process advisory messages to be disseminated to motorists during an incident period. The algorithm's objective was to provide speed, lane change, and/or detour advisory to drivers upstream of the incident location to mitigate the occurrence of SCs. The dashed rectangle in Figure 4-3 shows the part of the algorithm related to detour advisory, which was used for *with detour* scenarios.

The algorithm first determines if the vehicle approaching the incident location is a CV or not. If the vehicle is a CV, the algorithm checks whether it is within the DSRC range of the RSU close to the incident scene. When the CV is within range, the algorithm adjusts the CV driving behavior and retrieves the real-time vehicle data necessary to process the advisory messages. Data required include vehicle ID, speed, desired speed, link ID, lane number, desired lane, position, coordinate front, vehicle type, and travel time. Thus, the algorithm sends appropriate advisory messages in real-time to CVs within range. However, the algorithm also considers conventional car behaviors as they approach the incident location.

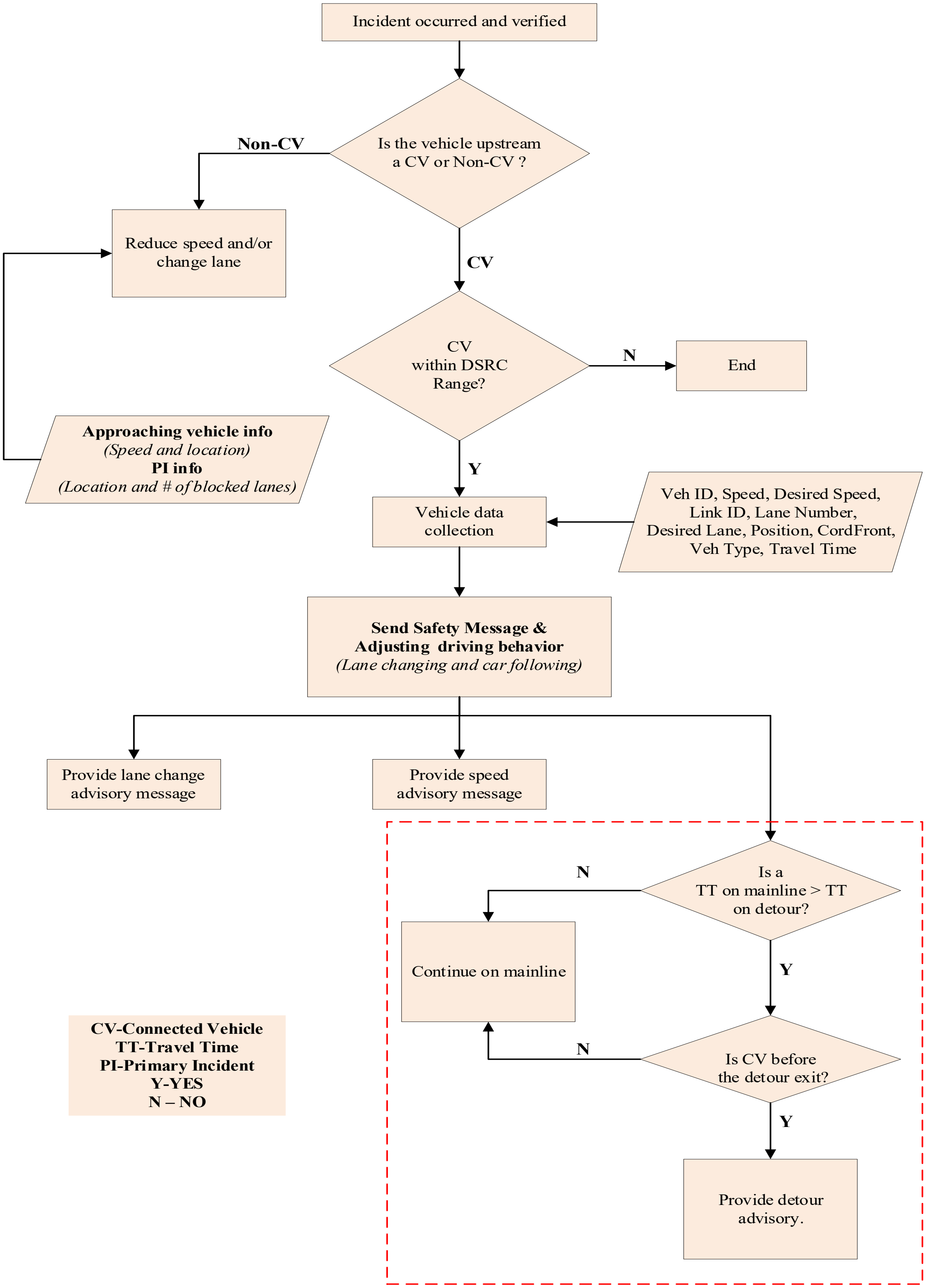

Figure 4-3 Algorithm to process advisory messages

Driver behavior in connected vehicle applications

VISSIM contains several customizable features for CV applications, such as driver models and capability to access objects data during simulation. It uses a psychophysical car-following model and rule-based model for longitudinal and lane-changing driving behavior, respectively. Additionally, VISSIM provides add-on APIs, such as COM and External Driver Model DLL, which provide users with the capability to incorporate their applications. In this study, COM API was used to access vehicle attributes and integrate CV applications during the run time. It should be noted that, in VISSIM, the value of perception reaction time is the same as the value of the simulation time step.

This study employed a Continuous Driving Behavior Adjustment (CDBA) method to model driving behavior for CV applications in VISSIM. The method is used for applications that give drivers continuous instructions to adjust their driving behavior for a particular goal (i.e., to mitigate SCs) during a specific period, as shown in Figure 4.4 (Songchitruksa et al., 2016). CDBA is applicable for CV applications, such as lane change assist (LCA) systems and variable speed limit (VSL).

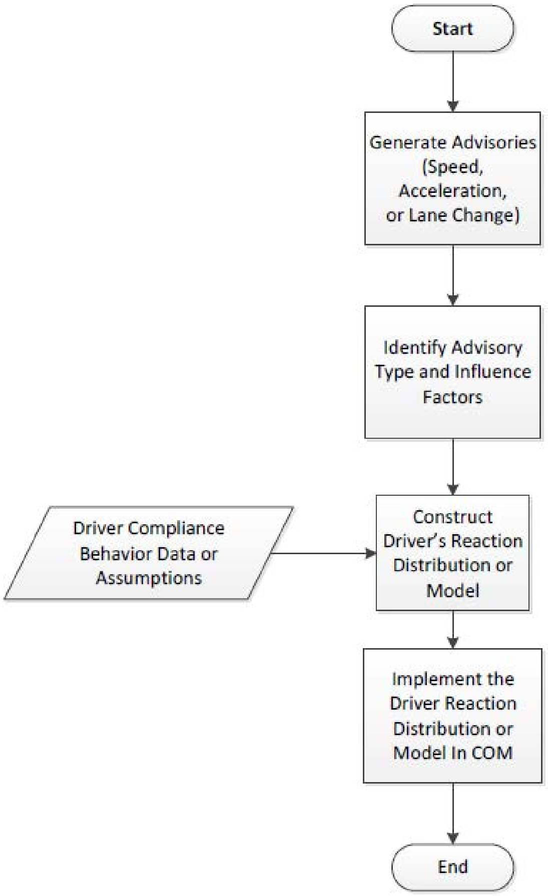

Figure 4-4 Process for Continuous Driving Behavior Adjustment (CDBA).

Changing of driving behavior and their potential use in simulating CV applications.

Primary incidents tend to disrupt traffic flow and induce queues. Consequently, the likelihood of rear-end and sideswipe crashes is increased, especially on freeways. Upon receiving the safety message, CVs adjust their driving status to maximize their safety benefits. In a V2V communication environment, a forward collision warning (FCW) application disseminates collision warning messages between leading and following CVs through OBUs. Also, a lane changing warning (LCW) application helps to enhance safe lane-change maneuvers. The mode of operation of these two V2V applications, i.e., FCW and LCW, is explained in Table 3-3. This study used V2I communication in which changes in both CV driving behaviors and advisory messages aimed at replicating the CV applications, including LCA systems (lane-changing advisory), VSL (speed advisory), and detour advisory.

In VISSIM, driving behavior parameters impact the simulated vehicles' aggressiveness or defensiveness, affecting overall traffic safety. Different models control vehicle movements in microscopic simulation, including car-following, lane-changing, and gap-acceptance models. The car-following model controls the interaction between two vehicles in the same lane, the lane-changing model governs the lateral movements of vehicles, and the gap-acceptance model dictates the merging of vehicles to a destined lane. One study performed a sensitivity analysis of VISSIM’s driver behavior parameters on simulated vehicles' safety using the SSAM software (Habtemichael & Santos, 2012). The findings were used in the present study as a basis for adjusting CV driving behavior to enhance safety benefits.

In longitudinal driving behavior, the number of observed preceding vehicles (in the ‘look ahead distance’ parameter set) controls how well vehicles can predict and react to the movement of other vehicles in the link. Setting the value to a maximum of 10 results in a smooth speed profile in traffic flow (Songchitruksa et al., 2016). For the car-following model, the simulated vehicle's safety distance is governed by two parameters – CC0 (standstill distance) and CC1 (headway time), as shown in Equation 1.

$$Safety\ distance = CCO + CC1 * speed \tag{1}$$

The safety distance is more affected by the multiplicative part (CC1) than the additive part (CC0), particularly for high-speed facilities like a freeway. A higher value of CC1 reflects a more cautious driver, enhancing safety by increasing the safety distance. CC2 (‘Following’ variation) controls how much more distance than the desired safety distance a driver allows before intentionally moving closer to the leading vehicle. Thus, the CC1 and CC2 values were set slightly higher for CVs than for conventional vehicles. It was observed that, the parameters considerably affect the travel time of a simulated vehicle, hence, attention is needed for their adjustment. Another important car-following parameter that significantly impacts the simulated vehicle's safety is the CC3 (the threshold for entering 'following'). It controls the deceleration process, in particular the number of seconds before reaching the safety distance. The driver recognizes a preceding slower vehicle at this stage, and the larger the CC# value, the more safety distance is assigned to the vehicle.

For the study corridor, both free and necessary lane-changing parameters were adjusted to enhance safe lane-changing maneuvers. In free lane-changing parameters, the ‘safety distance reduction factor’ most influences traffic safety. It controls the gap which a vehicle accepts for lane-changing maneuver. The larger the factor, the fewer the number of conflicts in the simulation. Regarding necessary lane-changing parameters, factors, such as lane-changing position, maximum deceleration of trailing vehicles, and acceleration reduction for trailing vehicles, are known to influence traffic safety (Habtemichael & Santos, 2012). In the present study, these three factors were adjusted to increase the safety of simulated vehicles.

