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Analyzing Benefits of Connected Vehicle Technologies During Incidents on Freeways and Diversion Strategies Implementation: A Microsimulation-Based Case Study of Florida's Turnpike

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ANALYZING BENEFITS OF CONNECTED VEHICLE TECHNOLOGIES DURING INCIDENTS ON FREEWAYS AND DIVERSION STRATEGIES IMPLEMENTATION: A MICROSIMULATION-BASED CASE STUDY OF FLORIDA'S TURNPIKE

By

Francisca Paulinus Kasubi

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THESIS CERTIFICATE OF APPROVAL

The thesis titled "Analyzing Benefits of Connected Vehicle Technologies During Incidents on Freeways and Diversion Strategies Implementation: A Microsimulation-Based Case Study of Florida's Turnpike" submitted by Francisca Paulinus Kasubi in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering has been:

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DEDICATION

This thesis is dedicated to;

The Lord Almighty God.

My late mother in heaven, Lt. Col. Regina Gelasi Kamanzi, may her soul rest in peace.

My beloved family on earth. My father Paulinus Kasubi. My brother Michael and My lovely sisters Mary and Dorothy.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHS	Automated Highway Systems
ANOVA	Analysis of Variance
API	Application Programming Interface
BMW	Bayerische Motoren Werke AG
BSM	Basic Safety Message
BSW	Blind Spot Warning
CAGR	Compound Annual Growth Rate
CDBA	Continuous Driving Behavior Adjustment
COM	Component Object Model
CV	Connected Vehicle
DOT	Department of Transportation
DSRC	Dedicated Short Range Communication
FCW	Forward Collison Warning
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GHz	GigaHertz
GPS	Global Positioning Systems
HCM	Highway Capacity Manual
HSD	Honest Significant Difference
Hz	Hertz

ICM	Integrated Corridor Management
ILB	Inner Lane Blocked
ITS	Intelligent Transportation systems
LCW	Lane Change Warnings
LOS	Level of Service
MHz	MegaHertz
MPR	Market Penetration Rate
NHTSA	National Highway Traffic Safety Administration
OBU	On-Board Unit
OLB	Outer Lane Blocked
PET	Post Encroachment Time
PTV	Planug Transport Verkehr (German)
RBC	Ring Barrier Controller
RSE	Road Side Equipment
RSU	Road Side Unit
SR	State Route
SSAM	Surrogate Safety Assessment Model
TIM	Traffic Incident Management
TMC	Traffic Management Center
TTC	Time-to-Collision
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
VISSIM	Verkehr In Städten – SIMulationsmodell (German)
VMS	Variable Message Sign
VSL	Variable Speed Limit
Wi-Fi	Wireless Fidelity

ABSTRACT

The full utilization of connected vehicles (CVs) is highly anticipated to become a reality soon. As CVs become increasingly prevalent in our roadway network, connected technologies have enormous potential to improve safety. This study conducted a microscopic simulation to quantify the benefits of CVs in improving freeway safety along a 7.8-mile section on Florida's Turnpike (SR-91) system. The simulation incorporated driver compliance behavior in a CV environment. The simulation was implemented via an existing VISSIM network model partially developed by the Florida Department of Transportation (FDOT). In addition, the study analyzed how CVs would assist in detour operations as a strategy for congestion management during traffic incidents on freeways. The Surrogate Safety Assessment Model (SSAM) software was used to evaluate the benefits of CVs based on time-to-collision (TTC) as the performance measure. The TTC was evaluated at various CV market penetration rates (MPRs) of 0%, 25%, 50%, 75%, and 100%. The results showed a decreasing trend of conflicts for morning and evening peak hours, especially from 25% to 100% CV MPRs. The benefits were statistically significant at a 95% confidence level for high CV MPR (above 25%). Upon an incident on the freeway, at higher CV MPRs simulations, the detour strategy seemed to reduce travel time on the freeway. Besides, the detour strategy was more helpful when the incident clearance duration lasted more than 30 minutes. Findings from this study may help the incident management process prepare for detour strategies based on the severity of the incident at hand and could explain the importance of CVs in supporting warning and management strategies for drivers to improve safety on freeways.

Keywords: Conflicts, Connected Vehicles, Driver Compliance Rate, Detour, Incident Modeling, Safety Surrogate Measures

CHAPTER 1 INTRODUCTION

1.1 Background

Modern society relies heavily on transportation systems to move from one destination to another. Ensuring these transportation systems' safety, mobility, reliability, efficiency, and sustainability is one of society's substantial interests. Traffic incidents, including vehicle crashes, disabled vehicles, and debris on the roadway, are associated with excessive delays and congestions, leading to safety issues (Amer et al., 2015). Police reported 2,736,257 motor vehicle crashes in 2019, whereby a minimum of one passenger vehicle was towed from the incident scene. These crashes resulted in an estimated 1,356,689 injured occupants of towed passenger vehicles, whereby 2.8% suffered a severe injury, 31.5% a moderate or minor injury, and 48.5% crashed with no injury (National Highway Traffic Safety Administration [NHTSA], 2020). Most of these crashes occurred because drivers exceeded the posted speed limit, leading to sideswipes and rear-end collisions. While driving, drivers may make several judgment errors that lead to crashes (NHTSA, 2015).

The Florida traffic crash general statistics reported 401,867 total crashes in 2019, whereby 236,753 involved injuries (Florida Highway Safety and Motor Vehicles [FLHSMV], 2019). Freeways have limited access with higher posted speed limits and capacity than arterials, collectors, or local roads. Traffic incident occurrences on freeways substantially reduce the freeways' Level of Service (LOS) (Highway Capacity Manual [HCM], 2016). The reduction in LOS is determined by the incident stochastic nature, such as the number of lanes blocked, incident duration, and current demand (peak hour or off-peak hour). Drivers tend to divert to arterial roadways to avoid congested conditions on the freeways even though the arterial roads may also have massive traffic leading to overcapacity operation, especially during peak hours. Hence,

misguided diversion of traffic from a jammed freeway to the arterial roadway may add to travel delays (Karaer et al., 2020; X. Li et al., 2014).

The development of alternate route plans has become an increasingly important component of traffic incident and emergency management programs nationwide. Several agencies acknowledge a need to develop alternate route plans due to severe traffic incidents. Alternate route plans apply to multiple highway system management program areas (Federal Highway Administration [FHWA], 2006). A proper communication channel between active drivers on the road can reform how people travel and interact with road infrastructure. Hence, connected vehicles (CVs), which can communicate with themselves and their surrounding environment, could help solve significant transport matters related to improving safety and mobility (Y. Ali et al., 2020; Hinda Salum et al., 2021).

The concept of CV technology was introduced in the 1990s by the Automated Highway Systems (AHS) research and was later advanced under the Vehicle Infrastructure Initiative (VII) in 2003 (Harding et al., 2014). The CV technology has increasingly advanced, and recently CV deployments have been carried out and tested in some areas in the US that show promising results in safety improvements. The advancement of CV technology was supported by the US Department of Transportation (USDOT) with a pilot deployment program that uncovered and addressed the remaining constraints, documented the lessons learned, and served as a template that assisted other early CV technology deployments.

The USDOT has awarded cooperative agreements collectively worth more than $45 million to three pilot sites, New York City, Tampa, and Wyoming, to implement a set of CV applications and technologies tailored to meet their region's unique transportation needs. These pilot sites are helping CVs make the final leap into real-world deployment so that they can deliver on their

promises to increase traffic safety and mobility. Improved safety and mobility enhance economic productivity, reduce environmental impacts, and increase sustainability through wireless communication between vehicles and infrastructure (United States Department of Transportation, 2016).

While several researchers have explored the benefits that come with the application of CV technology in safety improvement of freeways through microscopic simulation approaches, most of did not consider the human factor in CV modeling by assuming that the drivers comply 100% with the given advisory message (Lee & Park, 2012; Monyo, 2020; Rahman & Abdel-Aty, 2018; Soloka, 2019; Tang et al., 2014; Wu et al., 2015). It is implausible that under any circumstances, especially with new technology such as CVs, any system will ever attain 100% compliance from its users. Thus, understanding drivers' compliance behavior is crucial for the wide-scale deployment of CV technologies (Sharma et al., 2019).

1.2 Study Objective

The study's objective was to analyze the benefits of connected vehicle technologies during incidents on freeways. It further explored the safety benefits of the CV technologies during diversion strategies implementation. It examined the significance of incident clearance duration, CV market penetration rates (MPRs), and demand level during detour operations. Specifically, the study evaluated the effects of driver compliance rate in the varying CV MPRs such as 0%, 25%, 50%, 75%, and 100%. Such variations helped examine the influence of CV MPRs in improving freeway safety. The findings from this study could be used to inform policymakers on the importance of CVs in supporting warning and management strategies for safety improvement on freeways and aid in understanding and developing future incident management plans and Integrated Corridor Management (ICM) systems.

1.3 Thesis Organization

The thesis is organized into five chapters. Chapter one introduces and discusses the background of the research problem and the study's objectives. The second chapter synthesizes the literature relevant to the study, including CVs and their applications. Chapter three presents the study’s approach and methodology, including the study site and the simulation tests. It also describes the tools used in the study. Chapter four discusses the results obtained. Finally, chapter five presents the conclusions and recommendations based on the obtained results.

CHAPTER 2 LITERATURE REVIEW

This chapter discusses the existing studies concerning CVs technologies in improving freeway safety. An in-depth review was done on CVs, driver's behaviors, traffic simulation, and surrogate safety measures.

2.1 Connected Vehicle Overview

CVs are vehicles that can communicate bidirectionally with other systems inside and outside of the vehicle. For example, they can establish wireless communication between vehicles that are vehicle to vehicle (V2V), Vehicle to Everything (V2X) (Sharma et al., 2018), and Vehicle to Infrastructure (V2I) (Talebpour et al., 2016). The CVs technology can enhance traffic efficiency and mobility, reduce fuel consumption and emissions, and, most importantly, improve road safety (Zeng et al., 2012). However, these CVs co-exist in a mixed conventional and autonomous vehicle (AV) environment due to a lower market penetration rate. The following section will discuss the communication technology that enables the CVs and market growth estimations.

In selecting wireless technologies that meet the needs of numerous transportation applications, communication range and latency are the most important factors to consider. The communication range refers to the distance that a communications signal can travel. Some communications technologies have faster transmission speeds than others. This translates into communication latency, which is the time between when the transmission starts and when the transmission content is received. Latency indicates how fast information can spread over a designated region. Thus, low-latency technologies may be essential for applications carrying time-critical information.

Unfortunately, long-range and low latency cannot co-exist in practice; the user must settle for one or the other or compromise somewhere in between. Different wireless technologies like Wireless Access in Vehicular Environments (WAVE), Dedicated Short Range Communications (DSRC) radios, Universal Mobile Telecommunications System (UMTS), Long-Term Evolution (LTE), and Worldwide Interoperability for Microwave Access (WiMAX) are options to meet these diverse needs (Deng et al., 2017; Talebpour et al., 2016; Zeng et al., 2012).

CVs can communicate with each other or Roadside Unit (RSU) by transmitting a basic safety message (BSM) using a vehicular ad hoc network (VANET), as Figure 2-1 illustrates. A VANET consists of moving or stationary vehicles connected by a wireless network that provides safety and comfort to drivers in vehicular environments (Talebpour et al., 2016). The BSM data transmitted in VANETs includes vehicle location, speed, the distance measured by Millimeter Radar, and traffic conditions.

Connectivity for V2V and V2I communications can be provided by various wireless technologies such as Bluetooth, cellular, Dedicated Short Range Communications (DSRC), and long-term evolution. Unlike other communication plans, DSRC has fast network acquisition, designated licensed bandwidth, high security, reliability, and interoperability, making it used for local connectivity (Zeng et al., 2012). The V2V communication messages can detect threats obscured by traffic, weather, or terrain at a range of more than 984 ft. (300 m). The 984 ft. detection range provided by V2V through DSRC represents a significant improvement over existing state-of-the-art sensor-based technologies (e.g., camera or radar systems), which can reach just 492 ft. (150 m). Furthermore, due to the sharing of data between vehicles, V2V communications can provide the vehicle and driver with un-obstructed 360-degree situational

awareness, resulting in driver alerts and warnings about potential collisions that are not visible to existing sensor-based technologies (Bettisworth et al., 2015).

NHTSA (2011) research program identified the following V2V safety applications: emergency stop lamp warning, forward collision warning (FCW), intersection movement assist, blind spot and lane change warning (LCW), do not pass warning, and control loss warning. Emergency stop lamp warning allows drivers to transmit an emergency braking event where the leading vehicle driver warns other drivers of a probable threat. FCW informs the leading driver of a forthcoming rear-end collision with a vehicle traveling in the same direction and lane ahead. Intersection movement alerts leading vehicle drivers on the safety of entering an intersection, informs the chances of collision with a vehicle from the other side. Blind spot and lane change warning notify the driver if there is a vehicle in its blind spot after activating the turn signal; thus, drivers are warned not to perform the lane change maneuver. Do not pass warning informs drivers on the opposite vehicle approaching the passing zone as the driver wants to overtake a slower vehicle ahead.

According to Zha and Songchitruksa (2015), there are three components for steady connectivity: First, the On-Board Unit (OBU), the implanted equipment on CVs for information exchange, stores of messages to be displayed and track the position of vehicles; Second, the RSU, a roadside data broadcaster, and receiver, only operates when a vehicle is stationary and can only communicate with the vehicles within its range and OBUs. Third, the back-office server connects to the Road-Side Equipment (RSEs), represents the CV roadside devices, and monitors the entire traffic network. An RSE sends or receives messages from nearby vehicles using DSRC or other alternative wireless communications technologies.