Adjusting to CV’s driving behavior

A CV that receives the safety message will change its behavior under the crash condition by adjusting car-following and lane-change behaviors (Yang et al., 2017). In the simulation model, this was done by creating a separate driving behavior for a vehicle class *“CVs with the active message”,* which was added to the main link behavior types. This behavior was activated to all CVs within range by changing their vehicle type to one under the vehicle class “*CVs with the active message".* The vehicle type was returned back to its original type after passing the incident location, which restores original driving behavior. This change of the vehicle class was performed within the event-based script.

Lane-change advisory

Lane change messages were sent to all CVs within the communication range at a distance of 0.75 miles upstream of the incident location. Once received, the vehicles' desired lanes were set to those not blocked by the incident, making them change lanes once they get sufficient gaps on adjacent lanes.

Speed advisory

For speed advisory systems, speeds are sent directly into the OBU of an individual vehicle through V2I communication (Grumert & Tapani, 2012). The suggested speed that is given to a CV within a communication range depends on its distance from the suggested new speed point (incident location), its current speed, and the advised speed. The CV adjusts its speed, based on the desired speed distribution generated, to attain a smooth deceleration rate as it approaches the new recommended speed point.

For speed advisory messages, vehicles were only advised to reduce speeds when the average speed within 300 ft of the incident location deteriorated to 10% less than normal. Speed reductions were advised at 20 mph less than the speed limit, at 0.5 miles before the incident, and at 10 mph below the speed limit, at 0.75 miles before the incident location. It should be noted that the speed advisory varied with time and position upstream from the incident, depending on whether the primary incident was a single or double lane blockage.

Detour advisory

In this study, travel time was used as a performance measure to enhance traffic diversion during the incident duration. Vehicles were advised to consider a detour whenever the travel time through the incident scene becomes longer than using a detour.

Non-CV close to the incident location

Drivers in the blocked lane typically reduce speed and increase aggressiveness to change lanes as they approach the incident location (Hadi et al., 2007). Additionally, there also should be cooperation from a vehicle in the destination lane during the lane-changing maneuver. Thus, to replicate this reality, both speed and lane-change maneuvers of convectional vehicles were adjusted as they approached closer to the incident location.

4.6.6 Information dissemination

The developed communication plan has various ways of broadcasting information to motorists during an incident. In the simulation model, the RSU close to the incident scene generated incident-related information for CVs approaching the scene. CVs received advisory messages from the OBU and mobile devices mounted on the vehicles' dashboard. Dissemination of advisory messages was terminated when speed or travel time was improved to the specified thresholds, or at the end of incident duration.

Potential of smartphone applications

Crowdsourced data and smartphone applications, such as Waze and Twitter, are used to increase motorists' awareness of roadway conditions by detecting and disseminating incident-related information in real-time (Amin-Naseri et al., 2018; Gu et al., 2016). However, these applications receive data from users who might be slightly inaccurate in time or location and also do not provide a specific advisory message to motorists based on their location. This study went further and utilized vehicle data collected by the RSU in real-time to process the specific advisory message to different CVs based on their speed and position relative to the incident location. For severe incidents that induce long queues, smartphone applications could supplement and enhance detour advisories to motorists much further upstream of the incident location.

4.6.7 Simulations runs

The 90 scenarios, described in Table 4-6, were simulated by incorporating Visual Basic scripts in the VISSIM model through the event-based script, enabling the creation of the CV environment and controlling traffic behaviors during the simulation time. The resolution was set to 10-time steps per simulation second, which replicate a transmission frequency of 10 Hz for the BSMs. The VISSIM user manual recommends a minimum of five runs, depending on a simulated task (PTV, 2020). In order to eliminate the random effect, five simulation runs were conducted per single scenario, with a random seed increment of 10 for each run

4.7 Safety Evaluation

In this study, a 2-mile section upstream of the incident location was created in the VISSIM model to collect vehicle trajectories. This section replicates the V2I communication range of the RSU at the incident location through the use of DSRC technology. The vehicle trajectory files generated in each run, for each scenario, was then imported in the Surrogate Safety Assessment Model (SSAM) provided by the FHWA. SSAM facilitates the identification of conflicts through the use of statistical analysis of vehicle trajectory files generated from microscopic simulations.

Time to collision (TTC) and post-encroachment time (PET) was used as measurable traffic indicators to obtain quantitative data of traffic conflicts in the SSAM. Specific thresholds were adopted to determine critical conflicts i.e., 1.5 seconds for TTC and 5.0 seconds for PET, which are consistent with a previous study by Yang et al. (2017). Rear-end and lane-change conflicts, common in freeway operation, were considered to evaluate the CVs' potential in mitigating SCs.

CHAPTER 5 RESULTS AND DISCUSSION

This chapter discusses the conflict analysis results from the SSAM software. TTC and PET were used as safety surrogate measures, and the adopted thresholds were 1.5 seconds and 5.0 seconds for TTC and PET, respectively. Due to modeling limitations, occasionally an abrupt lane-changing behavior occurs, which can result in several simulated crashes with TTC = 0 seconds, as explained by previous studies (Gettman et al., 2008; Huang et al., 2013). In order to alleviate this challenge, the present study filtered out all simulated events with TTC = 0 seconds. Notably, SSAM classified the conflicts as rear-end or lane-changing conflicts, which are likely to occur on the freeway. Thus, the obtained conflicts were used as a surrogate measure to represent SCs.

This Chapter is categorized into two general parts. The first part entails the results from scenarios where one lane is blocked, while the second part discusses results from scenarios with two lanes blocked

5.1 Scenarios with one lane blocked

The study corridor used in the analyses consists of three lanes in each direction. To evaluate scenarios with one lane blocked, one out of the three northbound lanes was closed. The present study presents conflicts resulting from scenarios with a blocked inner lane and compares the findings with the previous study by Soloka (2019). Additionally, the detour strategy was analyzed when the outer or inner lane was blocked, and the results are presented in this section.

A previous phase of the current study (Soloka, 2019) presented results for scenarios in which the outer lane was blocked. The present study presents conflicts resulting from scenarios with a blocked inner lane and compares the findings with the previous study by Soloka (2019). Additionally, the detour strategy was analyzed when the outer or inner lane was blocked, and the results are presented in this section.

5.1.1 SSAM conflict results - AM period

Figure 5-1 presents the number of conflicts found during the AM pre-peak hour, AM peak hour, and AM post-peak hour. It shows the number of rear-end conflicts, lane-change conflicts, and total conflicts found for each 25% increment of CV penetration in each analysis period. Total conflicts are the sum of rear-end and lane-change conflicts for a specific CV penetration rate scenario. For the same analysis period, and the same CV penetration rate, the graphs show results from both scenarios: *Inner Lane Blocked (ILB)* and *Outer Lane Blocked (OLB)*. Furthermore, Table 5-1 shows a matrix that summarizes the percentage change in the number of conflicts as the CV penetration rate increases**.**

Total Conflicts

At any analysis period, for both the ILB and the OLB scenarios, the introduction of connected vehicles reduced the number of total conflicts. In ILB scenarios, as CV composition was increased, a more or less similar trend in conflict reduction was observed in all analysis periods. On the other hand, a varying pattern was observed when the outermost lane was blocked among different analysis periods. Notably, the results show a higher number of total conflicts in the OLB scenarios than in the ILB scenarios. More conflicts result in the OLB scenarios due to merge and diverge maneuvers.

Regarding ILB scenarios, results indicate a reduced number of total conflicts, by up to 98%, with full CV penetration. A reduction in conflicts was observed even at 25% MPR of CVs during the pre-peak, peak, and post-peak periods, as shown in Table 5-1. A consistent trend in conflict decline was observed for each 25% increment of CV composition

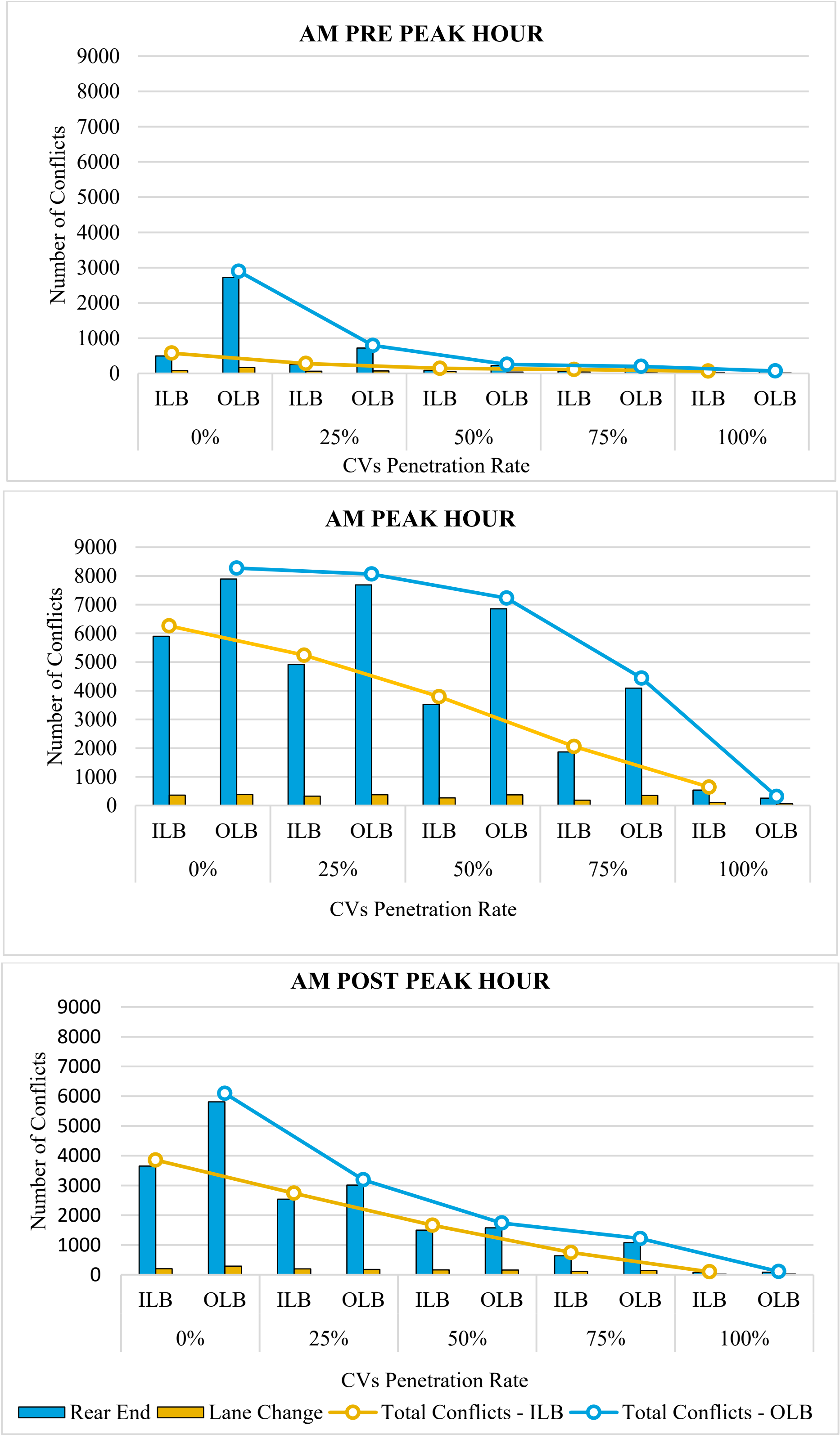

Figure 5-1 SSAM conflicts for scenarios with single lane blocked during the AM peak hour

Table 5-1: Percent change in conflicts for ILB and OLB scenarios (AM period).