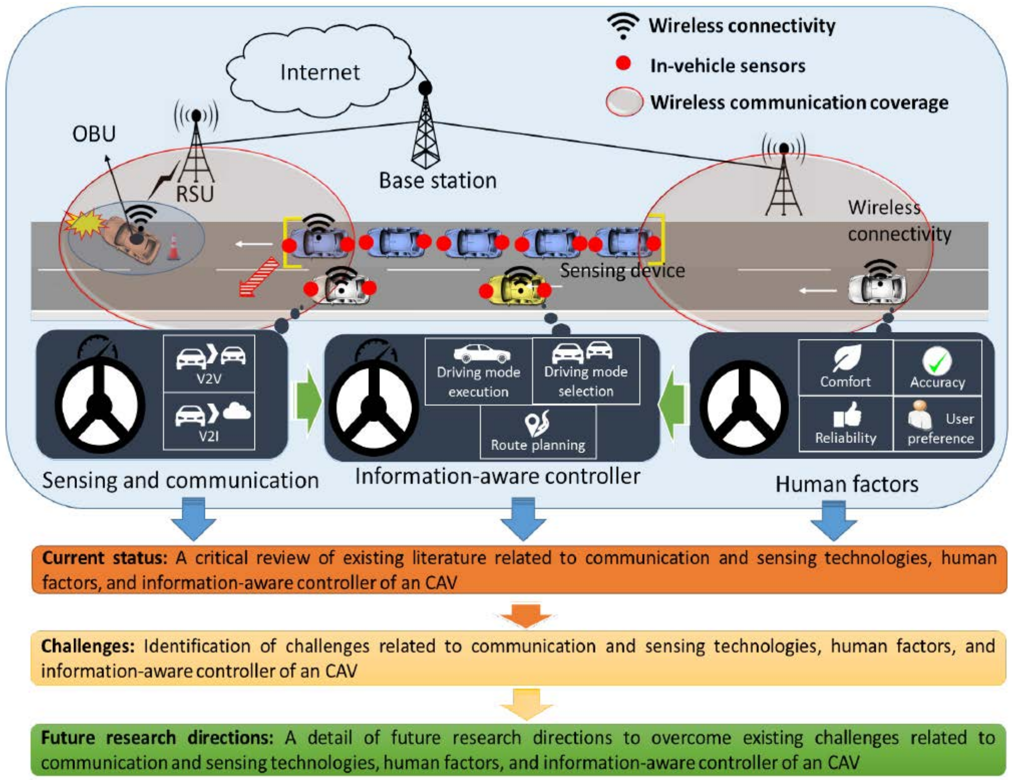


Figure 2-1: Sensing and communication technologies, human factors, and information-aware controller (Sarker et al., 2019)

2.2 Drivers' Behavior in Connected Vehicle Applications

CV applications adjust drivers' behavior into three significant categories; Event-based Driver Behavior Adjustment, Continuous Driver Behavior Adjustment (CDBA), and Semi-Automated/Automated Driving. These categories are described in detail below.

Event-based Driver Behavior Adjustment provides drivers with auditory or visual warnings or instructions about a forthcoming event. The event-based driver behavior adjustment acts only when a potentially dangerous event occurs, such as a stationary queue, an incident scene, or an upcoming amber signal. Collision warning, curve warning systems, queue warning, and lane-

changing warnings also indicate driver behavior adjustments. Almost all the suggested adjustments are for safety applications.

Perception Improvement

Most event-based information aims to provide auditory warnings, such as warnings about speed violation, congestion ahead, incident scene, and work zone (Sharma et al., 2018). Various studies researched how these advisory warnings can affect drivers' perceptions and deceleration actions. From driving simulator trials, the advisories can significantly shorten perception-reaction time from 0.77 s to 0.63 s. However, the deceleration rate did not decrease because of the warnings (Chang & Wei, 2013). Previous researchers also found that the range of 164 ft – 197 ft between the leading and following car is the best warning time.

Hazardous Behavior Adjustment

In addition to drivers' perceptions of the surrounding traffic situation, drivers' mistakes can potentially cause crashes. As soon as the potentially dangerous driving behavior is perceived, the driver will be warned to take mitigation strategies. The hazardous behavior adjustments consist of curve-speed warning systems and collision avoidance systems (Songchitruksa et al., 2016).

CDBA works under non-time-critical circumstances to advance the safety and efficiency of surrounding traffic flow. The advisory messages can help the driver achieve safer lane-changing, less fuel consumption, more efficient traffic flow, etc. Examples of these adjustments are the variable speed limit (VSL), eco-driving, and lane-changing assistant. The efficacy of these applications depends on drivers' compliance with these recommendations. CDBA is used in circumstances that are not very life-threatening. The adjustments aim to advance the effectiveness and safety of surrounding traffic flow.

CV application induces specific drivers' behaviors during a particular driving process, and the provided warning messages give drivers more reaction time to make decisions. Compliance rate has a significant impact on the effect of this type of application.

Though AVs and CVs are two disparate concepts, they can be mutually applied to produce a more effective traffic system. Semi-automated driving requires drivers to set up control parameters, although part of the vehicle's control is automated. Also, drivers have an option to take back control if necessary.

2.3 Drivers' Compliance Reaction to CV Instructions

Various human factors are significant components in transportation systems, specifically CV technology. However, most studies did not consider the human factors in CV modeling by assuming that the drivers comply 100% with the given advisory message (Monyo, 2020; Soloka, 2019; Talebpour et al., 2016; Talebpour & Mahmassani, 2016; Tang et al., 2014). These assumptions may not be realistic since humans cannot act like robots. When an advisory is given to a driver, the driver may either comply or ignore it entirely or partially. Thus, understanding and modeling drivers' compliance behavior is necessary for CV technologies' wide-scale deployment (Sharma et al., 2019).

Sharma et al. (2018) categorized the human factors influencing driver compliance into four groups: (i) personality traits, (ii) affective, cognitive, and psychomotor functions, (iii) acceptance and trust, and (iv) socio-economic characteristics. Further, the researchers performed a field test examining the freeway merging assistance systems for CVs. They concluded that compliance is higher for older drivers and independent of gender. However, 100% driver compliance is highly improbable due to these human factors.

A mixed model analysis study showed that scenario types, V2I suggestions, and driver age significantly affected drivers' compliance rates. No significant difference corresponded to gender, which is consistent with other previous studies on lane-changing and car-following (CF) behavior under V2I systems (Farah & Koutsopoulos, 2014; Q. Li et al., 2015). Factors that affect a drivers' compliance rate include driver's familiarity with the road, distraction level due to CV applications, trust in the CV application, age, existing traffic conditions, the advisory type provided, and the leading vehicle's behavior (Songchitruksa et al., 2016). Moreover, a driver's adaptation to new applications also affects the driver's reaction time. During this period, drivers are unaware of the application to act differently from expectations. A driver's attention also affects compliance behavior. A driver will become less likely to comply with the higher the number of alerts. Additionally, the more drivers get annoyed by the surrounding traffic conditions, the more likely they are to make aggressive choices and not comply with the provided safety messages (Songchitruksa et al., 2016).

2.4 Drivers' Compliance Behavior Modeling

Several researchers have developed various ways to model drivers' behavior in a CV environment. Sharma et al. (2019) modeled drivers' compliance in CV technology using the Prospect Theory (PT), a decision-making theory under risk (e.g., risk of rear-end collision). The study is based on drivers' compliance with the CF behavior in traditional vehicles and CV. Researchers conducted an experiment where participants drove a simulator car in a connected scenario with the baseline scenario as the traditional traffic environment. The results revealed that drivers in connected environments drive safely and efficiently compared to drivers' CF behavior in conventional vehicles. Furthermore, the driver's compliance rate increased as headway decreased, indicating that the driver's decision to comply depends on the observed headway.

Imants et al. (2021) performed a driving simulator study to analyze the effects of multiple sources of information on route choice. The study focused on the interaction between prescriptive route guidance provided by a navigation device and descriptive traffic information provided by variable message signs (VMS). The results showed that the driver's trust in information was higher when information came from multiple sources instead of one source. Thus, the driver's compliance to switch routes was higher when information came from both VMS and navigation devices than from only the navigation device. Moreover, in the case of a single source of information, participants preferred information from VMS than navigation devices. However, when VMS provided indecisive information, drivers used navigation devices to support route choices. Karlsson et al. (2015) demonstrated a similar finding. Their study suggested that using an adequately designed navigation system can help reduce workload. When the provision of indecisive information from the preferred source increases mental workload, the navigation device uses decisive information to reduce it again.

Jeihani et al. (2017) also conducted a driving simulator study to examine drivers' willingness to divert route when observing VMS on the main road, such as the "crash ahead, take the detour" sign. The study revealed a significant correlation between driver route choice behavior, actual travel time, and the need for GPS. The study indicated that driver behavior is compliant in each scenario if the subject chose the shortest path; otherwise, it was non-compliant. The results showed 23% as the lowest willingness of drivers observing VMS to divert. The study did not find significant effects of age, gender, and mileage on compliance with VMS. High compliance with the provided traffic information on VMS is also found in a field study by Romero et al. (2020).

Yu et al. (2019) conducted a field test to predict drivers' compliance and reactions after receiving speed advisory from V2I communication at a signalized intersection. The field tests were conducted in seven dissimilar intersection setups to analyze drivers' suggested compliance. On average, the study results indicated that drivers performed the intersection maneuvers differently when provided with the speed suggestions, which was about 18% of the increase in similar behavior suggested by the V2I technology.

Rahman et al. (2019) developed an acceleration system to recognize various approaches in modeling the behavior of CVs, AVs, and conventional vehicles without connectivity. Ruohua et al. (2018) investigated the effects of drivers' compliance rates on emissions at a signalized intersection. A total of 11 compliance rates were created between 0 and 1 at an interval of 0.1, with zero (0) being the minimum compliance rate and one (1) being the maximum compliance rate. Hayat et al. (2017) conducted a simplified field test of the freeway merge assistance system (FMAS) with 68 participants in Virginia Smart Road. Data on the driver behaviors on different types of advisory messages under various traffic scenarios in a controlled environment were collected. As presented in Table 2-1, the drivers showed a high compliance rate for lane-change advisory when a large or medium-sized gap was available for lane-change advisory rather than when a small gap was available for a lane-change. The study discovered that drivers comply with direct advisory messages rather than indirect messages.

Table 2-1: Compliance rates across gap size (Hayat et al., 2017)

Compliance rates	Large gap	Medium gap	Small gap	Ignore gap size
Variable speed Limit	72%	72%	45%	63%
Lane changing advisory	97%	91%	64%	84.3%
Merging Control Algorithm	95%	95%	65%	84.8%
General	88%	85%	58%	

According to Songchitruksa et al. (2016), one way to model compliance behavior requires constructing a model to reveal drivers' reactions by establishing frustration and activation variables. The variables can positively or negatively impact the traffic variable that the CV application attempts to adjust. Moreover, to broadly study the driver compliance impact in the mixed traffic flow of conventional vehicles and CVs, two driver-based compliance levels were considered, the low-compliance drivers and the high-compliance drivers. Besides, the compliance rate is preset to 70% in the continuous driver behavior adjustment. Component object model (COM) code was used as a random number generator between zero and one. When a driver receives the advisory message, i.e., speed advisory or lane-change, the driver will comply when the obtained random number is less than 0.7. Otherwise, the driver will not comply.

Hamdar et al. (2008) presented an acceleration model that avoids crashes, specifying behavioral mechanisms. An extension to this model was pre-sented by Talebpour et al. (2015), who recognized that drivers have different perceptions when encountering congested versus uncongested roadways. Accordingly, they introduced two value functions: modeling driver behavior in congested roads and modeling driver behavior in uncongested roads. The study used a game-theoretical system in modeling lane-changing behavior through V2V communications.

Dia and Panwai (2007) conducted a field behavioral survey of drivers on a real congested world commuting corridor to get the drivers' preferences for lane-changing advisory or route

detours. Furthermore, several neural network agent-based dynamic behavior models were conducted to determine the drivers' compliance rate factors. Moreover, microscopic traffic simulation was done to simulate the movements of drivers. The results showed that drivers' compliance rate depends on their socio-economic characteristics, the degree of familiarity with the network, and the expectation of improved travel time.

This study adopted the study's findings by Songchitruksa et al. (2016) in modeling vehicle movements in a CVs environment mixed with conventional vehicles. The study results were chosen because they incorporate driver compliance, a critical human factor for the success of CVs.

2.5 Lane Blockage on Freeways and Diversion Strategies

Traffic incidents involving the collision of one or more vehicles or moving objects are common on freeways due to higher posted speed limits than arterials or collector roads. Blockage of one or multiple lanes on freeways depends on the traffic incident type and incident severity. Additionally, blocked lanes depreciate the performance of the freeways to an estimate of 30% to 50% of the congestion problems, as a result affecting safety and causing energy and environmental problems (Khattak et al., 2011).

Incident-induced queues reduce once a percent of the traffic approaching upstream of the incident location on the freeway has been diverted to alternative routes, therefore, decreasing the amount of traffic nearer to the incident position. (Pulugurtha & Balaram Mahanthi, 2016). Researchers have used various microsimulation models, for example, AIMSUN, CORSIM, PARAMICS, SimTraffic, VISSIM, and VISTA, to analyze the effects of diversion strategies on freeways and adjacent arterial facilities. For instance, Liu et al. (2013) developed and calibrated a VISSIM model and used its COM interface to divert traffic from the freeway to the alternative

route in Seattle, Washington. The studys' performance measures to determine the optimum diversion rates were delay and throughput values of the freeway and alternative road. The freeway had a 123 s delay, while the alternative arterial route had 56 s. A diversion rate of 4% was the optimum portion for diversion.

Koorey et al. (2015) used a microsimulation software known as PARAMICS with distinct signal coordination to model an incident diversion strategy for a network in New Zealand and Auckland. The study results showed that an incident on the motorway increased travel time on both the freeway and the diversion route by 35% and 81%, respectively.

Zhou (2008) used CORSIM for microsimulation of diversion strategy from the freeway to the alternative arterial roadway due to an incident. The study also used SimTraffic to coordinate signal timings at intersections along the arterial road to account for the diverted traffic volume. The study compared 5% and 25% diversion rates and discovered that the freeway's delay reduced by 76.8%, whereas it increased by 48% along the arterial roadway. However, at a diversion rate of 25%, the total delay of the network was 21% lower than with the traffic conditions resulting from the diversion rate of 5%.

Kröller et al. (2021) explored the type of strategic routing interventions that drivers appreciate and reported understanding a two-stage study with 457 participants. The study revealed that essential factors affecting drivers' willingness to divert are the reason for detours and the additional driving time. Drivers were asked to take a predefined route diverting them from an area to reduce traffic. The acceptable detour duration seemed to be situation-dependent. Self-centered situations, for instance, avoiding danger, reached much higher effectiveness. Acceptance dropped to a 25% plateau at 8-min detours for jam-related conditions. Incentives increase the effectiveness

but only marginally increase user appreciation, indicating that users may mistrust strategic routing that relies too strongly on motivations.

The objective of Peeta et al. (2000) study was to model driver behavior that predicted the diversion probability of an individual under a specific VMS. The results showed that drivers' willingness to divert is 18.5% when the best detour strategy is provided, 14.5% when the VMS displays the expected delay only, 12.9% when the incident location is provided, and 12.5% when only the occurrence of an incident being mentioned.

Polydoropoulou et al. (1994) key finding was that attitudinal factors and information acquisition primarily influence en-route diversion. Responders' attitudes and preferences generally reflected that 16% changed their planned route upon alternative route advisory. And among the surveyed commuters, only 9% followed radio advice. Moreover, drivers' observations are essential factors affecting route switching. The study concluded that a reliable and frequently updated traffic information system would stimulate traffic information acquisition and affect route diversion.

2.6 Human Factors in Modelling Conventional Vehicles

Most studies consider conventional vehicles to have no communication capabilities hence don't receive updates from other vehicles or TMC. However, the drivers in conventional vehicles still observe road signs and perceive their surrounding drivers' behavior even though their indeterminate about other drivers' future driving behaviors. The ambiguity possibly will decrease the safety of the freeways or highways (Talebpour et al., 2016).

Furthermore, in the United States, the VMS has been increasingly utilized. Transportation agencies ensure that advisory messages regarding incidents are consistently informative to assist drivers in appropriate decision-making regarding the proposed desired route without significantly reducing their speed while reading the displayed message. However, drivers respond to VMS

messages differently, and their reaction to the displayed messages will affect the usefulness of these signs (Ardeshiri et al., 2012).

Conventional vehicles may not necessarily be uninformed of the occurring traffic changes. Mobile applications like google maps update drivers in conventional vehicles on future route delays and real-time speed limits. Some studies model conventional vehicles using the Intelligent Driver Model (IDM) since it incorporates human factors and error estimations (Sharma et al., 2019, 2021). Figure 2-2 shows several significant human factors that affect the dynamics in the traffic flow of conventional vehicles.

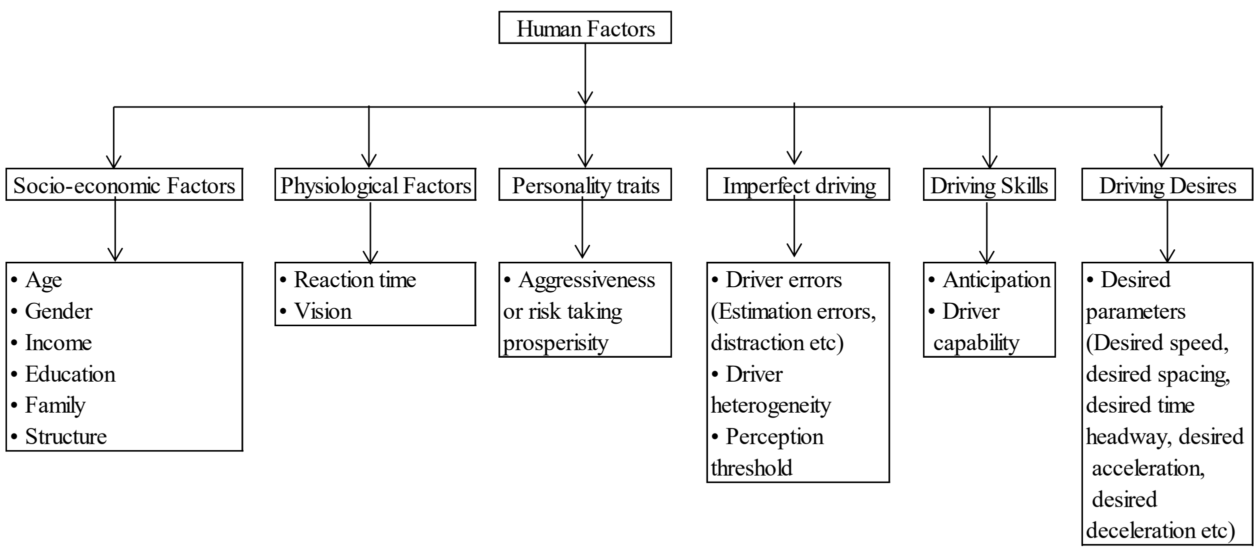


Figure 2-2: Human factors critical for modeling conventional vehicles (Sharma et al., 2018)

2.7 Surrogate Safety Measures

Safety is among the areas of concern in transportation engineering. Transportation safety is concerned with protecting life and property from crash, danger, risk, or injury through rules and regulations, managing, and technology development of all forms of transportation.

In the past, safety evaluation in transportation has been challenging due to the absence of knowledge on what constitutes an unsafe or safe facility and the absence of predictive models to identify crash potential (Gettman & Head, 2003). Recently, software tools can analyze surrogate measures produced by simulation models. The microscopic simulation models provide detailed estimates versus the subjective criteria constructed on human observers, such as the traffic conflicts technique. Since the driver behaviors included in microscopic simulation models have an assumption that drivers behave safely, the derivation of surrogate safety measures must consider this essential detail (Gettman & Head, 2003).

Tarko et al. (2009) presented two conditions that surrogate safety measures should satisfy. One, a surrogate measure should be based on an observable non-crash event that is physically related predictably and reliably to crashes; Two, a practical method exists for converting the non-crash events into a corresponding crash frequency and severity.

For a better evaluation of surrogate safety measures, the microscopic simulations must model the following; behavioral modeling, variable driver reaction time, intersection box movements, variable acceleration and deceleration rates, variable time steps, time steps of < 1.0 s, variable queue discharge headway, variable headways, gap acceptance criteria change by delay, vehicle length, vehicle length considered by gap logic, parameterized turning speed, reaction to yellow, vehicle interactions with pedestrians, friendly merging, parking maneuvers, and U-turns.

Behavioral modeling includes driver behaviors such as car-following behavior, gap acceptance behavior, and lane-changing behavior that produce opportunities for crashes. Thus, microscopic simulations include these behaviors in the model to evaluate surrogate safety measures accurately. The variable driver reaction time model should have the ability to mimic the

delay experienced between the driver's identification of a potential collision and the application of control measures (braking, acceleration, or lane change) to avoid a collision. Experience and age are among the factors that affect variable driver reaction times.

Intersection box movements are significant for the microscopic simulation to model the movement of vehicles in an intersection for better valuation of surrogate safety measures. Variable acceleration and deceleration rates modeling involves different vehicle capabilities by type of vehicle, acceleration, and deceleration rates distributions. Sight distance limits are the microscopic simulation that models driver's types/driver look ahead distance when required to make decisions. Rolling yield is the adequate modeling of vehicle yield points (Gettman & Head, 2003).

2.8 Traffic Simulation

VISSIM is a microscopic, time step, and behavior-based traffic flow simulation tool widely used to model real traffic conditions and estimate speed-based vehicle emissions in urban and rural traffic and pedestrian flows. The VISSIM model can simulate traffic flow based on different parameters, such as lane allocation, vehicle composition, signal control, and detection of private and public transport vehicles. Thus, VISSIM helps researchers to master a wide variety of traffic-related challenges like junction layout comparison (roundabout vs. signal control, multimodal, etc.), transport development planning (road works management, building evacuation, etc.), capacity analysis (increase in demand, a roundabout with pedestrian flows, etc.), active traffic management (temporary use of the hard shoulder, etc.), and public transport simulation like prioritization and railway stations (PTV, 2021).

This study used PTV VISSIM 2021, the current version at the time, which had more features to create the base models than the previous versions. It is the leading microscopic

simulation program for modeling multimodal transport operations. It is said to be realistic and accurate in every detail and creates the best conditions to test different traffic scenarios before their realization (PTV, 2021). VISSIM can model incidents or blocked lanes, an advantageous criterion in this study. Further, the traffic flow model in VISSIM is based on a car-following model and a lane-changing model that favors this study in modeling traffic flow in Florida's Turnpike mainline.

2.9 Literature Review Summary

Recent studies focus on transportation systems management and operations (TSM&O) and intelligent transportation systems (ITS) toward escalating automatic incident detection systems to deal with roadway incidents. TSM&O strategies optimize the performance of existing multimodal infrastructure to improve the mobility and safety of the transportation system. Several studies were carried out to determine the operational and safety benefits of TSM&O strategies (Ali et al., 2022: Ali et al., 2021a,2021b; Kodi et al., 2021a,2021b,2021c; Alluri et al., 2020; Kodi 2019). Moreover, other studies focused on ITS in detecting incidents, traffic congestion, and jamming, which cause damage to precious human lives and financial losses (Iqbal & Khan, 2018). The availability of CV/AV technologies is expected to add to the complexity of the ITS investment decision-making process. CV technology is one of the ITS incident detection methods used in the developed communication plan.

Through the V2V and V2I wireless communications established between CVs, the vehicles can share their real-time status among themselves and the infrastructure. Data exchanged include lateral acceleration, reduced speed warnings, break status, location, travel direction, blind spot, emissions, forward collision warning, and roadway and traffic conditions. Drivers would use short-range radio signals for communications; for practical and reliable communications, the DSRC at 5.9 GHz is highly suggested (NHTSA, 2011).

Most existing automatic incident detection systems use fixed detectors to detect traffic parameters like occupancy, speed, and lane-change information. These systems are prone to delay, inaccuracies, and false alarms during data collection and processing due to weather conditions, driver's driving patterns, road repairing, a line of sight, and short-range communication. Moreover, these systems are designed for highways and are less compatible with city scenarios due to their highly variable traffic density.

Microsimulation models help in planning for the future, and they can be used to model CV environments to analyze the benefits of various CV applications. Conflict analysis via surrogate safety measures and microsimulation models have recently been appropriate means to evaluate the safety benefits of CV applications (Gettman & Head, 2003). This study utilized the V2V safety applications for lane change warnings (LCW), forward collision warning (FCW), and V2I reduced speed warnings. The next chapter explains further the study approach.

CHAPTER 3 METHODOLOGY

3.1 Study Site

The study was conducted on Florida's Turnpike Mainline (SR-91) system. The study corridor is a 7.8-mile freeway road section, with 6-lanes, i.e., 3-lanes in each direction on Florida's Turnpike Mainline (SR-91). The freeway section crosses four roadways in Broward County: Sample Road, Copans Road, Coconut Creek Road, and Atlantic Boulevard. Each interchange roadway ranges from 1 to 2 miles distinctly, with access to the Turnpike at each interchange except for the Copans Road crossing. This study site was chosen based on the Signal Four Analytics database observations because of its relatively high number of crashes in the past years. The secondary study area was the arterial road, Lyons road, parallel to Florida's Turnpike. This was used as an alternative route in situations where there is congestion on the freeway. Figure 3-1 shows the map of the study corridor, and the red star marks the simulated incident location.

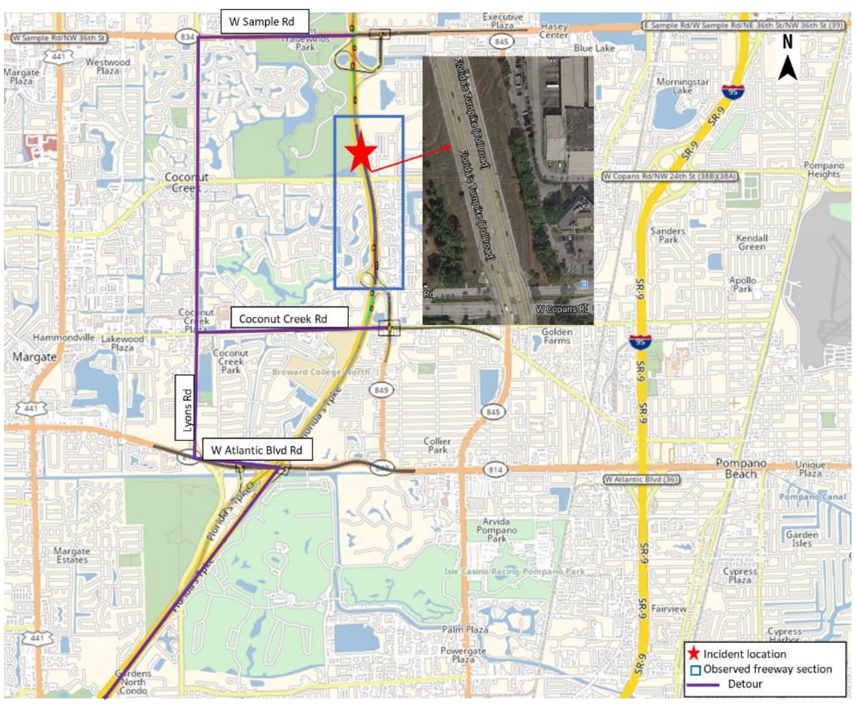


Figure 3-1: Study area

3.2 Data Collection

The study used data from the FDOT report obtained from the model development and calibration report for the existing 2016 morning and evening peak conditions for the Broward County SW 10th Street project. The data collected in the report were gathered following the FHWA's Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software.