	WHEN THE INNER LANE IS BLOCKED (ILB)											
	AM Pre-peak hour				**AM Peak hour**				**AM Post-peak hour**			
	Total Conflicts											
	Initial Composition (%)				Initial Composition (%)				Initial Composition (%)			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-44.90%				-16.30%				-29.00%			
50	-75.00%	-65.90%			-39.40%	-27.60%			-56.90%	-39.30%		
75	-82.00%	-73.10%	-28.10%		-67.10%	-60.70%	-45.80%		-79.80%	-71.60%	-53.20%	
100	-89.60%	-86.20%	-58.20%	-41.90%	-94.90%	-94.00%	-91.60%	-84.60%	-97.50%	-96.50%	-94.20%	-87.70%
	Rear-End Conflicts											
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-48.90%				-16.70%				-30.50%			
50	-82.60%	-65.90%			-40.20%	-28.30%			-59.00%	-41.00%		
75	-86.30%	-73.10%	-21.20%		-68.30%	-61.90%	-46.90%		-82.60%	-75.00%	-57.60%	
100	-92.90%	-86.20%	-59.50%	-48.50%	-95.60%	-94.80%	-92.70%	-86.20%	-97.90%	-96.90%	-94.80%	-87.70%
	Lane-Change Conflicts											
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-19.80%				-10.70%				-2.20%			
50	-27.40%	-9.50%			-26.40%	-17.60%			-18.80%	-16.90%		
75	-55.30%	-44.20%	-38.40%		-48.60%	-42.40%	-30.10%		-28.90%	-27.30%	-12.50%	
100	-68.40%	-60.50%	-56.40%	-29.20%	-83.60%	-81.70%	-77.80%	-68.20%	-91.10%	-90.90%	-89.10%	-87.50%
	WHEN THE OUTER LANE IS BLOCKED (OLB)											
	AM Pre-peak hour				**AM Peak hour**				**AM Post-peak hour**			
	Total Conflicts											
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-72.60%				-2.50%				-47.70%			
50	-91.10%	-69.30%			-12.60%	-10.40%			-71.50%	-45.50%		
75	-93.10%	-75.30%	-22.90%		-46.30%	-44.90%	-38.60%		-80.00%	-61.80%	-29.90%	
100	-97.60%	-92.30%	-72.90%	-64.90%	-96.20%	-96.10%	-95.60%	-92.90%	-98.30%	-96.70%	-93.90%	-91.40%
	Rear-End Conflicts											
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-73.60%				-2.60%				-48.10%			
50	-91.90%	-69.30%			-13.10%	-10.80%			-72.90%	-47.70%		
75	-93.50%	-75.30%	-19.60%		-48.10%	-46.80%	-40.30%		-81.50%	-64.30%	-31.70%	
100	-98.00%	-92.30%	-74.90%	-68.70%	-96.70%	-96.70%	-96.20%	-93.70%	-98.50%	-97.20%	-94.60%	-92.10%
	Lane-Change Conflicts											
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-57.60%				-0.80%				-38.60%			
50	-78.30%	-48.90%			-3.00%	-2.20%			-44.20%	-9.10%		
75	-87.50%	-70.60%	-42.40%		-8.80%	-8.10%	-6.00%		-51.10%	-20.30%	-12.40%	
100	-91.60%	-80.30%	-61.40%	-33.00%	-84.40%	-84.30%	-84.00%	-82.90%	-92.80%	-88.30%	-87.10%	-85.30%
				🟩	Conflict reduction			🟧	Conflict increase			

For the OLB scenarios, a pronounced reduction in conflicts was noticed at 25% CV MPR during the pre-peak and post-peak hours. In these periods, successive increments of CV composition beyond 25% resulted in a slight decline in conflicts. However, during the peak hour period, a greater reduction in conflicts was observed in the transition between 50% and 75% CV composition. It should be noted that the reduction in total conflicts was a result of a reduction in rear-end or lane-change conflicts or both. A detailed discussion on conflict reduction, per specific conflict type, is presented in the following subsections.

Rear-end Conflicts

In all scenarios, rear-end conflicts were more prominent than lane-change conflicts. This is because the freeway is a high-speed facility, so drivers may not find enough time to react to the incident ahead of their path. This effect may propagate to upstream traffic in a short time and result in many rear-end conflicts. These results are consistent with a previous freeway study that used VISSIM and SSAM tools and reported more rear-end conflicts compared to other conflicts (Atamo, 2012). As shown in Figure 5-1, fewer rear-end conflicts were observed for ILB compared to OLB scenarios. This difference may be due to the merge and diverge maneuvers side restriction for OLB scenarios. Notably, for both OLB and ILB scenarios, the overall reduction in the number of rear-end conflicts follows a similar trend as discussed in total conflicts.

With a 25% composition of CVs, a vast conflict reduction was reported for ILB scenarios during pre- and post-peak hours, by about 45% and 29%, respectively. Similarly, for the OLB scenarios, 73% and 48% of conflicts were reduced during pre- and post-peak hours, respectively. However, with only 25% of CV penetration, a lower conflict reduction was reported (approximately 2% for the OLB and 16% for the ILB) in the peak hour. Lower traffic volumes for the pre- and post-peak hours, unlike in the peak hour, might be a reason for the difference in conflict reduction among the peak periods. In all analyzed scenarios, rear-end conflicts decreased as the CV penetration rate increased. The high reductions in rear-end conflicts in the presence of CVs are associated with the decrease in vehicle speeds and change in driver behaviors, which were accounted for by early warnings of the incident and the advance advisory messages.

Lane-Change (LC) Conflicts

As shown in Figure 5-1, fewer lane-change conflicts were observed compared to rear-end conflicts. A minimal difference in the number of lane-change conflicts was observed between the ILB and the OLB scenarios. As the CV adoption rate increased, a relatively small reduction in LC conflicts resulted, despite which lane was blocked. The reduction was more pronounced in low traffic periods, pre- and post-peak hours in particular, than in the peak hour. For the OLB scenarios, little conflict reduction was observed in the peak hour until 100% penetration of CVs. This is possibly due to a situation whereby either a leading or lagging vehicle is not a CV, resulting in not enough cooperation in creating a gap for a lane-changing maneuver. Thus, with 100% composition of CVs, both leading and lagging vehicles are aware and behave cooperatively for lane-changing maneuvers, which results in a considerable reduction of the lane-change conflicts.

5.1.2 SSAM conflict results - PM period

Figure 5-2 presents the number of conflicts found during the PM peak periods. It shows the conflicts and scenarios similar to those discussed in the AM peak periods. The results are presented in a 25% increment of CV composition for pre-peak, peak, and post-peak hours. Again, the outermost or innermost lane blockage was considered with the primary incident for the analysis. Table 5-2 shows a matrix that summarizes the percentage change in the number of conflicts as CV penetration rate increases.

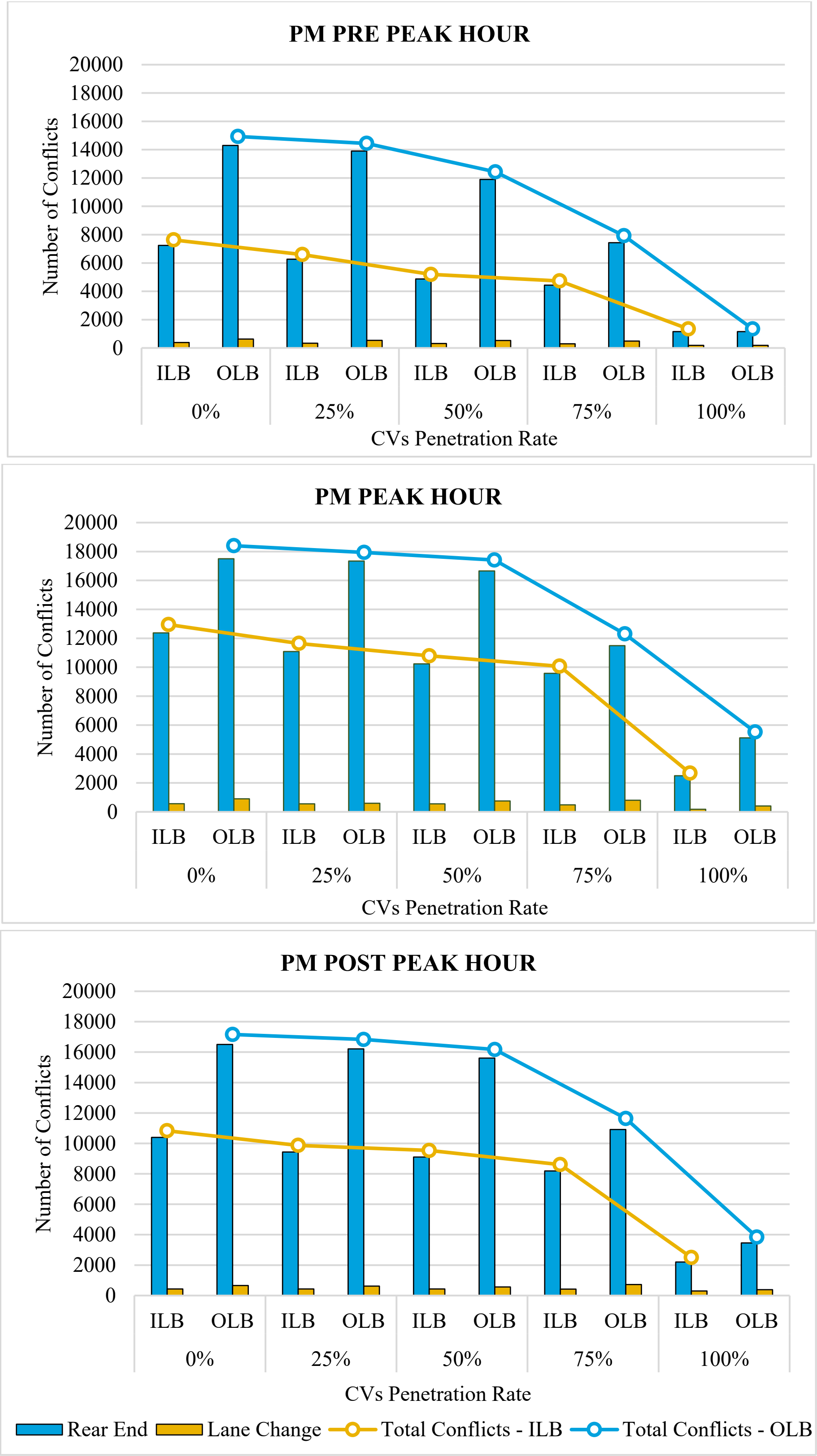

Figure 5-2 SSAM conflicts for scenarios with single lane blocked during the PM peak hour

Table 5-2: Percent change in conflicts for ILB and OLB scenarios (PM period).