3.3 Application of VISSIM Microsimulation Model and Calibration

This study used an existing VISSIM network model partially developed by FDOT, including the previously developed VISSIM models for the Sawgrass Expressway and Interstate 95 (I-95). The 2016 aerial imagery was used to add the SW 10th Street segment, roadway features, and other corresponding dimensions that were site verified. The arterials model limits extended 0.5 miles outside of the construction project limits to capture the extent of real-world congestions in the modeled network. Figure 3-2 shows the overall project model, and the red rectangle indicates the section that experienced more crashes hence selected for this study. 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.

This study extends the previous work done by Monyo (2020) by incorporating drivers' compliance behavior for both CVs and conventional vehicles and analyzing detouring strategies during traffic incidents on the freeway. The VISSIM model for a detour was modified to analyze the effects of freeway incidents on operational characteristics of both the arterial roadway and the freeway; both roads were evaluated for different scenarios of increasing incident clearance duration and CV MPRs. Figure 3-3 illustrates how Lyons Road, a parallel arterial, was included

in the model to give two diversion options. The first diversion is from the Turnpike exit on Coconut Creek Road, then connected to Lyons Road and W Sample Road. And the second diversion is from the Turnpike exit on W Atlantic Blvd Road, then connected to Lyons Road, and finally, to W Sample Road. The second detour was only activated if the queue reached point C (see Figure 3-3). The study aimed at defining the significance of the factors: incident clearance duration, CV MPRs, and demand level.

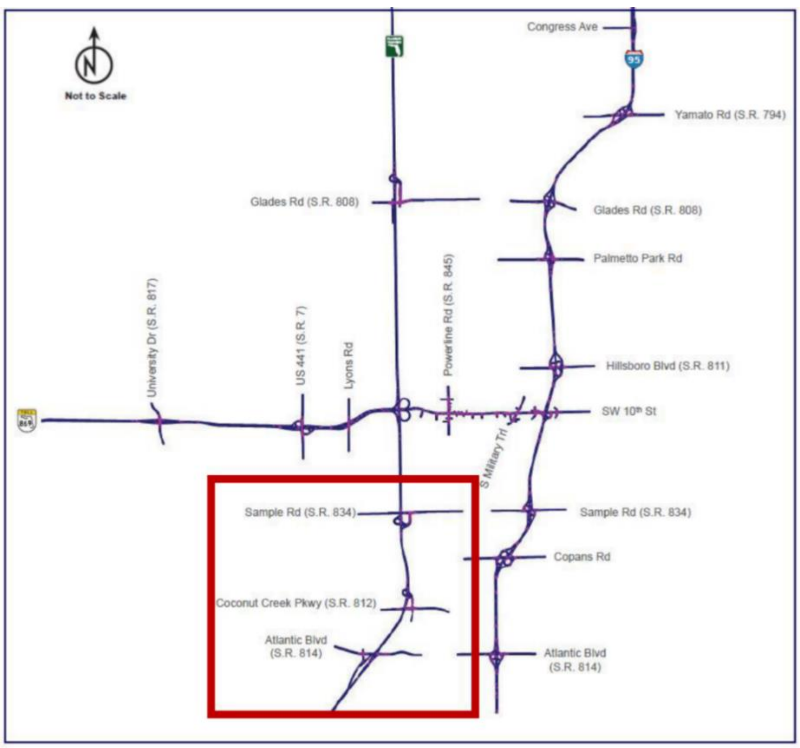


Figure 3-2: Turnpike VISSIM model

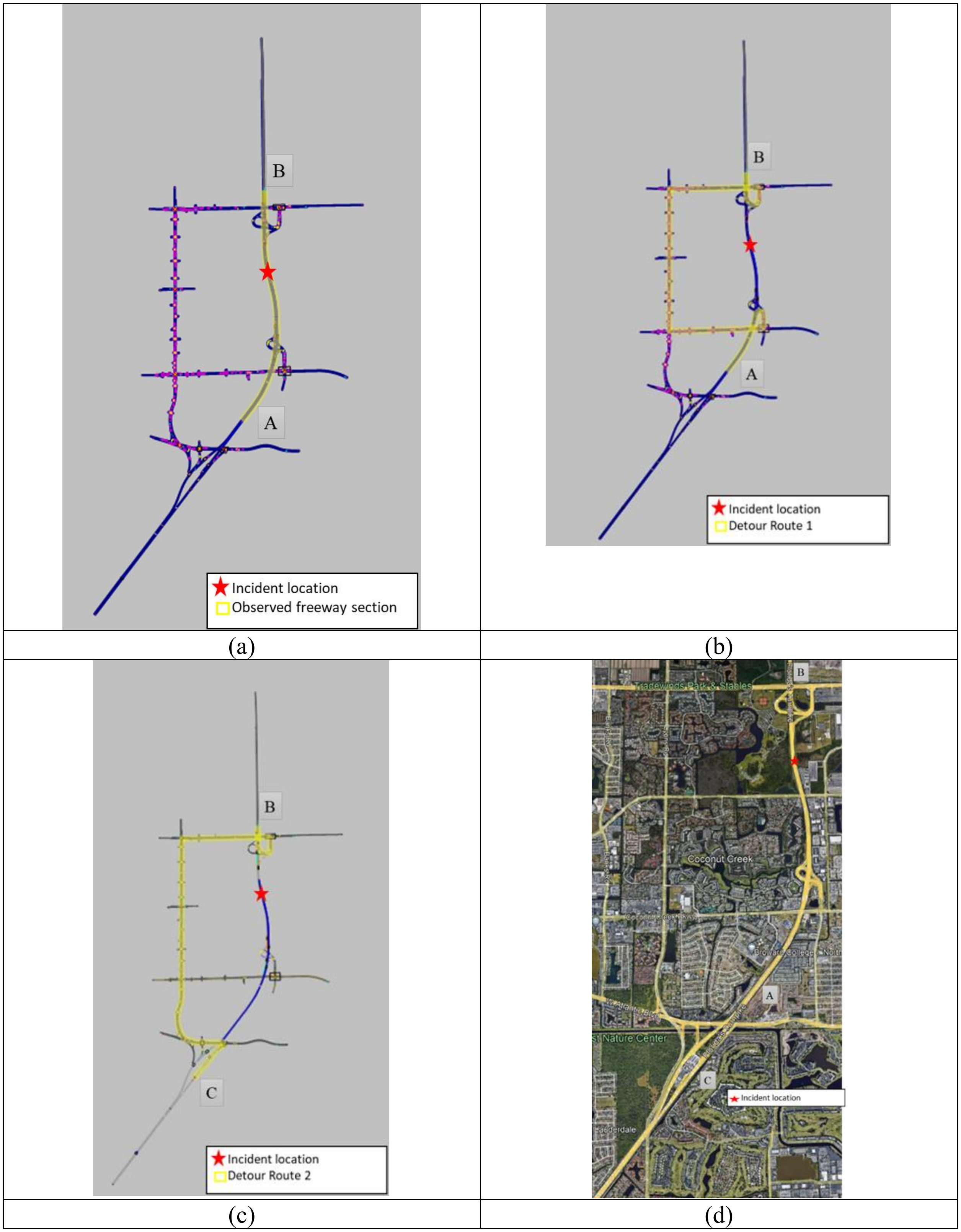


Figure 3-3: Point A/C to B by freeway or diversion during a traffic incident on the freeway (a, b, c) from simulation (d) from GoogleEarth Pro

3.3.1 Traffic Volume Inputs

This study used traffic volumes recorded in the FDOT report during the model development and calibration report for the existing 2016 morning and evening peak conditions for the SW 10th Street project. The focus was on the peak-hour traffic volumes. The timing was divided into the pre-peak, peak, and post-peak hours for morning and evening. The morning peak hours were from 6:30-9:30 AM, with the highest congestion being from 7:30-8:30 AM, and the evening peak hours were from 4:00-7:00 PM, with the most increased congestion being from 5:00-6:00 PM. All three hours were included in the model, thus developing a depicted buildup and dissipation of congestion in the study area corridor. Moreover, a 30-minute seeding time was added to the network to achieve traffic equilibrium between the number of vehicles entering and the existing network. Hence, the entire simulation period was 6:00-9:30 AM and 3:30-7:00 PM for the morning and evening peak hours.

Loading factors were used to convert the balanced 2016 peak hour volumes into pre-peak, peak, and post-peak hour volumes, Table 3-1 illustrates the hourly volume conversion factor. The factors were developed based on time-slicing factors derived from the hourly traffic volume distribution recorded in the field (*SW 10th Street PD&E VISSIM Model Calibration Florida's Turnpike to I-95*, 2017). The breakdown of volumes along Florida's Turnpike freeway and the ramp volumes on each on and off-ramp used in the model are shown in Tables 3-2 and 3-3.

Table 3-1: Hourly volume conversion factor

	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%	

Table 3-2: Freeway volumes and ramp volumes used in the simulation model for AM period

Freeway Volumes – AM			
Location	Demand Volume	Location	Demand Volume
Turnpike Northbound		Turnpike Southbound	
Turnpike Mainline before Atlantic Boulevard off-ramp	6,090	Turnpike Mainline after on-ramp from Sawgrass Expressway	5,460
Turnpike Mainline after Atlantic Boulevard off-ramp	4,860	Turnpike Mainline after on-ramp from Sample Road	5,740
Turnpike Mainline after on-ramp from Coconut Creek Parkway	4,810	Turnpike Mainline after on-ramp from Coconut Creek Road	4,910
Turnpike Mainline after on-ramp from Sample Road	4,160	Turnpike Mainline after on-ramp from Atlantic Boulevard	5,840
Ramp Volumes – AM			
Location	Demand Volume	Location	Demand Volume
Northbound		Southbound	
Turnpike Off-ramp to Atlantic Boulevard	1,230	Turnpike On-ramp from Atlantic Boulevard	930
Turnpike Off-ramp to Coconut Creek Parkway	710	Turnpike Off-ramp to Coconut Creek Parkway	1,230
Turnpike on-ramp from Coconut Creek Parkway	660	Turnpike On-ramp from Coconut Creek Parkway	400
Turnpike off-ramp to Sample Road	1,200	Turnpike Off-ramp to Sample Road	690
Turnpike on-ramp from Sample Road	550	Turnpike On-ramp from Sample Road	970

Table 3-3: Freeway volumes and ramp volumes used in the simulation model for the PM period

Freeway Volumes – PM			
Location	Demand Volume	Location	Demand Volume
Turnpike Northbound		Turnpike Southbound	
Turnpike Mainline before Atlantic Boulevard off-ramp	5,720	Turnpike Mainline after on-ramp from Sawgrass Expressway	3,980
Turnpike Mainline after Atlantic Boulevard off-ramp	4,830	Turnpike Mainline after on-ramp from Sample Road	4,610
Turnpike Mainline after on-ramp from Coconut Creek Road	5,560	Turnpike Mainline after on-ramp from Coconut Creek Parkway	4,660
Turnpike Mainline after on-ramp from Sample Road	5,140	Turnpike Mainline after on-ramp from Atlantic Boulevard	5,900
Ramp Volumes – PM			
Location	Demand Volume	Location	Demand Volume
Northbound		Southbound	
Turnpike Off-ramp to Atlantic Boulevard	890	Turnpike On-ramp from Atlantic Boulevard	1,240
Turnpike Off-ramp to Coconut Creek Parkway	400	Turnpike Off-ramp to Coconut Creek Parkway	620
Turnpike On-ramp from Coconut Creek Parkway	1,130	Turnpike On-ramp from Coconut Creek Parkway	670
Turnpike Off-ramp to Sample Road	1,060	Turnpike Off-ramp to Sample Road	400
Turnpike On-ramp from Sample Road	640	Turnpike On-ramp from Sample Road	1,030

3.3.2 Modeling Procedure

Incident Modeling

This study used VISSIM COM API to attain a CV environment in the microsimulation model. VISSIM enables users to model traffic behavior and conditions during simulation runs using an external programming language. Thus, a decision-making CV control algorithm was developed in the Visual Basic Scripting language (VBS) and applied in PTV VISSIM using the event-based scripts.

VISSIM does not have a built-in incident formation parameter; however, it offers various ways to implement an incident. Previous studies used a bus stop to represent an incident (Hadi et

al., 2007; Wang et al., 2009; H. Zhou & Tian, 2012). The bus arrival time was considered the beginning of the incident and the dwell time was used to represent the duration of an incident. Other studies used a parking lot and parking lot routing decision with a given parking duration to simulate an incident (Karaer et al., 2020; Liu et al., 2013). Even though the bus stop and parking event approach may sound more realistic, the researcher cannot determine the exact incident start time since it depends on the vehicle's decision to enter the bus stop or parking lot. For researcher's total control over the precise time of incident occurrence, other studies used the COM interface in VISSIM to add a vehicle with zero speed at the beginning of the incident and keep it for the incident duration (Chou & Miller-Hooks, 2011; Hong et al., 2013; Monyo, 2020; Soloka, 2019).

According to the Highway Capacity Manual (2010), the incident duration can be divided into four typical phases: incident detection, incident response, incident clearance, and traffic recovery. With the advancement of information collection and dissemination technology, the time needed for incident detection and response has been dramatically shortened in the past few decades. However, it remains reasonable to set the diversion period lagging a little behind the incident start time, allowing a short period for the information to be delivered to the travelers

Thus, this study introduced a stationary vehicle in the model during the peak hour to simulate an incident blockage, as indicated in Figure 3-3 above. This method used the *"AddVehicleAtLinkPostion"* function existing in VISSIM COM Interface. The function allows users to add or remove a vehicle at a specific time selected. The added vehicle was with zero speed and stayed at the incident location for the chosen incident period, and it was set to be removed when the incident was cleared. Multiple vehicles with an exact placement time and removal time were placed on the outer and inner lanes to simulate two or more lanes blockage. The incident

duration varied in respect to the scenarios. An incident clearance duration of 30 and 90 minutes was applied for single and two-lane blockages scenarios with detour operations, respectively. The span was between the minimum and maximum duration for one lane and two lanes closed, as shown in Exhibit 11-22 of the HCM (2016) presented in Table 3-4. Incident modeling was done northbound, and the safety analysis considered only northbound traffic.

Table 3-4: 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	0.0
Duration (mean)	34.0	34.6	53.6	67.9	67.9
Duration (standard deviation)	15.1	13.8	13.9	21.9	21.9
Duration (minimum)	8.7	16.0	30.5	36.0	36.0
Duration (maximum)	58.0	58.2	66.9	93.3	93.3

Incident detection and verification

This study assumed that the RSU automatically detected an incident once it occurred. In the VISSIM COM environment, the RSU was modeled at the point close to the incident location. Through the COM interface in VISSIM, vehicle speed was tracked to detect any significant drop, thus, verifying incident occurrence. The desired speed distribution governs vehicle speed in the network by defining the probability distribution of vehicle speed between the lower and upper bound. The data collection points placed close to the incident location operated as stationary sensors on freeways. The sensors collected vehicle data at each simulation time step, particularly speed. After that, 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.

Advisory Messages

The simulation software assigned the proposed algorithm to a specific vehicle category, creating a CV environment. V2V and V2I safety communications were assumed to increase drivers' awareness and mitigate traffic incidents. Basic safety messages including speed advisory, forward collision warnings, and lane-change warnings, were given to vehicles upstream after the incident. The advisory messages informed drivers to either change lanes only, reduce speed or reduce speed and change lanes. Lane-change messages were sent to all CVs within the communication range at a distance of 2 miles upstream of the incident location. After the incident clearance, advisory messages were sent downstream to clear the desired lane.

The basic safety messages were sent assuming no latency, therefore, instantly received by CVs downstream and upstream of the incident. After the termination of messages at the end of the incident, the corridor-level safety impact of CVs was finally evaluated using the SSAM in both the upstream and downstream sections, as Figure 3-1 shows. The different drivers' reactions towards provided advisory messages were accounted for during the modeling of the CVs. Again, VISSIM COM and Visual Basics were used to model driver compliance rate to the given advisory messages during run time.

Compliance Behavior Modeling

VISSIM COM accesses the VISSIM network using specific external interfaces. Thus, Visual Basic was used to code the driver's compliance rate. COM can control the whole process of the CV application, including the alert algorithm, drivers' reaction to the alert, time step by time

step, and vehicle by vehicle. In COM, the program can run VISSIM simulation time step by time step. The program can loop through all the vehicles in the whole network and access the vehicle's attributes such as type, position, speed, and acceleration in each time step.

This study considered speed limit and lane-change alerts. CVs were assigned a unique vehicle type. The penetration rate of the CV was modeled to 0%, 25%, 50%, 75%, 100% in the simulation. In each time step, the vehicles were looped through, and if they belong to the CV type and are currently traveling towards the created incident, their speed will be compared to the speed limit. A warning will be issued if a vehicle's speed is higher than the speed limit. Again, if the CV type is not in the incident lane, a lane-changing advisory was only issued if the vehicle is in the incident lane. The speed limit was stored in a reference database in advance.

After giving the advisory, the immediate problem is the compliance behavior of the CV drivers. Understanding and modeling drivers' compliance behavior is a challenging task. As highlighted in the literature review, researchers have adopted various methods for addressing this problem. This study used the Songchitruksa et al. (2016) method because it is the most applicable in microsimulation models; the compliance rate was a preset situation, set to 70 percent. COM via Visual Basics code randomizes numbers between zero and one. Every time a driver receives a warning, if the random number is less than 0.7, the driver will comply and reduce the speed to the posted speed limit or change to the new desired lane. Otherwise, the driver will keep ignoring the warnings. Figure 3-4 shows the entire modeling process in VISSIM COM.

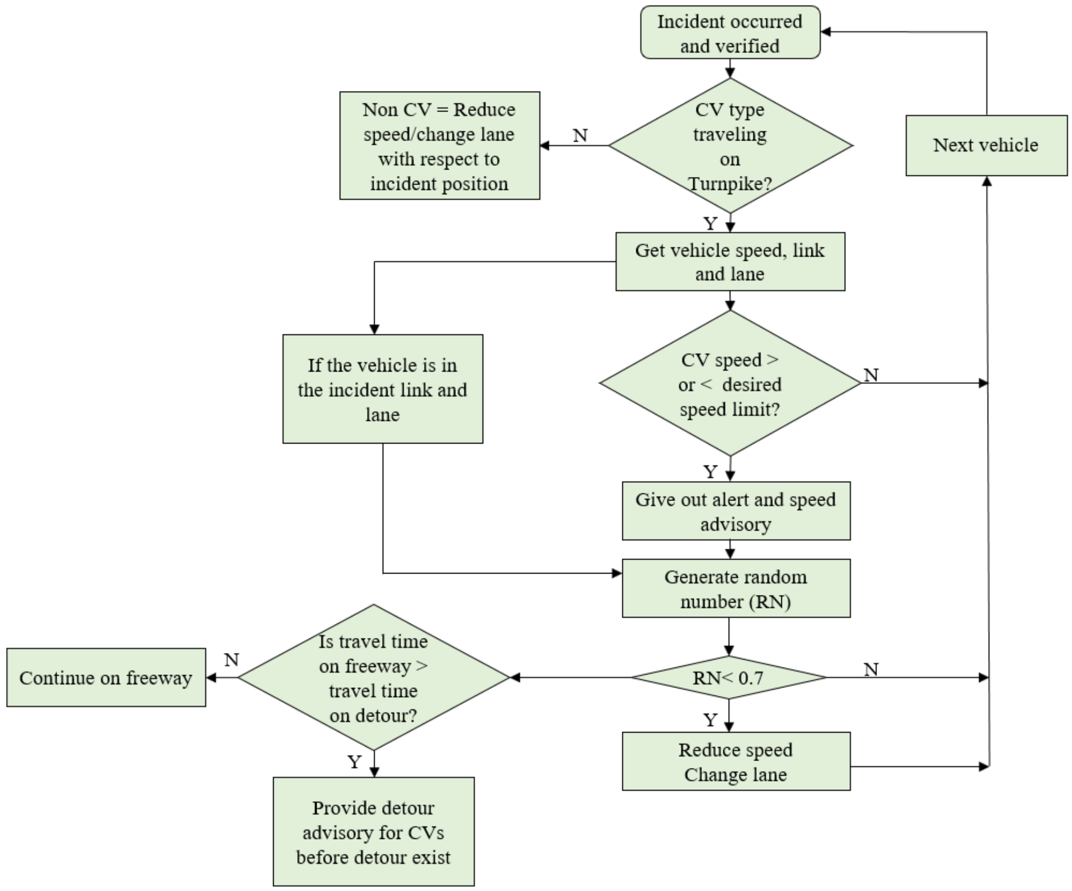


Figure 3-4: Modelling process in VISSIM COM

Modeling Conventional Vehicles Behavior in a Connected Environment

The driver's ability to see ahead is needed for vehicles' safe and efficient operation on a freeway. In most roads, the designers provide a sufficient length of sight distance that enables a vehicle to drive near or at the design speed to avoid striking an unexpected stationary object in the traveled way. While more extraordinary lengths of visible roadway are desirable, the sight distance at every point along a road is designed to be at least needed for a below-average driver or vehicle to stop (American Association of State Highway and Transportation Officials [AASHTO], 2011).

Moreover, the technology has advanced so that most drivers in conventional vehicles are aware of the surrounding road condition via mobile apps like maps, Waze, and Twitter. Some

drivers may perceive and assess other surrounding vehicles' status then adjust their car-following behavior and lane-changing behavior accordingly (Amin-Naseri et al., 2018; Gu et al., 2016).

The study used decision sight distance to model the conventional vehicle's behavior in VISSIM COM. The decision sight distance is the distance a driver needs to perceive information source or detect an unexpected obstacle in a roadway environment. It offers drivers an additional margin for error. It affords drivers a sufficient length to maneuver their vehicles at the same or reduced speed rather than stopping abruptly. Its values are substantially greater than stopping sight distance (AASHTO, 2011). Speed reduction and lane-changing advisory were given to conventional vehicles in the incident lane within 1455 ft from the incident position depending on the vehicle speed distribution, queue length, and distance. The braking component is replaced in avoidance maneuvers C, D, and E with a maneuver distance based on maneuver times, between 3.5 and 4.5 s, that decrease with increasing speed, as shown in Table 3-5.

Table 3-5: Decision sight distance (AASHTO, 2011)

Metric						U.S Customary					
Design Speed (km/h)	Decision Sight Distance (m)					Design Speed (mph)	Decision Sight Distance (ft)				
	Avoidance Maneuver						Avoidance Maneuver				
	A	B	C	D	E		A	B	C	D	E
50	70	155	145	170	195	30	220	490	450	535	620
60	95	195	170	205	235	35	275	590	525	625	720
70	115	235	200	235	275	40	330	690	600	715	825
80	140	280	230	270	315	45	395	800	675	800	930
90	170	325	270	315	360	50	465	910	750	890	1030
100	200	370	315	355	400	55	535	1030	865	980	1135
110	235	420	330	380	430	60	610	1150	990	1125	1280
120	265	470	360	415	470	65	695	1275	1050	1220	1365
130	305	525	390	450	510	70	780	1410	1105	1275	1445
						75	875	1545	1180	1365	1545
						80	970	1685	1260	1455	1650

Avoidance Maneuver A: Stop on a rural road, t= 3 seconds; Avoidance Maneuver B: Stop on an urban road, t= 9.1 seconds
Avoidance Maneuver C: Speed/path/direction change on a rural road, t varies between 10.2 and 11.2 seconds
Avoidance Maneuver D: Speed/path/direction change on a suburban road, t varies between 12.1 and 12.9 seconds
Avoidance Maneuver E: Speed/path/direction change on an urban road, t varies between 14 and 14.5 seconds

3.3.3 Scenario Design

The study corridor used in the analyses consists of three lanes in each direction. This study considered lane blockage as a traffic incident. Various lane blockage scenarios were analyzed, as indicated in Table 3-6. The analysis also considered the effect of the period, thus the AM and PM periods. A sensitivity analysis was performed using varying CV MPRs. A total of 97 scenarios were considered in the study, as described in Table 3-6, whereby 36 scenarios were provided to evaluate route choice and diversion patterns. The scenarios include 30 minutes and 90 minutes incident clearance durations. Ninety minutes is the maximum allowable incident clearance duration after the notice is given to the responsible authorities (Florida Department of Transportation, 2012).

Table 3-6: Different scenarios considered in this study

Scenario	Period	Incident clearance duration	CV penetration
One outer lane blocked (AM)	Peak, Pre-peak, Post-peak	30 minutes	0%, 25%, 50%, 75%, and 100%
One outer lane blocked (PM)	Peak, Pre-peak, Post-peak	30 minutes	0%, 25%, 50%, 75%, and 100%
One inner lane blocked (AM)	Peak, Pre-peak, Post-peak	30 minutes	0%, 25%, 50%, 75%, and 100%
One inner lane blocked (PM)	Peak, Pre-peak, Post-peak	30 minutes	0%, 25%, 50%, 75%, and 100%
Two outer lanes blocked without detour (AM)	Peak, Pre-peak, Post-peak	30 minutes	0%, 50%, and 100%
Two outer lanes blocked without detour (AM)	Peak, Pre-peak, Post-peak	90 minutes	0%, 50%, and 100%
Two outer lanes blocked with detour (AM)	Peak, Pre-peak, Post-peak	30 minutes	0%, 50%, and 100%
Two outer lanes blocked with detour (AM)	Peak, Pre-peak, Post-peak	90 minutes	0%, 50%, and 100%
Two outer lanes blocked with detour (AM)		No incident	

The function “GetbyLocation” was used to return vehicle collection data within a 2-mile communication range in the COM environment. Vehicle attributes collected include vehicle ID, speed, desired speed, link ID, lane number, desired lane, location, coordinate front, and vehicle type. The data collection followed a distance distribution that specifies the 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.

Simulations run

The scenarios, described in Table 3-6, 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 simulation resolution was set to 10-time steps per simulation second, which replicated a transmission frequency of 10 Hz for the BSMs. The simulation resolution impacts the behavior of vehicles and the way they interact. This is why simulations using different simulation resolutions produce different results (PTV, 2021). The VISSIM user manual recommends a minimum of five runs, depending on a simulated task. Ten simulation runs were conducted per single scenario, with a random seed increment of five for each run to eliminate the random effect. Note that the random seed allows simulating stochastic variations of vehicle arrivals in the network. Due to the stochastic nature of microsimulation models, it is necessary to take an average of multiple runs with different random seed numbers to provide statistically meaningful results.

3.4 Safety Evaluation

This study created a 2-mile section upstream of the incident location in the VISSIM model to collect vehicle trajectories. This section replicates the V2I communication range of the RSU at the incident location through DSRC technology. For each scenario, the vehicle trajectory files generated in each run were then imported into the SSAM provided by the FHWA. The SSAM facilitates the identification of conflicts through statistical analysis of vehicle trajectory files generated from microscopic simulations.

3.4.1 Performance Measures

Time to Collision (TTC)

TTC was used as a measurable traffic indicator to obtain quantitative data of traffic conflicts in the SSAM. The SSAM software used trajectory data extracted from the VISSIM microscopic simulation model to identify conflict events and derive surrogate safety measures. Specifically, the following trajectory data were considered: AM and PM pre-peak, peak, and post-peak hours. According to the SSAM software, conflict events were categorized as lane-changing and rear-end conflicts. In contrast, crossing conflicts were not observed due to the nature of the simulation model, having no crossing points in freeway traffic.

TTC is the time required for two vehicles to collide if they continue at their present speeds on the same path (Rahman et al., 2019). There is a statistically significant correlation between crashes and simulated conflicts obtained by TTC (Gousios et al., 2009). Specific thresholds were adopted to determine critical conflicts, i.e., 1.5 seconds for TTC, 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.