WHEN THE INNER LANE IS BLOCKED (ILB)												
	PM pre-peak hour				**PM peak hour**				**PM post-peak hour**			
Total Conflicts												
	Initial Composition (%)				Initial Composition (%)				Initial Composition (%)			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-13.50%				-10.90%				-9.20%			
50	-31.90%	-21.30%			-17.40%	-7.40%			-11.90%	-3.00%		
75	-38.60%	-29.10%	-9.80%		-22.90%	-13.60%	-6.70%		-20.50%	-12.50%	-9.70%	
100	-82.40%	-79.70%	-74.10%	-71.30%	-79.50%	-77.00%	-75.20%	-73.40%	-76.90%	-74.60%	-73.80%	-71.00%
Rear-End Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-13.40%				-11.20%				-9.20%			
50	-32.70%	-22.20%			-18.10%	-7.70%			-12.40%	-3.50%		
75	-38.70%	-29.20%	-9.00%		-23.30%	-13.60%	-6.40%		-21.20%	-13.30%	-10.10%	
100	-84.00%	-81.50%	-76.20%	-73.90%	-80.00%	-77.50%	-75.60%	-73.90%	-78.80%	-76.70%	-75.80%	-73.10%
Lane-Change Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-14.60%				-3.10%				-8.90%			
50	-18.50%	-4.50%			-3.90%	-0.80%			-1.70%	7.90%		
75	-37.40%	-26.70%	-23.20%		-15.00%	-12.20%	-11.50%		-3.10%	6.40%	-1.40%	
100	-53.10%	-45.10%	-42.50%	-25.10%	-69.50%	-68.50%	-68.20%	-64.10%	-31.10%	-24.40%	-30.00%	-29.00%
WHEN THE OUTER LANE IS BLOCKED (OLB)												
	PM pre-peak hour				**PM peak hour**				**PM post-peak hour**			
Total conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-3.30%				-2.50%				-1.90%			
50	-16.70%	-13.90%			-5.40%	-2.90%			-5.80%	-3.90%		
75	-47.00%	-45.20%	-36.30%		-33.20%	-31.40%	-29.40%		-32.20%	-30.90%	-28.00%	
100	-91.00%	-90.70%	-89.20%	-83.10%	-70.00%	-69.20%	-68.30%	-55.10%	-77.60%	-77.20%	-76.20%	-67.00%
Rear-End Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-2.80%				-0.90%				-1.70%			
50	-16.80%	-14.40%			-4.80%	-3.90%			-5.40%	-3.70%		
75	-48.00%	-46.50%	-37.50%		-34.30%	-33.70%	-31.00%		-33.90%	-32.70%	-30.10%	
100	-91.90%	-91.70%	-90.30%	-84.40%	-70.80%	-70.50%	-69.30%	-55.50%	-79.10%	-78.70%	-77.90%	-68.30%
Lane-Change Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-14.10%				-33.80%				-6.40%			
50	-15.70%	-1.80%			-16.40%	26.20%			-15.00%	-9.20%		
75	-22.90%	-10.20%	-8.50%		-10.40%	35.20%	7.20%		10.20%	17.60%	29.60%	
100	-71.10%	-66.40%	-65.70%	-62.60%	-55.00%	-32.00%	-46.10%	-49.80%	-41.10%	-37.10%	-30.70%	-46.50%
		🟩	Conflict reduction				🟧		Conflict increase			

Total Conflicts

There were many conflicts reported from the analysis of the PM period, compared to the AM peak hours. Appendix A shows the difference in the number of conflicts observed during the AM and PM peak hours for all scenarios. During the PM period, the OLB scenarios reported more conflicts compared to the ILB. In all scenarios, the adoption of CVs reduced the number of total conflicts. With a blocked inner lane, the increase in CV composition resulted in conflict reduction, with a similar trend for the pre-peak, peak, and post-peak hours. A large reduction was found in the transition from 75% to 100% composition of CVs. Another consistent pattern of conflict reduction was seen in the OLB scenarios, as shown in Figure 5-2. Up to 50% CV penetration, a 5% reduction was observed for the peak and post-peak hours, whereas it was approximately 16% for the pre-peak hour. The transition from 50% to 75% penetration of CVs resulted in a considerable reduction in total conflicts for all peak hours. A following section gives a detailed discussion on conflict reduction per specific conflict type.

Rear-end Conflicts

The results show a larger number of rear-end conflicts in the PM period than their respective AM scenarios. These conflicts were more prominent than the lane-change conflicts. Unlike the AM peak hours, the PM period experienced a lower reduction of rear-end conflicts as CV composition increased. For instance, with up to 50% of CV penetration for OLB scenarios, a 5% reduction was observed for the peak and post-peak hours, whereas it was about 16% for the pre-peak hour. There was greater conflict reduction at low penetration rates (up to 50%) for the ILB than the OLB scenarios. As explained for the AM period, merge and diverge maneuvers side restriction contributed to more rear-end conflicts in the OLB than in the ILB scenarios. Notably, in both scenarios, maximum benefits in conflict reduction (about 80%) were reported at a full penetration of CVs.

The results show less reduction in conflicts at lower penetration of CVs during the PM peak hours. This result is possibly because of the higher traffic volume in the analyzed segment, as shown in Table 4-1 (b). Higher traffic volumes cause vehicles to move close to each other, and when the incident happens, only CVs get information and advisory messages. Thus, there are many conventional vehicles with neither incident information nor advisory messages at low CV penetration rates. Therefore, when a CV receives a speed reduction warning, a conventional vehicle(s) behind the CV may delay reducing speed. Consequently, the lack of cooperation among convectional and connected vehicles to perform safe maneuvers resulted in many rear-end conflicts. Nevertheless, with the full penetration, all vehicles receive an early warning and speed advisory, resulting in a considerable reduction in rear-end conflicts.

Lane-change Conflicts

With high traffic demand during the PM period, the results show less decline in lane-change conflicts as CV composition increased. The maximum reduction (approximately 70%) was experienced with full penetration of CVs during the pre-peak hour under the OLB scenario. Surprisingly, in some scenarios, conflicts increased with the increase in CV composition, as shown in Table 5-2. For example, during the peak hour for the OLB scenarios, conflicts elevated as CV penetration increased from 25% to 75%. This result may be attributed to many CVs receiving a lane-change advisory, unlike conventional vehicles. Thus, the lack of cooperation for lane-changing maneuvers among vehicles results in an overall increase in lane-change conflicts.

5.1.3 Statistical Analysis for scenarios with a single lane blocked

The safety indicators used for statistical analysis were the number of conflicts obtained from the SSAM safety evaluation. For a standard comparison among scenarios with different compositions of CVs, a 2-mile segment (CV communication range) upstream of the primary incident location was used as an exposure variable. The objective was to check the significance of CV technologies at various penetration rates in the mitigation of SCs (represented as traffic conflicts). The statistical analysis of the average number of conflicts employed a one-tailed t-test with the null and alternative hypotheses. The student *t*-test is used to determine if the means of two sets of data are significantly different from each other.

The null hypothesis was that the mean difference between the average number of conflicts between 0% and a succeeding percentage of CV compositions is zero. The null was tested against an alternative hypothesis that the mean difference between the average number of conflicts between the two scenarios is greater than zero.

- Null Hypothesis, H_0: $\mu_1 - \mu_2 = 0$, OR $\mu_1 = \mu_2$
- Alternate Hypothesis, H_A: $\mu_1 - \mu_2 > 0$, OR $\mu_1 > \mu_1$

where,
μ_1 = mean number of conflicts at 0% penetration of CVs
μ_2 = mean number of conflicts at *i*% penetration of CVs

Tables 5-3 and 5-4 shows the statistical test results at a 95% confidence level for the ILB and the OLB scenarios, respectively.

Furthermore, the statistical test was done to check whether there is a significant difference in the number of conflicts between the ILB and OLB scenarios. The null hypothesis was that, for a given MPR of CVs, the mean difference between the average number of conflicts between the ILB and the respective OLB scenario is zero. It was tested versus an alternate hypothesis that the mean difference between the average number of conflicts between the two scenarios is less than zero.

- Null Hypothesis, H_0: $\mu_i - \mu_o = 0$, OR $\mu_i = \mu_o$
- Alternate Hypothesis, H_A: $\mu_i - \mu_o < 0$, OR $\mu_i < \mu_o$

where,
μ_i = mean number of conflicts for the inner lane closure at *i*% penetration of CVs
μ_o = mean number of conflicts for the outer lane closure at *i*% penetration of CVs

Table 5-5 presents results from the statistical test at a 95% confidence level.

Table 5-3: Summary of paired t-test results for number of conflicts *(ILB scenarios)*

Period	**CV Composition**	**N**	Total conflicts					Rear-end Conflicts					Lane-change Conflicts				
			Mean	**St Dev**	**t-value**	**p-value**	**Significant**	**Mean**	**St Dev**	**t-value**	**p-value**	**Significant**	**Mean**	**St Dev**	**t-value**	**p-value**	**Significant**
AM Pre-peak hour	0%	5	574	125				495	126				79	3			
	25%	5	280	128	3.7	<.00318	YES	253	91	3.2	0.004	YES	63	10	3.5	0.004	YES
	50%	5	144	19	7.6	<.001	YES	86	16	7.2	<.001	YES	57	6	7.6	<.001	YES
	75%	5	112	28	8.1	<.001	YES	68	25	7.5	<.001	YES	42	14	6.0	<.001	YES
	100%	5	64	21	9.0	<.001	YES	35	11	8.2	<.001	YES	31	14	7.6	<.001	YES
AM Peak hour	0%	5	6259	313				5895	313				364	21			
	25%	5	5237	453	4.2	0.0016	YES	4912	439	4.1	0.002	YES	325	20	3.0	0.009	YES
	50%	5	3792	581	8.4	<.001	YES	3524	547	8.4	<.001	YES	268	35	5.3	<.001	YES
	75%	5	2057	505	15.8	<.001	YES	1870	491	15.4	<.001	YES	187	21	13.2	<.001	YES
	100%	5	643	25	38.2	<.001	YES	540	98	36.5	<.001	YES	103	15	22.3	<.001	YES
AM Post-peak hour	0%	5	3855	302				3653	290				203	14			
	25%	5	2738	16	8.3	<.001	YES	2540	15	8.6	<.001	YES	198	14	0.9	0.199	NO
	50%	5	1663	231	12.9	<.001	YES	1498	220	5.4	<.001	YES	165	11	2.5	0.020	NO
	75%	5	747	53	22.7	<.001	YES	635	45	7.0	<.001	YES	113	18	3.6	0.003	YES
	100%	5	96	5	27.8	<.001	YES	78	5	8.0	<.001	YES	17	5	5.8	<.001	YES
PM Pre-peak hour	0%	5	7626	273				7238	247				388	28			
	25%	5	6597	701	3.1	0.008	YES	6266	690	3.0	0.009	YES	331	11	4.2	0.001	YES
	50%	5	5191	302	13.4	<.001	YES	4875	297	13.7	<.001	YES	316	14	5.2	<.001	YES
	75%	5	4734	226	18.2	<.001	YES	4439	211	19.3	<.001	YES	295	32	4.9	<.001	YES
	100%	5	1343	84	49.2	<.001	YES	1160	84	52.1	<.001	YES	182	21	13.2	<.001	YES
PM Peak hour	0%	5	12948	634				12378	615				570	40			
	25%	5	11645	82	4.6	<.001	YES	11090	69	4.7	<.001	YES	556	14	0.8	0.2	NO
	50%	5	10785	468	6.1	<.001	YES	10234	450	6.3	<.001	YES	551	18	1.0	0.2	NO
	75%	5	10066	725	6.7	<.001	YES	9578	676	6.9	<.001	YES	488	49	2.9	0.0	YES
	100%	5	2675	229	34.1	<.001	YES	2500	255	33.2	<.001	YES	175	25	18.6	<.001	YES
PM Post-peak hour	0%	5	10830	420				10394	423				436	4			
	25%	5	9872	196	4.6	<.001	YES	9438	205	4.5	<.001	YES	434	35	0.1	0.455	NO
	50%	5	9537	609	3.9	0.002	YES	9108	595	3.9	0.002	YES	428	14	1.2	0.141	NO
	75%	5	8609	770	5.7	<.001	YES	8186	756	5.7	<.001	YES	422	19	1.5	0.081	NO
	100%	5	2500	383	32.7	<.001	YES	2204	354	33.2	<.001	YES	296	36	8.7	<.001	YES