However, an abrupt lane-change behavior limitation was observed in VISSIM when modeling an actual lane-change behavior of vehicles in a queue, resulting in crashes with TTC = 0, denoting vehicles colliding in their conflicting paths. This situation is different from what happens in the real world; thus, the conflicts with TTC = 0 were filtered during analysis in the SSAM. Therefore, this study analyzed the results of conflicts at $0 < TTC \leq 1.5$. The exclusion of the conflicts with TTC = 0 was applied to obtain more accurate data and account for the modeling limitation mentioned above, which results in conflicts with a TTC = 0, denoting vehicles colliding in their conflicting paths.

Travel time

For operational analysis, travel time was used as a performance measure to enhance traffic diversion during the incident duration. Travel time was collected at specific time intervals as vehicles' travels started between the start and destination. Thus, on moving from point A to B, as Figure 3-3 illustrates, if a high travel time is detected through the incident scene, the diversion plan is activated to increase the flow rate of the detour route and decrease the flow rate on the freeway. CVs received advisory messages from the OBU, RSU, and mobile devices mounted on the vehicles' dashboards. Dissemination of advisory messages was terminated when speed or travel time was improved to the specified thresholds or at the end of incident duration. For drivers to start lane-change movements towards the detour, detour advisory messages were sent to CVs 0.5 miles to the turnpike exit. This study measured traveled time using the '*Vehicle Travel Time Measurements Tool'* in VISSIM.

In modeling conventional vehicles, the present study assumed that drivers would see queue dissipation when an incident occurs on the freeway. The VMSs sign concerning the incident and detour strategy might have been added to different locations in the network. Moreover, mobile

apps like google maps give drivers the estimated arrival time and possible alternative routes in case of queues on the freeway. Hence in increased travel times at freeways, the app suggests detouring due to possible congestion. Therefore, this study assumed that 12.5% of the conventional vehicles would divert (Peeta et al., 2000). The results are discussed in chapter 4 to see how drivers complied with the VMSs and BSMs.

Moreover, to eliminate the random errors of microsimulation, this study used ten simulation runs for each CVs MPR for both AM and PM periods. For each CVs market penetration, all the ten simulated vehicle trajectory files were processed in the SSAM, and an average of the resulting conflicts was discussed in the following subsection. Likewise, average travel times from all simulation runs in VISSIM were used for analysis.

3.4.2 Statistical Analysis

This study performed statistical analysis using the analysis of variance (ANOVA) Tukey multiple comparisons of means, Tukey Honest Significant Difference (HSD). ANOVA means analysis of variation in means of different groups of a population or different populations. If one or more groups fall outside the range of variation predicted by the null hypothesis (all group means are equal), the test is statistically significant. While both ANOVA and *t*-test are popular and are widely used, most studies often go for ANOVA test over *t*-test to confirm if the behavior occurring is more than once (Imants et al., 2021; Karaer et al., 2020; Rahman & Abdel-Aty, 2018). Although the *t*-test compares the means between the two samples, ANOVA can be used for more than two conditions. In this study, five CV MPRs (0%, 25%, 50%, 75%, 100%) were compared. Therefore, ANOVA was chosen to compare the means between and within the groups. Moreover, the Tukey HSD was performed to determine the significance between groups.

CHAPTER 4 RESULTS AND DISCUSSION

This section discusses the conflict analysis results of the safety surrogate measures using the SSAM software and travel time on the freeway and diversion route during detour operations. As mentioned in the previous chapter, the analysis was done using the trajectory data extracted from the VISSIM microscopic simulation model for AM and PM pre-peak, peak, and post-peak hours. This study used TTC as the surrogate measure for assessing the benefit of CVs on the safety performance of the freeway facilities.

4.1 One Lane Blockage Scenarios

The study had two scenarios involving one lane blockage for morning and evening peak periods: the outer lane blocked (OLB) and inner lane blocked (ILB).

4.1.1 Morning Peak Period Results

Results indicated that the number of conflicts decreased significantly with high CV MPR. A comparison between CV MPR of 0%, 25%, 50%, 75%, and 100% showed that the CV MPR has a linear impact on the percentage of conflict reductions. Figure 4-1 presents the number of conflicts observed in AM pre-peak, peak, and post-peak hours for every 25% increment of CV MPR. The percentage change in the number of conflicts between each interval at different MPR is shown in Table 4-1.

Total Conflicts

The results showed a significant difference in total conflicts as the CVs MPRs increased. The percent change in total conflicts was higher in OLB than ILB scenarios for pre-peak and peak hours, as shown in Table 4-1. Post-peak hours resulted in fewer total conflicts than pre-peak and peak hours in all scenarios. The reason being pre-peak and post-peak hours had fewer traffic

volumes. However, the pre-peak period scenario has a higher number of conflicts than the post-peak period scenarios because the conflict results were analyzed cumulatively from the beginning to the end of simulation time for all the scenarios. Generally, the number of total conflicts decreased roughly linearly as the market penetration of CVs increased from 0% to 100%.

Rear-end Conflicts

Fewer rear-end conflicts were observed in ILB than OLB scenarios; thus, the percent change in conflicts was lower in ILB scenarios than OLB. The maximum reduction of rear-end conflicts from 0% to 100% CVs MPRs was 95.5% in the OLB scenario at peak hour.

Lane-change Conflicts

A maximum reduction of 84% was observed during peak hours in the OLB scenario between 0% to 100% CV MPR, indicating that the CV applications can improve traffic safety. The reduction of lane-change conflicts with increased CVs MPR was less than the reduction observed in the rear-end conflicts.

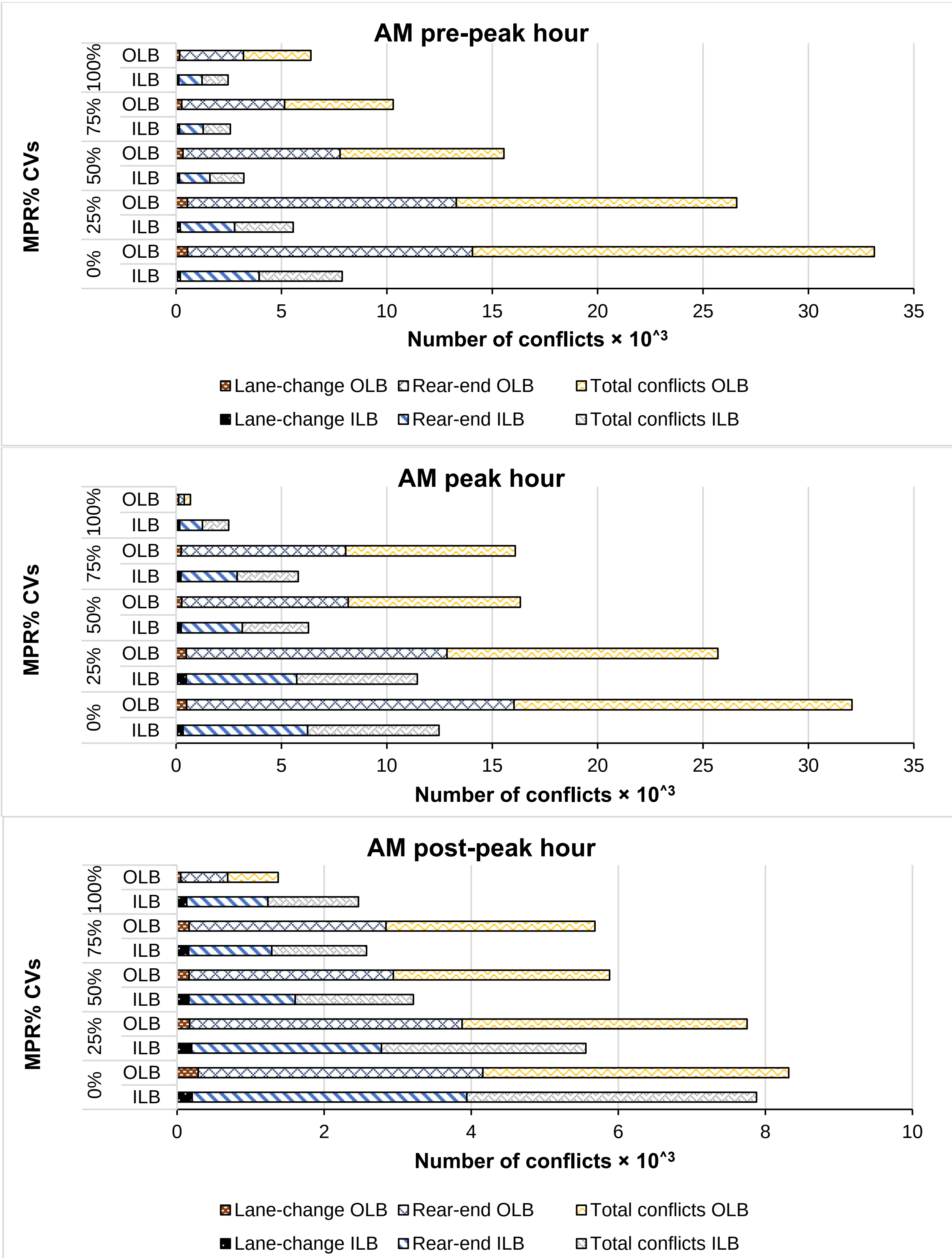


Figure 4-1: Conflict results for one lane blockage scenarios during AM period

Table 4-1: Conflict change in percent for ILB and OLB scenarios for AM periods

	INNER LANE BLOCKED (ILB)											
	AM Pre-peak Hour				**AM Peak Hour**				**AM Post-peak Hour**			
	Total Conflicts				**Total Conflicts**				**Total Conflicts**			
	Initial Composition				Initial Composition				Initial Composition			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-29.46%				-18.80%				-12.48%			
50	-59.22%	-43.96%			-38.06%	-23.73%			-43.74%	-35.72%		
75	-67.31%	-56.20%	-19.83%		-41.88%	-28.43%	-6.17%		-67.64%	-63.03%	-42.48%	
100	-68.69%	-57.33%	-23.20%	-4.21%	-62.68%	-54.04%	-39.75%	-35.79%	-91.00%	-89.72%	-84.01%	-72.19%
	Rear-end Conflicts				**Rear-end Conflicts**				**Rear-end Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-30.90%				-19.57%				-13.14%			
50	-61.28%	-43.96%			-39.67%	-24.99%			-45.18%	-36.88%		
75	-69.74%	-56.20%	-21.85%		-43.64%	-29.93%	-6.59%		-69.59%	-64.99%	-44.53%	
100	-70.51%	-57.33%	-23.86%	-2.57%	-63.95%	-55.18%	-40.25%	-36.04%	-93.11%	-92.07%	-87.43%	-77.34%
	Lane-change Conflicts				**Lane-change Conflicts**				**Lane-change Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-3.21%				-5.07%				-1.75%			
50	-21.91%	-19.32%			-9.68%	-4.86%			-20.49%	-19.08%		
75	-23.17%	-20.62%	-1.62%		-10.74%	-5.97%	-1.17%		-36.05%	-34.91%	-19.56%	
100	-35.44%	-33.30%	-17.33%	-15.97%	-40.18%	-36.99%	-33.77%	-32.99%	-56.85%	-56.08%	-45.73%	-32.53%
	OUTER LANE BLOCKED (OLB)											
	AM Pre-peak Hour				**AM Peak Hour**				**AM Post-peak Hour**			
	Total Conflicts				**Total Conflicts**				**Total Conflicts**			
	Initial Composition				Initial Composition				Initial Composition			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-30.25%				-18.92%				-6.80%			
50	-59.21%	-41.63%			-24.50%	-6.89%			-29.29%	-24.12%		
75	-72.98%	-61.75%	-33.76%		-45.70%	-33.03%	-28.08%		-31.69%	-26.70%	-3.39%	
100	-83.22%	-76.28%	-58.86%	-37.89%	-95.21%	-94.09%	-93.66%	-91.18%	-83.46%	-82.25%	-76.61%	-75.79%
	Rear-end Conflicts				**Rear-end Conflicts**				**Rear-end Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-31.10%				-19.38%				-4.30%			
50	-59.78%	-41.63%			-24.74%	-6.65%			-28.29%	-25.07%		
75	-73.65%	-61.75%	-34.48%		-46.44%	-33.56%	-28.83%		-30.84%	-27.73%	-3.55%	
100	-83.65%	-76.28%	-59.36%	-37.98%	-95.57%	-94.51%	-94.12%	-91.74%	-83.57%	-82.83%	-77.08%	-76.24%
	Lane-change Conflicts				**Lane-change Conflicts**				**Lane-change Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-1.43%				-5.25%				-40.36%			
50	-39.93%	-39.06%			-17.49%	-12.91%			-42.65%	-3.84%		
75	-50.40%	-49.68%	-17.44%		-23.81%	-19.58%	-7.66%		-43.07%	-4.53%	-0.73%	
100	-68.46%	-68.00%	-47.50%	-36.41%	-84.32%	-83.45%	-81.00%	-79.42%	-82.04%	-69.88%	-68.68%	-68.45%

Conflict reduction

4.1.2 Evening Peak Period Results

Overall, the analysis showed that more conflicts were observed in the PM peak period compared to the AM peak period. The outcome was expected as the traffic volume was higher in the PM peak period compared to the AM peak period. The conflicts observed in the PM peak during pre-peak, peak and post-peak hours for each CV MPR were illustrated in Figure 4-2. Table 4-2 presents the percentage change in conflicts between intervals at different CV MPR.

Total Conflicts: The number of total conflicts decreased as the CV MPR increased. The reduction in the total number of conflicts was up to 92% in the transition from 0% to 100% CVs MPRs during the pre-peak hour for both ILB and OLB, as indicated in Table 4-2. Additionally, the OLB scenarios reported more conflicts compared to the ILB. In all scenarios, the adoption of CVs reduced the number of total conflicts.