Table 5-4: Summary of paired t-test results for number of conflicts (*OLB scenarios*)

Period	**CV Composition**	**N**	Total conflicts					Rear-end Conflicts					Lane-change Conflicts				
			Mean	**St Dev**	**t-value**	**p-value**	**Significant**	**Mean**	**St Dev**	**t-value**	**p-value**	**Significant**	**Mean**	**St Dev**	**t-value**	**p-value**	**Significant**
AM Pre-peak hour	0%	5	2897	136				2727	163				170	3			
	25%	5	793	157	22.6	<.001	YES	721	96	23.7	<.001	YES	72	10	21.5	<.001	YES
	50%	5	257	19	43	<.001	YES	221	14	34.2	<.001	YES	37	5	47.2	<.001	YES
	75%	5	199	32	43.1	<.001	YES	178	27	34.4	<.001	YES	21	14	22.4	<.001	YES
	100%	5	70	15	46.2	<.001	YES	56	6	36.6	<.001	YES	14	14	24.2	<.001	YES
AM Peak hour	0%	5	8273	413				7891	413				382	28			
	25%	5	8064	589	0.6	0.2674	NO	7686	570	0.7	0.266	NO	379	26	0.2	0.428	NO
	50%	5	7227	523	3.5	0.0039771	YES	6856	492	3.6	0.003	YES	371	31	0.6	0.294	NO
	75%	5	4441	595	11.8	<.001	YES	4092	580	11.9	<.001	YES	349	25	1.9	0.044	YES
	100%	5	317	91	42.1	<.001	YES	257	87	40.4	<.001	YES	60	14	23.1	<.001	YES
AM Post-peak hour	0%	5	6096	423				5809	363				287	13			
	25%	5	3189	18	15.4	<.001	YES	3013	17	17.2	<.001	YES	176	1	19.7	<.001	YES
	50%	5	1736	295	18.9	<.001	YES	1576	264	21.1	<.001	YES	160	11	17	<.001	YES
	75%	5	1217	62	25.5	<.001	YES	1076	50	28.9	<.001	YES	140	24	12.1	<.001	YES
	100%	5	105	5	31.7	<.001	YES	85	4	35.2	<.001	YES	21	5	44.4	<.001	YES
PM Pre-peak hour	0%	5	14930	437				14300	358				630	34			
	25%	5	14441	1051	1	0.183	NO	13900	1020	0.8	0.216	NO	541	13	5.5	<.001	YES
	50%	5	12432	484	8.6	<.001	YES	11901	506	8.7	<.001	YES	531	20	5.7	<.001	YES
	75%	5	7919	408	26.2	<.001	YES	7433	359	30.3	<.001	YES	486	42	6	<.001	YES
	100%	5	1342	42	69.2	<.001	YES	1160	75	80.4	<.001	YES	182	40	19.1	<.001	YES
PM Peak hour	0%	5	18400	1331				17500	1230				900	60			
	25%	5	17933	139	0.8	0.2	NO	17337	109	0.3	0.388	NO	596	20	10.7	<.001	YES
	50%	5	17407	739	1.5	0.1	NO	16655	630	1.4	0.104	NO	752	23	5.1	<.001	YES
	75%	5	12298	1485	6.8	<.001	YES	11492	1284	7.6	<.001	YES	806	80	2.1	0	YES
	100%	5	5520	46	21.6	<.001	YES	5115	122	22.4	<.001	YES	405	40	15.3	<.001	YES
PM Post-peak hour	0%	5	17160	883				16500	847				660	6			
	25%	5	16832	334	0.8	0.2	NO	16214	325	0.7	0.25	NO	618	53	1.8	0.059	NO
	50%	5	16170	961	1.7	0.064	NO	15609	833	1.7	0.066	NO	561	18	11.9	<.001	YES
	75%	5	11636	1578	6.8	<.001	YES	10909	1437	7.5	<.001	YES	727	31	-4.7	<.001	YES
	100%	5	3843	77	33.6	<.001	YES	3454	170	33.8	<.001	YES	389	56	10.8	<.001	YES

Table 5-5: Summary of paired t-test results- comparing conflicts (*ILB* and *OLB scenarios).*

Period	**CV Composition**	**N**	Total Conflicts			Rear-end Conflicts			Lane-change Conflicts		
			t-value	**p-value**	**Significant**	**t-value**	**p-value**	**Significant**	**t-value**	**p-value**	**Significant**
AM Pre-peak hour	0%	5	-28.1	<.001	YES	-24.2	<.001	YES	-47.6	<.001	YES
	25%	5	-5.6	<.001	YES	-7.9	<.001	YES	-1.4	0.093	NO
	50%	5	-9.3	<.001	YES	-14.1	<.001	YES	5.8	<.001	YES
	75%	5	-4.6	<.001	YES	-6.6	<.001	YES	2.3	0.024	YES
	100%	5	-0.5	0.311	NO	-3.7	0.003	YES	1.9	0.046	YES
AM Peak hour	0%	5	-8.7	<.001	YES	-8.6	<.001	YES	-1.1	0.146	NO
	25%	5	-8.5	<.001	YES	-8.6	<.001	YES	-3.7	0.003	YES
	50%	5	-9.8	<.001	YES	-10.1	<.001	YES	-5.0	<.001	YES
	75%	5	-6.8	<.001	YES	-6.5	<.001	YES	-11.1	<.001	YES
	100%	5	5.3	<.001	YES	4.8	<.001	YES	4.7	<.001	YES
AM Post-peak hour	0%	5	-9.6	<.001	YES	-10.4	<.001	YES	-11.1	<.001	YES
	25%	5	-41.3	<.001	YES	-47.4	<.001	YES	36.6	<.001	YES
	50%	5	-0.4	0.336	NO	-0.5	0.312	NO	0.7	0.259	YES
	75%	5	-12.9	<.001	YES	-14.8	<.001	YES	-2.0	0.038	YES
	100%	5	-3.1	0.008	YES	-2.3	0.024	YES	-1.2	0.142	NO
PM Pre-peak hour	0%	5	-31.7	<.001	YES	-36.3	<.001	YES	-12.4	<.001	YES
	25%	5	-13.9	<.001	YES	-13.9	<.001	YES	-27.2	<.001	YES
	50%	5	-28.4	<.001	YES	-26.8	<.001	YES	-19.8	<.001	YES
	75%	5	-15.3	<.001	YES	-16.1	<.001	YES	-8.1	<.001	YES
	100%	5	0.0	0.489	NO	0.0	0.498	NO	0.0	0.5	NO
PM Peak hour	0%	5	-8.3	<.001	YES	-8.3	<.001	YES	-10.2	<.001	YES
	25%	5	-86.9	<.001	YES	-108.6	<.001	YES	-3.7	0.003	YES
	50%	5	-16.9	<.001	YES	-18.5	<.001	YES	-15.3	<.001	YES
	75%	5	-3.0	0.008	YES	-2.9	0.009	YES	-7.6	<.001	YES
	100%	5	-27.2	<.001	YES	-20.7	<.001	YES	-10.9	<.001	YES
PM Post-peak hour	0%	5	36.6	<.001	YES	-14.4	<.001	YES	-65.3	<.001	YES
	25%	5	-40.2	<.001	YES	-39.4	<.001	YES	-6.5	<.001	YES
	50%	5	-13.0	0.002	YES	-14.2	<.001	YES	-13.4	<.001	YES
	75%	5	-3.9	<.001	YES	-3.8	0.003	YES	-18.7	<.001	YES
	100%	5	-7.7	<.001	YES	-7.1	<.001	YES	-3.1	0.007	YES

For the ILB scenarios, the difference in total conflicts and rear-end conflicts was statistically significant for every 25% increment in CV composition. More penetration of CVs was required to significantly reduce lane-change conflicts during the AM post-peak, PM peak, and PM post-peak hours. During low traffic volume (AM pre- and post-peak hours), under OLB scenarios, a significant reduction of total and rear-end conflicts were observed as CVs increased. However, at high traffic volumes (AM peak and PM period), there was a significant reduction beyond 50% CV penetration. This shows that CV applications are a viable solution for reducing rear-end conflicts and lane-change conflicts. The results are more pronounced, even with low penetration of CVs, for low traffic volume situations than during congested periods

5.1.4 Detour strategy for scenarios with a single lane blocked

The modeled detour, discussed in Section 4.2, was used to analyze the potential benefits of using CVs and detour advisory messages to reduce traffic conflicts when an incident occurs. The analysis considered both the AM and PM periods with either an innermost or outermost lane blockage. Notably, the analysis used travel time as a criterion to advise traffic to take a detour. Surprisingly, even at high traffic volumes (during the PM peak period), it rarely happened that travel time in the mainline traffic was be greater than using a detour.

Thus, less than 2% of all vehicles received a detour advisory message during the entire analysis period. This is because the interchanges along the study corridor are spaced further apart (about two miles) to enhance the mobility function as a toll expressway. Additionally, the detour route has a lower posted speed limit (35 mph) and four signalized intersections that the traffic must navigate through before re-entering the freeway. Consequently, it takes much longer for traffic to use the detour to get back to the mainline. This finding is in line with a previous study, which concluded that a detour strategy has the potential for incident duration higher than 30 minutes with multiple lane closures (Chou & Miller-Hooks, 2011). Overall, in the present study, a safety evaluation using the SSAM indicated a more or less similar conflict reduction pattern for both with and without detour scenarios. These results necessitate further analysis of the use of CVs and a detour advisory when an incident results in the blockage of two lanes; results are presented in Section 5.2.

5.2 Scenarios with two lanes blocked

The corridor segment used for analyzing scenarios with a single lane blockage was also used to analyze scenarios with two lanes blocked. The incident location was consistent with scenarios in which a single lane was closed. Two outer lanes, out of the three northbound lanes, were closed. The study analyzed the blockage of outer lanes since the results from a single lane closure showed higher traffic conflicts for the outer lane blockage. These following subsections discuss the conflicts resulting from scenarios in which the two outermost lanes were blocked, for both with and without detour advisory.

5.2.1 SSAM conflict results - AM period

Three morning peak hours consisting of low, high, and moderate traffic volume were chosen to analyze scenarios in which two outer lanes are closed. In all the three analysis periods, an incident that blocks two lanes resulted in a rapid formation of queues upstream of the incident location. The speed of queue formation was a function of the analysis period when the incident occurred. It seemed most severe during the peak period, with fewer queues during the pre-peak hour. This is because of the difference in traffic volumes among the analyzed periods. Unlike scenarios in which a single lane was closed, more vehicles experienced longer travel time using the Turnpike mainline than if they opted for the Lyons Road (parallel arterial) detour, which is consistent with previous studies (Chou & Miller-Hooks, 2011).

The '*processing of information and advisory messages'* stage of the proposed communication plan has an algorithm that uses travel time as a performance measure to send detour advisory messages (see Figure 4-3). Thus, when two lanes were blocked, detour advisory scenarios experienced less congestion than those without detour advisory. The safety implication of employing the proposed communication plan was analyzed using the SSAM software. Figure 5-3 shows the number of traffic conflicts observed for different penetration rates of CVs with (W) and without (W/O) detour advisory messages. Table 5-6 shows a matrix that summarizes the percentage change in the number of conflicts as CV penetration rate increases**.**

Total Conflicts

Surprisingly, during the peak period, for both with and without detour advisory, 25% CV penetration resulted in an increase in total conflicts. This could be due to fewer CVs in the network that receive less cooperation from convectional vehicles while the CVs were adjusting their driving status for safety benefits. A reduction in total conflicts was observed from 50% penetration of CVs in scenarios with detour advisory, a slightly higher reduction than those without the advisory. With full penetration of CVs, results showed a decrease in the total conflicts of about 20% and 15% for with and without detour advisory, respectively.

For pre- and post-peak scenarios, with full CV penetration, results indicate a reduced number of total conflicts of up to 71% and 64% for with and without detour advisory, respectively. The number of conflicts reduced, even at 25% MPR of CVs, during these scenarios, as shown in Table 5-6. A consistent trend in conflict decline was observed for every 25% increment of CV composition. The following section gives a detailed discussion on conflict reduction, per specific conflict type.

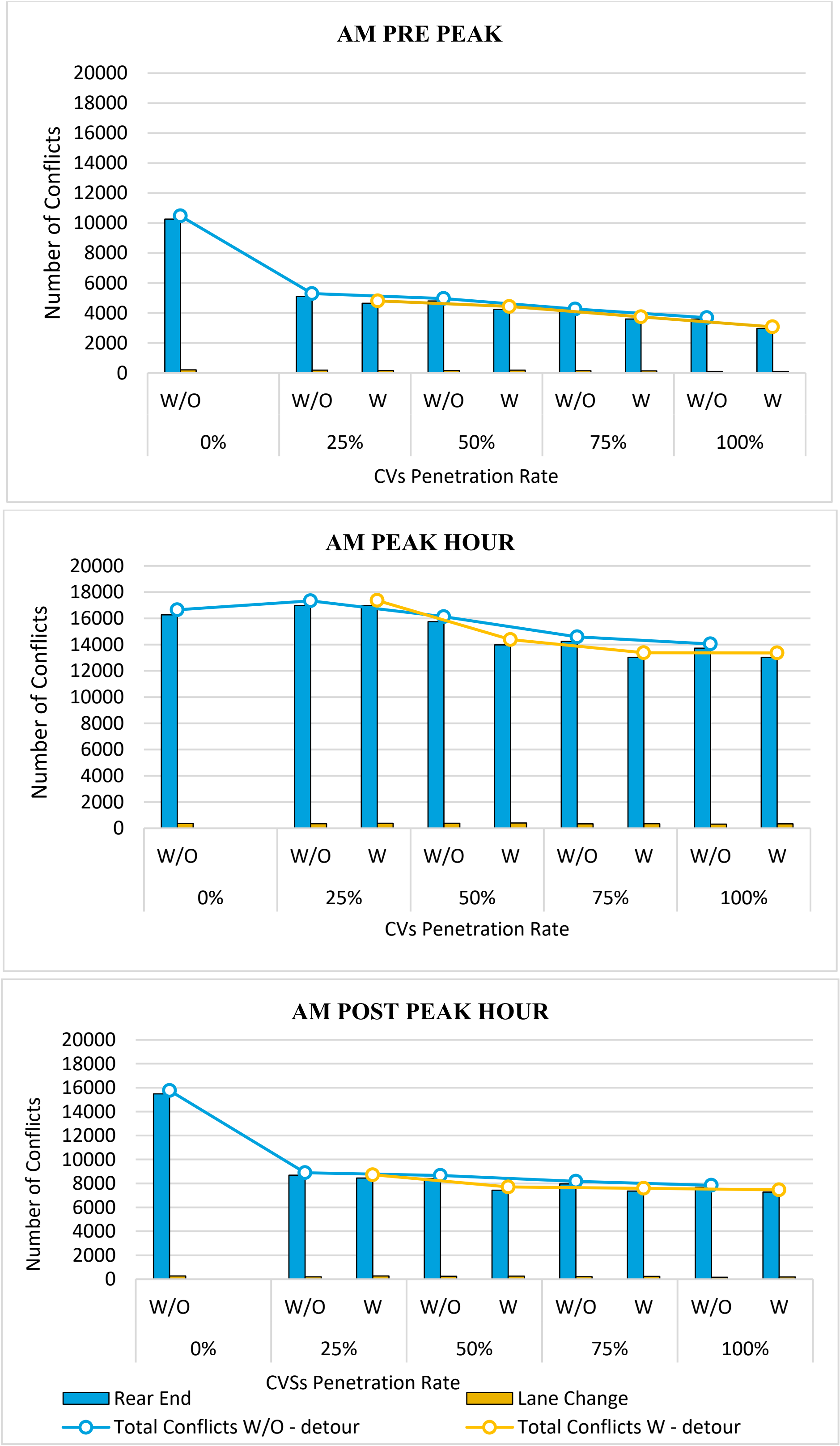

Figure 5-3 SSAM conflicts for scenarios with two outer lanes blocked during the AM peak hour

Table 5-6: Percent change in conflicts- Two outer lane blocked (*W* and *W/O* detour advisory)

TWO OUTER LANE BLOCKED - WITHOUT DETOUR ADVISORY												
	AM Pre-peak hour				AM Peak hour				AM post hour			
Total Conflicts												
	Initial Composition (%)				Initial Composition (%)				Initial Composition (%)			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-49.45%				4.11%				-43.56%			
50	-52.61%	-6.23%			-3.15%	-6.97%			-44.97%	-2.50%		
75	-59.26%	-19.41%	-14.05%		-12.38%	-15.84%	-9.53%		-48.11%	-8.07%	-5.71%	
100	-64.79%	-30.34%	-25.70%	-13.56%	-15.62%	-18.96%	-12.88%	-3.70%	-50.24%	-11.83%	-9.57%	-4.10%
Rear-End Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-50.25%				4.36%				-43.85%			
50	-53.23%	-5.98%			-3.23%	-7.27%			-45.61%	-3.12%		
75	-59.88%	-19.36%	-14.23%		-12.42%	-16.08%	-9.50%		-48.60%	-8.46%	-5.51%	
100	-65.05%	-29.76%	-25.28%	-12.89%	-15.62%	-19.15%	-12.81%	-3.66%	-50.41%	-11.68%	-8.83%	-3.52%
Lane-Change Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-10.65%				-6.64%				-27.23%			
50	-22.24%	-12.98%			0.42%	7.57%			-9.65%	24.16%		
75	-29.09%	-20.64%	-8.80%		-10.73%	-4.38%	-11.11%		-20.82%	8.81%	-12.36%	
100	-51.81%	-46.06%	-38.02%	-32.04%	-15.72%	-9.73%	-16.08%	-5.59%	-40.63%	-18.42%	-34.29%	-25.02%
TWO OUTER LANE BLOCKED - WITH DETOUR ADVISORY												
	AM Pre-peak hour				AM Peak hour				AM post hour			
Total conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-54.08%				4.29%				-44.63%			
50	-57.63%	-7.73%			-13.61%	-17.17%			-51.10%	-11.69%		
75	-64.25%	-22.14%	-15.62%		-19.67%	-22.97%	-7.01%		-51.80%	-12.95%	-1.43%	
100	-70.63%	-36.05%	-30.69%	-17.86%	-19.73%	-23.03%	-7.08%	-0.08%	-52.61%	-14.41%	-3.09%	-1.68%
Rear-End Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-54.69%				4.36%				-45.39%			
50	-58.60%	-3.91%			-14.10%	-17.69%			-51.94%	-12.00%		
75	-64.93%	-10.24%	-15.29%		-19.92%	-23.27%	-6.78%		-52.45%	-12.93%	-1.05%	
100	-71.06%	-16.37%	-30.09%	-17.48%	-19.94%	-23.29%	-6.80%	-0.02%	-53.00%	-13.94%	-2.20%	-1.17%
Lane-Change Conflicts												
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-24.14%				1.01%				-2.45%			
50	-10.27%	18.30%			7.33%	6.26%			-4.25%	-1.85%		
75	-30.99%	-9.02%	-23.09%		-8.55%	-9.46%	-14.79%		-15.71%	-13.59%	-11.96%	
100	-49.81%	-33.83%	-44.07%	-27.27%	-10.52%	-11.41%	-16.63%	-2.15%	-30.84%	-29.10%	-27.77%	-17.95%
				🟩	Conflict reduction			🟧	Conflict increase			

Rear-end Conflicts

As expected, in all scenarios, rear-end conflicts were more prominent than lane-change conflicts. The blocking of two lanes disrupted the traffic on a high-speed facility, i.e., freeway, which resulted in long queues, creating many stop-and-go situations for vehicles. Consequently, a higher number of rear-end conflicts was observed than during the blockage of a single lane, as observed in a previous study (Atamo, 2012). As shown in Figure 5-3, more reduction in rear-end conflicts were observed when the detour advisory was disseminated under the increased penetration of CVs. This could be due to the reduction of traffic approaching the incident scene after the detour advisory. Moreover, early speed and lane-change advisories to CVs help drivers adjust their driving behavior as they approach the scene.