Rear-end Conflicts: Reduction in the rear-end conflicts was above 90% in the transition from 0% to 100% CVs MPR for ILB and OLB. As vehicles move in a platoon at higher CV MPR (>50%), they experience a considerable reduction in rear-end conflicts upon receiving advisory messages such as speed advisory messages to avoid a collision. However, with low CV MPR (between 0% and 50%), a conventional vehicle(s) behind the CV may delay reducing speed. Consequently, the lack of cooperation among convectional and CVs to perform safe maneuvers resulted in more rear-end conflicts than lane-change conflicts.

Lane-change Conflicts: The reduction of lane-change conflicts with increased CVs MPR was less than the reduction observed in the rear-end conflicts. A maximum reduction of 51.5% was observed for ILB and 82.4% for OLB.

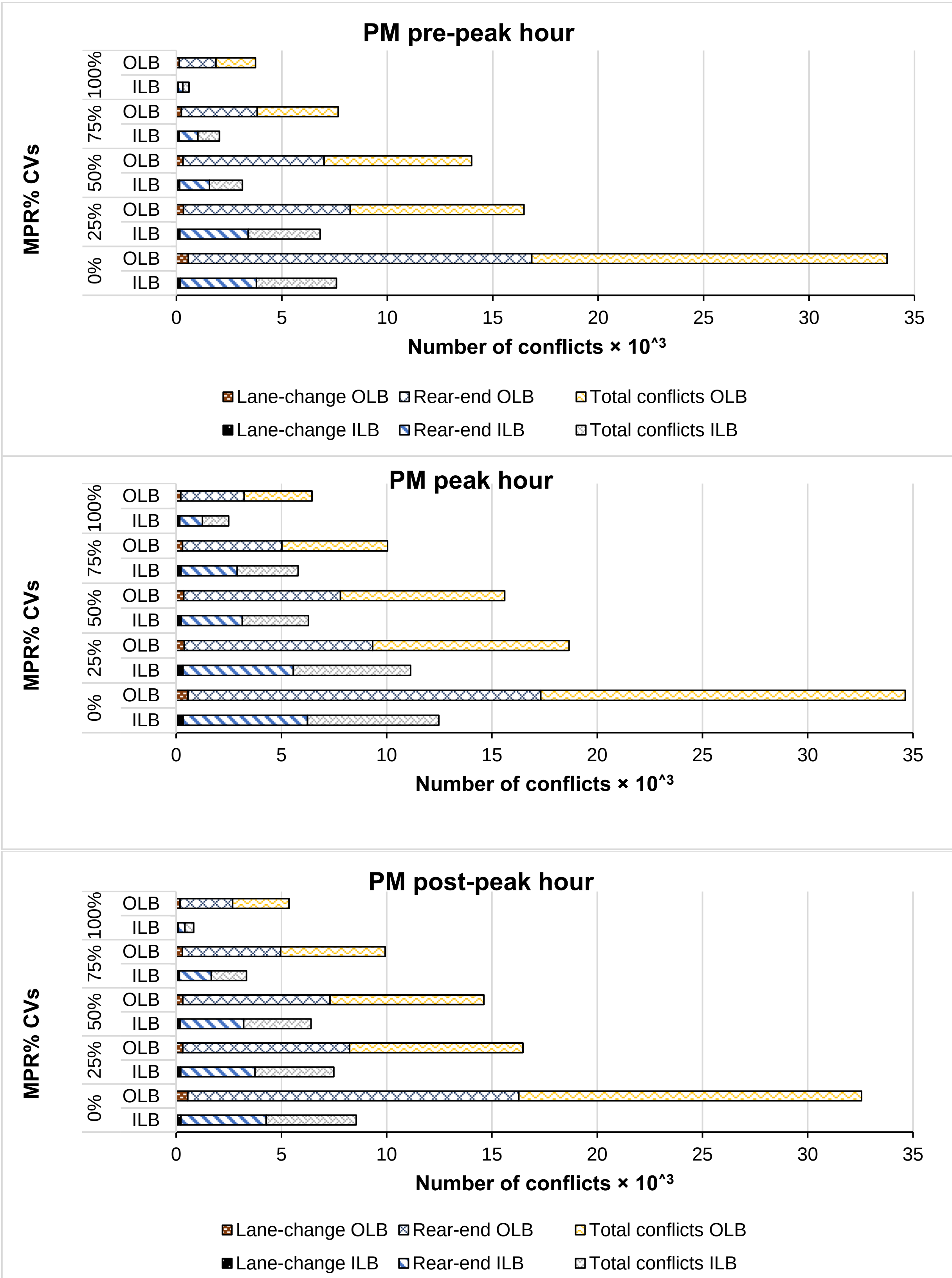


Figure 4-2: Conflict results for one lane blockage scenarios during the PM period

Table 4-2: Conflict results for PM peak period

INNER LANE BLOCKED (ILB)

	PM Pre-peak Hour				PM Peak Hour				PM Post-peak Hour			
	Total Conflicts				**Total Conflicts**				**Total Conflicts**			
	Initial Composition				Initial Composition				Initial Composition			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-10.20%				-10.73%				-12.43%			
50	-58.77%	-56.40%			-49.63%	-43.58%			-25.08%	-14.44%		
75	-73.14%	-72.80%	-34.85%		-53.56%	-47.98%	-7.80%		-60.95%	-55.41%	-47.88%	
100	-92.16%	-93.68%	-80.97%	-70.79%	-79.99%	-77.58%	-60.27%	-56.91%	-90.27%	-88.89%	-87.02%	-75.09%
	Rear-end Conflicts				**Rear-end Conflicts**				**Rear-end Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-9.93%				-11.27%				-13.04%			
50	-60.73%	-56.40%			-50.95%	-44.72%			-25.44%	-14.25%		
75	-75.50%	-72.80%	-37.63%		-54.87%	-49.14%	-7.99%		-62.52%	-56.90%	-49.74%	
100	-94.30%	-93.68%	-85.50%	-76.75%	-81.75%	-79.43%	-62.78%	-59.55%	-92.02%	-90.83%	-89.30%	-78.72%
	Lane-change Conflicts				**Lane-change Conflicts**				**Lane-change Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-15.32%				-1.08%				-1.26%			
50	-21.72%	-7.56%			-26.25%	-25.44%			-18.56%	-17.52%		
75	-28.44%	-15.49%	-8.58%		-30.34%	-29.58%	-5.55%		-32.25%	-31.39%	-16.81%	
100	-51.52%	-42.75%	-38.07%	-32.26%	-48.77%	-48.20%	-30.53%	-26.45%	-58.29%	-57.76%	-48.78%	-38.43%

OUTER LANE BLOCKED (OLB)

	PM Pre-peak Hour				PM Peak Hour				PM Post-peak Hour			
	Total Conflicts				**Total Conflicts**				**Total Conflicts**			
	Initial Composition				Initial Composition				Initial Composition			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-67.10%				-46.10%				-49.39%			
50	-72.06%	-15.43%			-54.94%	-16.39%			-55.11%	-11.30%		
75	-84.69%	-54.43%	-45.19%		-71.00%	-46.20%	-35.65%		-69.50%	-39.73%	-32.06%	
100	-92.51%	-77.95%	-73.18%	-51.07%	-81.37%	-65.43%	-58.65%	-35.75%	-83.54%	-67.48%	-63.34%	-46.04%
	Rear-end Conflicts				**Rear-end Conflicts**				**Rear-end Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-67.45%				-46.60%				-49.62%			
50	-72.47%	-15.43%			-55.60%	-16.86%			-55.54%	-11.74%		
75	-85.17%	-54.43%	-46.11%		-71.84%	-47.27%	-36.58%		-70.30%	-41.04%	-33.20%	
100	-92.82%	-77.95%	-73.93%	-51.62%	-82.07%	-66.42%	-59.61%	-36.31%	-84.15%	-68.53%	-64.35%	-46.63%
	Lane-change Conflicts				**Lane-change Conflicts**				**Lane-change Conflicts**			
%CVs	0	25	50	75	0	25	50	75	0	25	50	75
25	-56.02%				-31.27%				-42.75%			
50	-59.05%	-6.89%			-35.10%	-5.58%			-42.83%	-0.13%		
75	-69.42%	-30.48%	-25.34%		-45.81%	-21.16%	-16.50%		-46.58%	-6.68%	-6.56%	
100	-82.43%	-60.06%	-57.11%	-42.55%	-60.42%	-42.42%	-39.02%	-26.97%	-66.13%	-40.84%	-40.76%	-36.61%

Conflict reduction

4.2 Two Lane Blockage Scenarios

This study modeled two-lane blockages on the freeway with a scenario of 30- and 90-minutes incident clearance duration to analyze the effect of CVs in detour strategy implementation and conflict reduction. The results were at three morning peak hours scenarios, i.e., pre-peak, peak, and post-peak. Generally, the drivers encountered lane closures, congestion on the freeway in all the scenarios while the detour had free-flowing traffic. The following subsections discuss travel time and conflicts results.

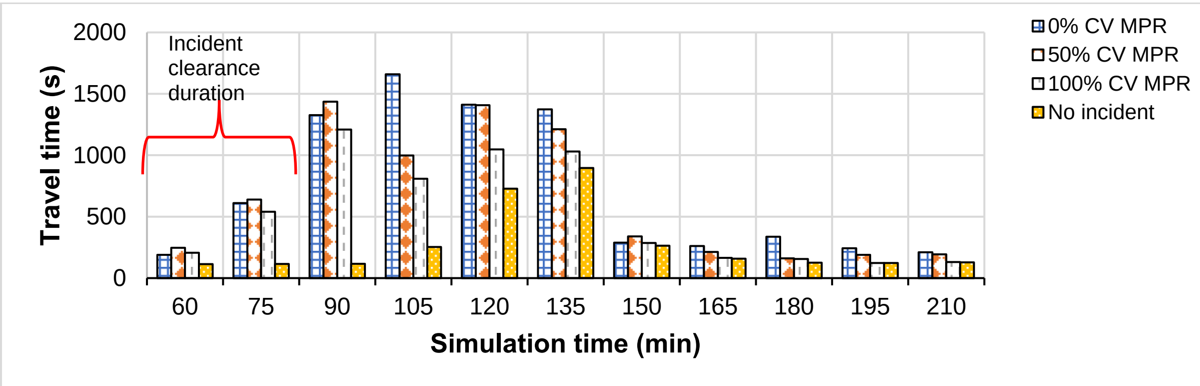
4.2.1 Travel Time Results for With/Without Detour Strategy

Two lanes out of three northbound lanes on the freeway were blocked, assuming that an incident had occurred on the freeway resulting in a rapid formation of queues upstream of the incident location. The rapid queue formation was a function of the analysis period when the incident occurred. Generally, fewer queues were observed during the pre-peak hour, and the queue became severe as the peak hour approached. This is because of the difference in traffic volumes among the analyzed periods.

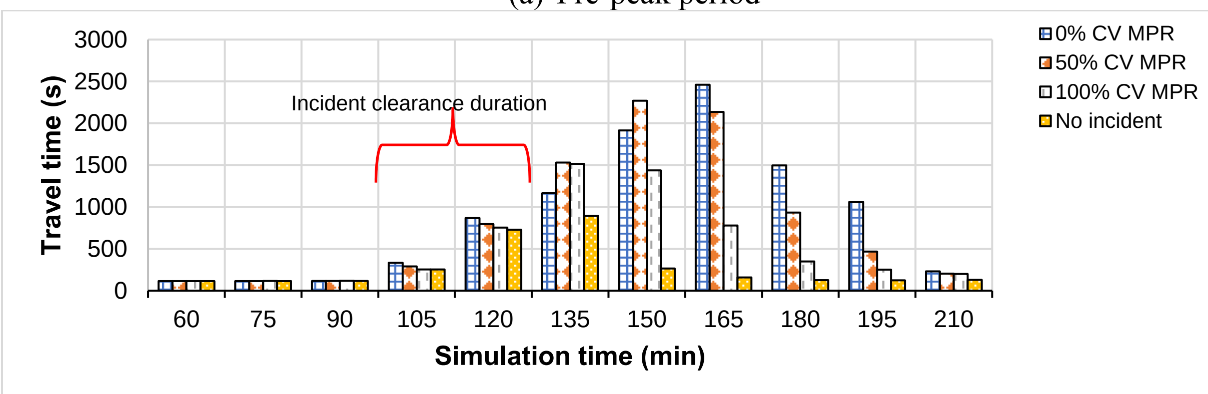
Incidents with 30 Minutes Incident Clearance Duration

During scenarios without detours, the incident during the pre-peak period caused travel times to increase on the freeway as the peak period approached. However, the travel time was reduced as the post-peak period was reached. Likewise, during the post-peak period, the incident caused increased travel times on the freeway. The freeway travel time was lower at 100% CV MPRs than 0% CV MPRs scenarios. Reasons are a high number of CVs have information on the incident and receive lane-change advisory to the detour, thus reducing congestion on the freeway. However, between 120-135 min simulation time, the travel time increased dramatically at 50%

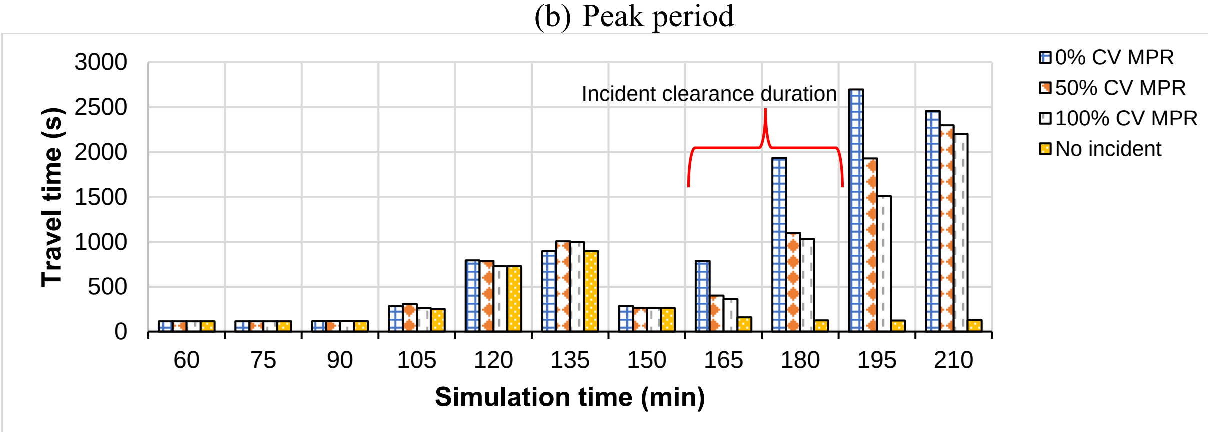
CV MPR, possibly caused by confusion between the conventional and CVs when adjusting their driving behaviors, as shown in Figure 4-3.