During the peak period, queue dissipation to normal traffic conditions was not observed during the analysis period. A similar finding was observed in a previous study by Pulugurtha and Balaram Mahanthi (2016). Greater conflict reduction (about 25 percent) was observed in the transition from 25% to 50% penetration of CVs for both scenarios. The difference in conflict reduction between *with* and *without* detour advisory was less for the transitions to higher CV penetration rates. This is because, during the peak period, Lyons Road also experience high traffic. Thus, the number of CVs receiving detour advisory was limited.

For pre-peak scenarios, conflict reduction was observed even at 25% MPR of CVs. The conflict reduction was 55 percent and 49 percent for with and without detour advisory. The parallel arterial used as a detour had less traffic during the pre-peak. Thus, more CVs received the detour advisory and increased the safety benefit, even at lower penetration. A similar trend in the reduction of rear-end conflicts was observed during the post-peak hour.

Lane-Change (LC) Conflicts

In all the scenarios, fewer lane-change conflicts were observed than rear end conflicts, as shown in Figure 5-3. As discussed in the analysis of a single lane closure, CVs in congested periods experienced less cooperation from convectional vehicles during lane-changing maneuvers. Thus, there was an increase in lane-change conflicts with lower CV penetration in high traffic volume, as shown in Table 5-6. Moreover, more conflicts were observed for scenarios with the detour advisory than those without the advisory. The reason could be due to an increase in conflicts as CVs changed lanes to access the detour.

5.2.2 *Statistical analysis of conflicts reduction for scenarios with two lanes blocked*

As was discussed in Section 5.1.3, the null hypothesis was that the mean difference between the average number of conflicts between 0% and a succeeding percentage of CV composition is zero. The null was tested against an alternative hypothesis that the mean difference between the average number of conflicts between the two scenarios is greater than zero.

- Null Hypothesis, H_0: μ_1 - $\mu_2 = 0$, OR $\mu_1 = \mu_2$
- Alternate Hypothesis, H_A: $\mu_1 - \mu_2 >0$, OR $\mu_1 > \mu_1$

where,
μ_1 = mean number of conflicts at 0% penetration of CVs
μ_2 = mean number of conflicts at *i*% penetration of CVs

Tables 5-7 and 5-8 shows the statistical test results at a 95% confidence level for the *with* and *without* detour advisory scenarios, respectively. The statistical test was performed to check whether there is a significant difference in the number of conflicts between the with and without detour advisory scenarios. The null hypothesis was that, for a given MPR of CVs, the mean difference between the average number of conflicts between the two scenarios is zero. It was tested versus an alternate hypothesis that the mean difference between the average number of conflicts between the two scenarios is greater than zero.

- Null Hypothesis, H_0: $\mu_i - \mu_o = 0$, OR $\mu_i = \mu_o$
- Alternate Hypothesis, H_A: $\mu_i - \mu_o > 0$, OR $\mu_i > \mu_o$

where,

μ_i = mean number of conflicts for the W/O detour advisory at *i*% penetration of CVs
μ_o = mean number of conflicts for the W detour advisory at *i*% penetration of CVs

For the periods with less traffic volume i.e., pre- and peak hours, both with and without detour advisory, the reduction in total conflicts and rear-end conflicts was statistically significant for every 25% increment in CV composition. More penetration of CVs (about 75%) was required to significantly reduce lane-change conflicts during the post-peak hour. On the other hand, during high traffic volume (peak hour) a significant reduction in total and rear-end conflicts was observed in the transition from 50% to 75% of CV composition for scenarios without the detour advisory. For scenarios with detour advisory, a significant reduction was observed in the transition from 25% to 50% CVs. In regards to lane-change conflicts, a less significant benefit was observed during the peak hour.

When comparing scenarios with and without detour advisory, no significant reduction was observed in the number of rear-end conflicts using the detour strategy during the peak hour. Also, with full penetration of CVs, conflicts reduced by adopting the detour advisory was not statistically significant. As the CVs take the detour, a point is reached where the travel time using the detour becomes longer then not taking the detour, thus no more CVs get diverted. Except for lane-change conflicts, other scenarios showed a statistical significance of using the detour to reduce traffic conflicts, as shown in Table 5-9.

Table 5-7: Summary of paired t-test results for number of conflicts (*W/O detour advisory*)

Period	CV Composition	N	Total conflicts					Rear-end Conflicts					Lane-change Conflicts				
			Mean	St Dev	t-value	p-value	Significant	Mean	St Dev	t-value	p-value	Significant	Mean	St Dev	t-value	p-value	Significant
AM Pre-peak hour	0%	5	10474	422				10264	404				210	24			
	25%	5	5294	229	24.1	<.001	YES	5106	233	24.7	<.001	YES	188	7	2.0	0.040	YES
	50%	5	4964	153	27.4	<.001	YES	4801	156	28.2	<.001	YES	164	15	3.7	0.003	YES
	75%	5	4267	280	27.4	<.001	YES	4118	282	27.9	<.001	YES	149	18	4.5	0.001	YES
	100%	5	3688	199	32.5	<.001	YES	3587	200	33.1	<.001	YES	101	9	9.5	<.001	YES
AM Peak hour	0%	5	16649	1319				16272	1283				377	49			
	25%	5	17334	1043	-0.9	0.195	NO	16982	1025	-1.0	0.181	NO	352	23	1.0	0.168	NO
	50%	5	16125	1387	0.6	0.279	NO	15747	1372	0.6	0.274	NO	378	22	-0.1	0.475	NO
	75%	5	14587	1224	2.6	0.017	YES	14251	1209	2.6	0.017	YES	336	25	1.6	0.071	NO
	100%	5	14048	699	3.9	0.002	YES	13730	702	3.9	0.002	YES	317	20	2.5	0.019	YES
AM Post-peak hour	0%	5	15759	588				15482	586				278	14			
	25%	5	8895	133	25.5	<.001	YES	8693	134	25.3	<.001	YES	202	23	6.2	<.001	YES
	50%	5	8672	223	25.2	<.001	YES	8421	235	25.0	<.001	YES	251	25	2.1	0.034	YES
	75%	5	8177	297	25.7	<.001	YES	7957	307	25.4	<.001	YES	220	19	5.5	<.001	YES
	100%	5	7842	496	23.0	<.001	YES	7677	497	22.7	<.001	YES	165	17	11.7	<.001	YES

Table 5-8: Summary of paired t-test results for number of conflicts (*W detour advisory*)

Period	CV Composition	N	Total conflicts					Rear-end Conflicts					Lane-change Conflicts				
			Mean	St Dev	t-value	p-value	Significant	Mean	St Dev	t-value	p-value	Significant	Mean	St Dev	t-value	p-value	Significant
AM Pre-peak hour	0%	5	10474	422				10264	404				210	24			
	25%	5	4810	397	21.9	<.001	YES	4651	376	22.7	<.001	YES	160	27	3.2	0.007	YES
	50%	5	4438	170	29.7	<.001	YES	4249	175	30.5	<.001	YES	189	7	1.9	0.045	YES
	75%	5	3745	306	28.9	<.001	YES	3600	297	29.7	<.001	YES	145	13	5.3	<.001	YES
	100%	5	3076	274	32.9	<.001	YES	2971	267	33.6	<.001	YES	106	21	7.3	<.001	YES
AM Peak hour	0%	5	16649	1319				16272	1283				377	49			
	25%	5	17363	470	-1.1	0.144	NO	16982	457	-1.2	0.139	NO	380	26	-0.2	0.442	NO
	50%	5	14382	471	3.6	0.003	YES	13978	480	3.7	0.003	YES	404	16	-1.2	0.135	NO
	75%	5	13374	159	5.5	<.001	YES	13030	164	5.6	<.001	YES	344	11	1.4	0.096	NO
	100%	5	13364	791	4.8	<.001	YES	13027	769	4.9	<.001	YES	337	32	1.5	0.086	NO
AM Post-peak hour	0%	5	15759	588				15482	586				278	14			
	25%	5	8726	123	26.2	<.001	YES	8455	120	26.3	<.001	YES	271	15	0.8	0.237	NO
	50%	5	7706	375	25.8	<.001	YES	7440	366	26.0	<.001	YES	266	10	1.5	0.082	NO
	75%	5	7596	149	30.1	<.001	YES	7362	147	30.1	<.001	YES	234	4	6.8	<.001	YES
	100%	5	7468	84	31.2	<.001	YES	7276	84	31.0	<.001	YES	192	18	8.4	<.001	YES

Table 5-9: Results of paired t-test– Comparing conflicts (*W/O and W detour advisory)*

Period	**CV Composition**	**N**	**Total Conflicts**			**Rear-end Conflicts**			**Lane-change Conflicts**		
			t-value	**p-value**	**Significant**	**t-value**	**p-value**	**Significant**	**t-value**	**p-value**	**Significant**
AM Pre-peak hour	25%	5	2.4	0.023	YES	2.3	0.025	YES	2.3	0.025	YES
	50%	5	5.1	<.001	YES	5.3	<.001	YES	-3.4	0.005	YES
	75%	5	3	0.011	YES	2.8	0.011	YES	0.4	0.349	NO
	100%	5	4	0.002	YES	4.1	0.002	YES	-0.4	0.347	YES
AM Peak hour	25%	5	-0.1	0.478	NO	0.0	0.500	NO	-1.8	0.052	NO
	50%	5	2.7	0.014	YES	2.7	0.013	YES	-2.1	0.034	YES
	75%	5	2.2	0.030	YES	2.2	0.028	YES	-0.7	0.258	NO
	100%	5	1.4	0.093	NO	1.5	0.085	NO	-1.2	0.142	NO
AM Post-peak hour	25%	5	2.1	0.035	YES	3.0	0.009	YES	-5.6	<.001	YES
	50%	5	5.0	<.001	YES	5.0	<.001	YES	-1.2	0.124	NO
	75%	5	3.9	0.002	YES	3.9	0.002	YES	-1.6	0.070	NO
	100%	5	1.7	0.068	NO	1.8	0.057	NO	-2.5	0.019	NO

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study proposed and simulated a communication plan for the mitigation of SCs. The plan leverages the application of connected vehicle technologies that utilize V2I communications, and aims at mitigating the risk of SCs on freeways caused by the unawareness of motorists when a primary incident occurs. It includes incident detection, verification, processing of safety advisory messages (speed, lane change, and detour advisory), and information dissemination to motorists through V2V and V2I communication.

A microscopic simulation approach was used to mimic and evaluate the effectiveness of the proposed communication plan. VISSIM microscopic simulation software was used to demonstrate traffic flow characteristics under the CV environment. To the extent possible, the script was written in Visual Basics to incorporate the proposed communication plan and V2I communication into the simulation environment. The study designed various simulation scenarios, including blockage of either the inner lane, the outer lane, or the two outer lanes to reflect a primary incident. It also considered the effect of varying traffic volumes by analyzing traffic data from different periods. Since full penetration of CVs is not anticipated soon, the study performed a sensitivity analysis by considering varying MPRs of CVs. In each scenario, a safety evaluation was performed in SSAM software by importing trajectory files from VISSIM to analyze the associated traffic conflicts. The change in the number of simulated conflicts (representing SCs) was used to evaluate the safety benefits of the proposed communication plan, with an emphasis on CV technologies.

Results indicate a reduction in conflicts by up to 98 percent using the proposed communication plan with CV technologies. The high reduction was observed on low traffic volume, even with low penetration of CVs, e.g., a 50% reduction at a 25% rate of CVs during AM pre-peak hour. High penetration was required to achieve significant conflict reduction for high traffic volumes, e.g., only 33% reduction at a 75% rate of CVs during the PM peak hour. It was also observed that incidents that block the outer lane result in more traffic conflicts than incidents that block the inner lane. Thus, with the same penetration of CVs, more conflict reduction was observed when the inner lane was blocked than when the outer lane was blocked. This could be due to less restriction to merge and diverge maneuvers when the inner lane is closed, unlike the outer lane. Additionally, more conflicts were observed when two lanes were closed, unlike single lane closures. The detour advisory was significant for an incident that blocks multiple lanes.

Previous studies have shown the relationship between traffic conflicts and crashes. Thus, the reduction in the number of conflicts with the use of the proposed communication plan and CV technologies signifies a potential reduction in SCs. As was observed, the required penetration rate of CVs to achieve significant benefits is a function of the prevailing traffic volume, the severity of the primary incident (number of lanes closed), and the side of the road on which the incident blocks the lane(s). Moreover, the effectiveness of detour advisory depends on the influence of the primary incident and both traffic and geometric characteristics of both the mainline and the detour route.

6.2 Limitations of the study and recommendations for future work

This study encountered some limitations that could be addressed in future research. The study analyzed the safety effects of only traffic in the direction that contained an incident, which ignores the SCs that could occur in the opposite direction of travel, due to the rubbernecking phenomenon or "onlookers" and other humanistic factors. Future studies may research the effects of human factors and incorporate them in microscopic simulation to closely mimic the reality of traffic flow. These endeavors could enhance the analysis of overall safety benefits for both traffic directions

The study assumed a 100% driver compliance rate of the received advisory messages. However, human decision behavior depends on behavioral and psychological aspects, personal experience and preferences, and uncertainty. Thus, driver compliance upon receipt of advisory messages warrants future research. Furthermore, studies on CV and AV technologies, such as FCW with automation, could be considered to increase automation that reduces a drivers' driving tasks to comply with received advisory messages.

Also, the study assumed that no communication latency and data loss occurred within the defined range of communication. However, signal strength is affected by other factors, such as traffic density and weather. Future studies could delve deeper into the effect of data loss on signal propagation. Additionally, the effects of weather could be added as one of variables in the simulation model to determine the proposed plan's benefits in adverse weather conditions.

This study's primary focus was to mitigate SCs using the proposed communication plan and CV applications. The adopted methodology used vehicular conflicts from the microscopic simulation as a proxy for the risk of the SCs. However, with the current state of the art, there is no direct quantitative link between simulated traffic conflicts and the number of possible SCs. Future research could investigate and establish the link between the simulated traffic conflicts and SCs.

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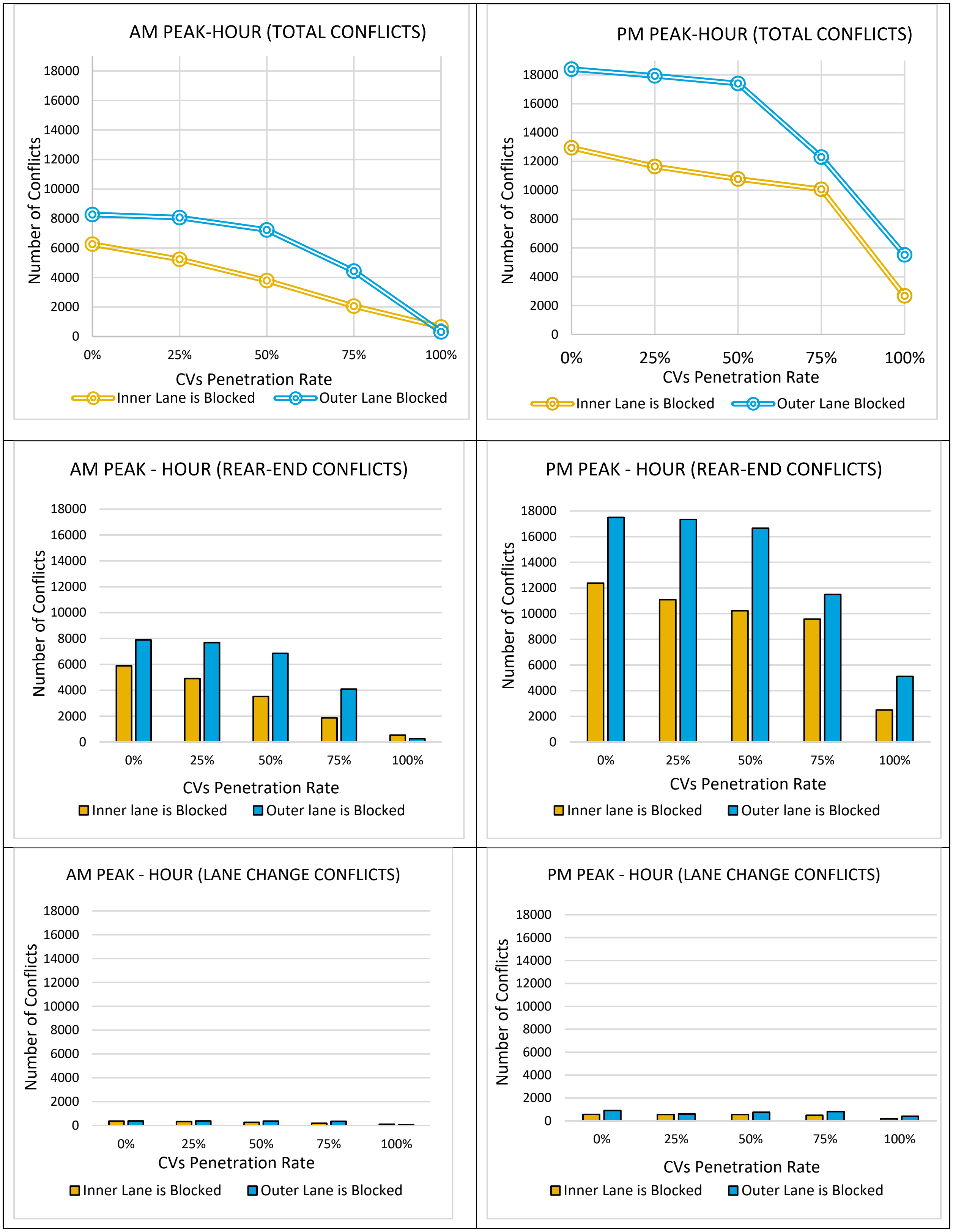
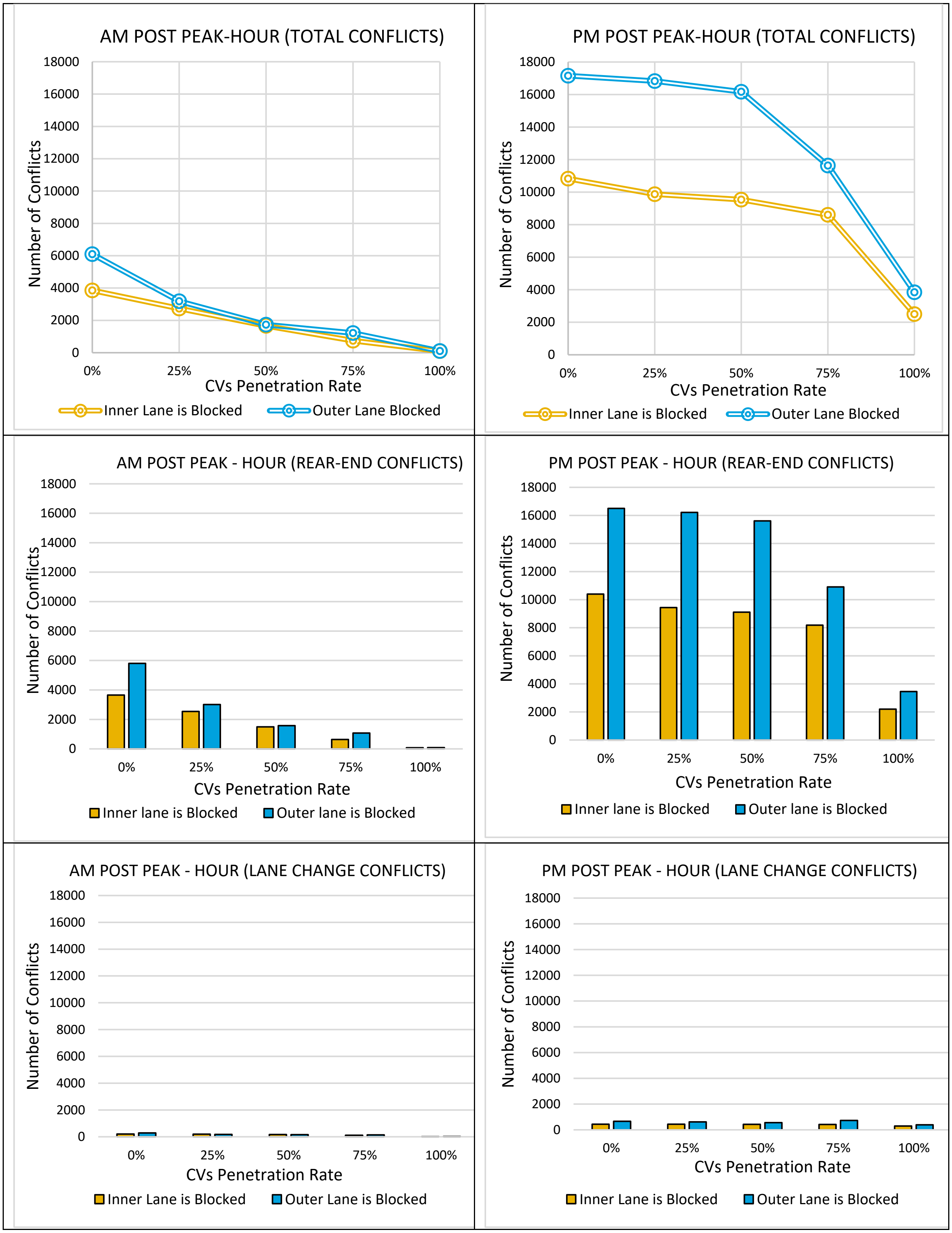
APPENDIX A
Comparison of the Number of Conflicts between the AM and PM peak Hours.

A-1: SSAM conflicts for scenarios with a single lane closure during the AM and PM pre-peak hours



A-2: SSAM conflicts for scenarios with a single lane closure during the AM and PM post peak hours



A-3: SSAM conflicts for scenarios with a single lane closure during the AM and PM peak hours

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