(a) Pre-peak period



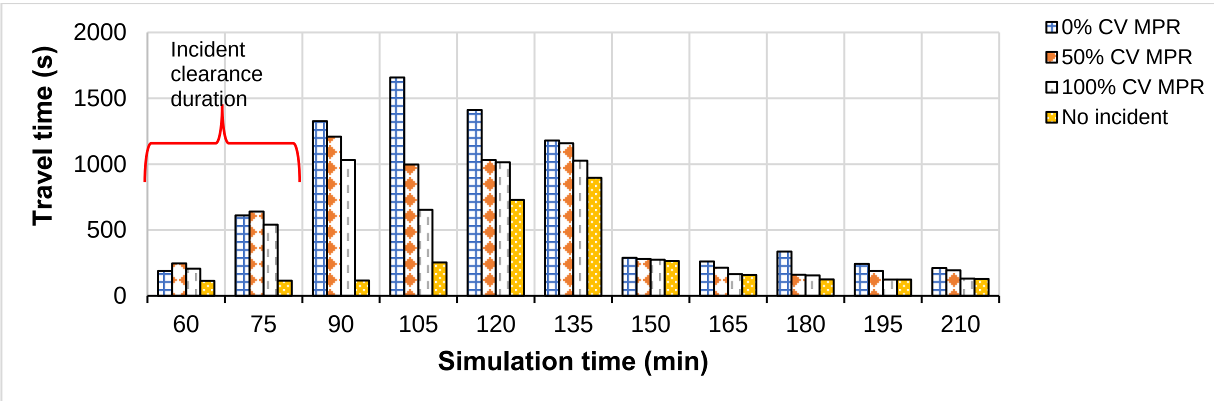
(b) Peak period



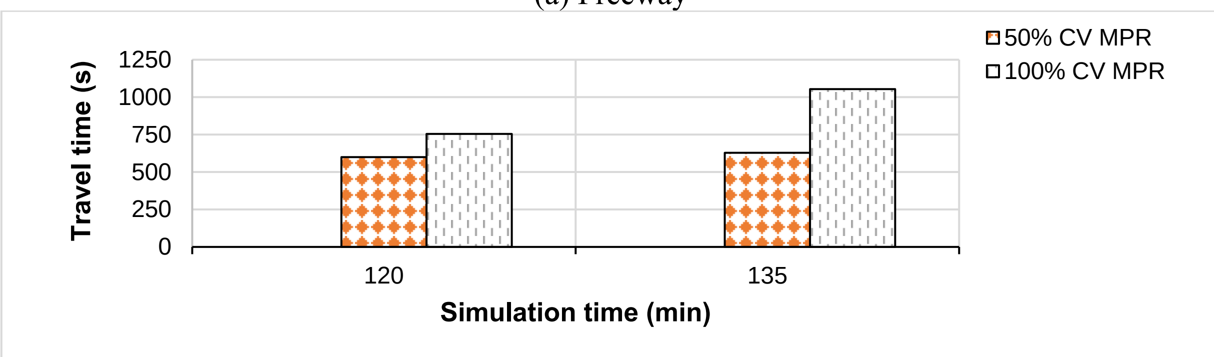
(c) Post-peak period

Figure 4-3: Travel time on the freeway during 30 minutes incident clearance duration for without detour strategy

For the detour strategy, vehicles started to divert to the alternative route during the peak hour. However, the travel time decreased as the incident was cleared and the post-peak period approached. Figure 4-4 illustrates a scenario where the incident occurred during the pre-peak hour.



(a) Freeway

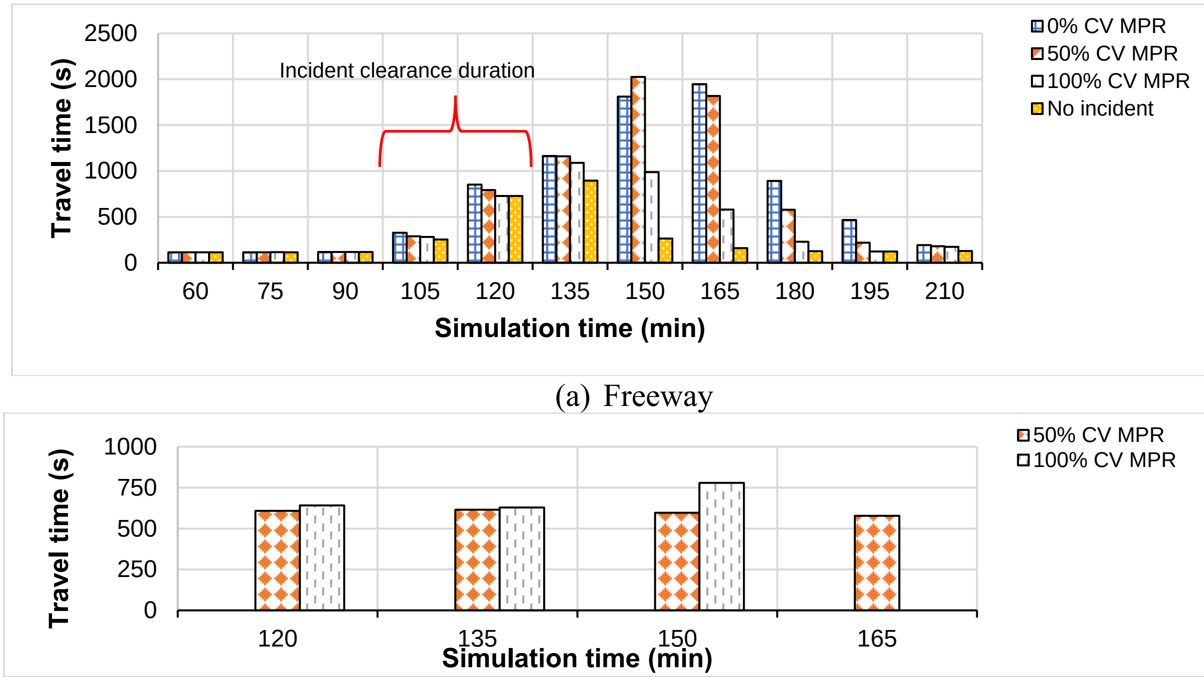


(b) Diversion route

Figure 4-4: Travel time for 30 minutes incident clearance duration during the pre-peak hour

In the scenarios where the incident occurred during peak hours, the diversion route had less travel time 15 minutes after the incident occurred; thus, CVs were advised to divert. For the 100% CV MPR scenario, the travel time on the freeway became less than travel time on the alternative route after 150 minutes of the incident. Thus, the incident was cleared on the freeway, and, as a result, traffic operations returned to normal early. Unlike the 50% CV MPR, not all

vehicles have information to divert; thus, the freeway travel time remained higher than the alternative route travel time until 180 minutes of simulation time, as shown in Figure 4-5.

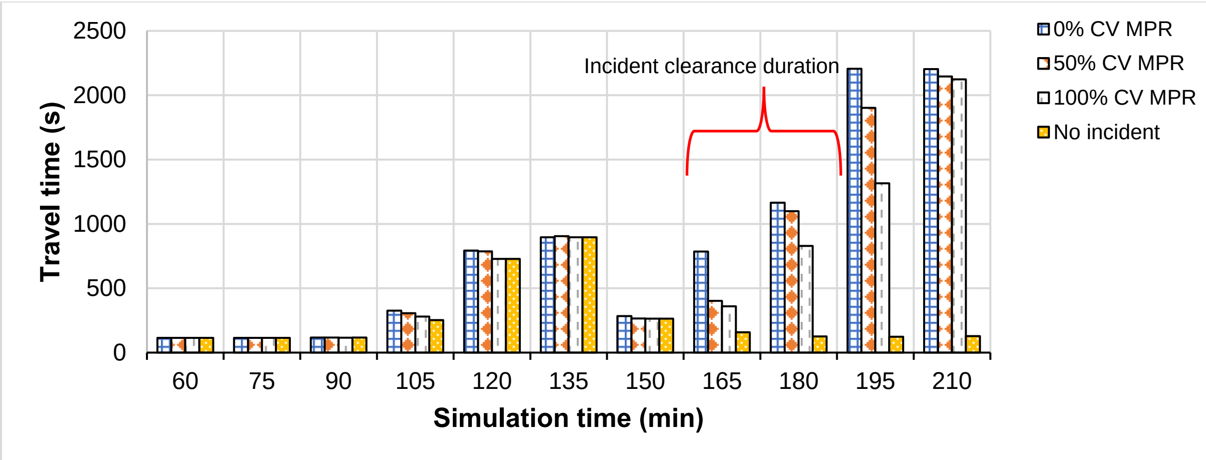


(a) Freeway

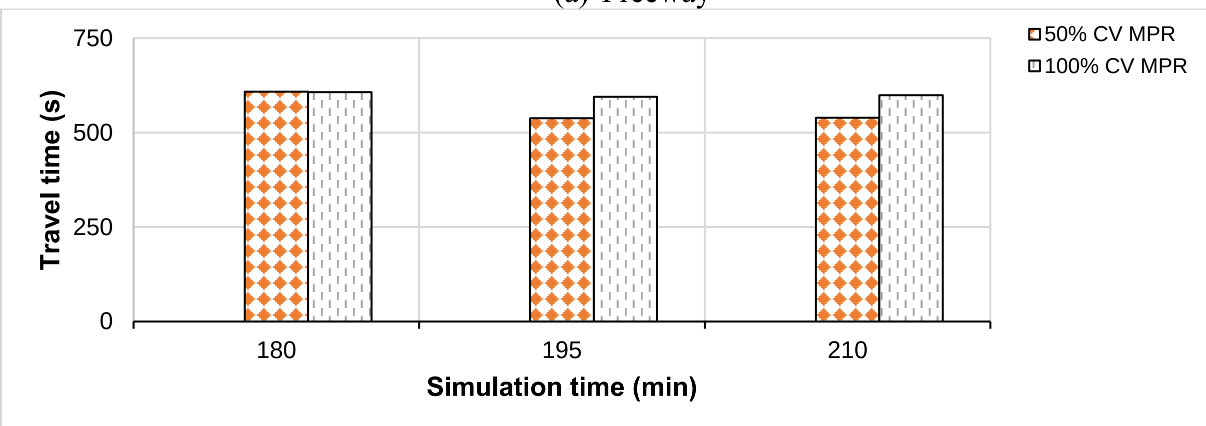
(b) Diversion route

Figure 4-5: Travel time for 30 minutes incident clearance duration during peak hour

During the post-peak scenarios, the incident occurred 150 minutes after simulation began, thus continuing congestions on the freeway that was already naturally created due to the peak hour. The vehicles start to divert to the alternative route at 180-minute simulation time, as illustrated in Figure 4-6. The increased travel times on the alternative route during the 100% CV MPRs versus the 50% CV MPRs in all the morning peak hours scenarios maybe because at 100% CV MPRs most CVs received the detour advisory message compared to 50% CV MPRs.



(a) Freeway

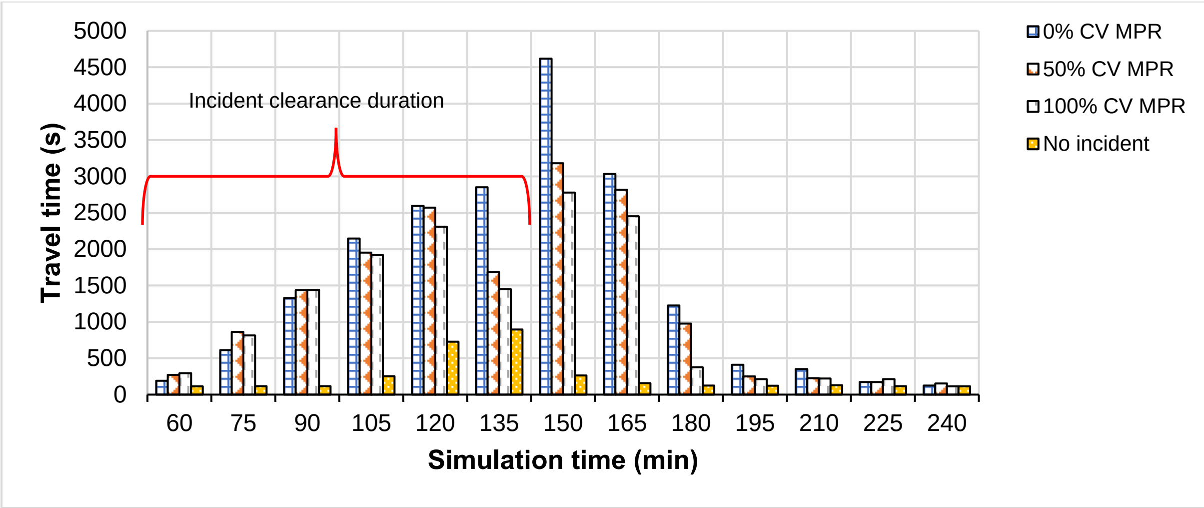


(b) Diversion route

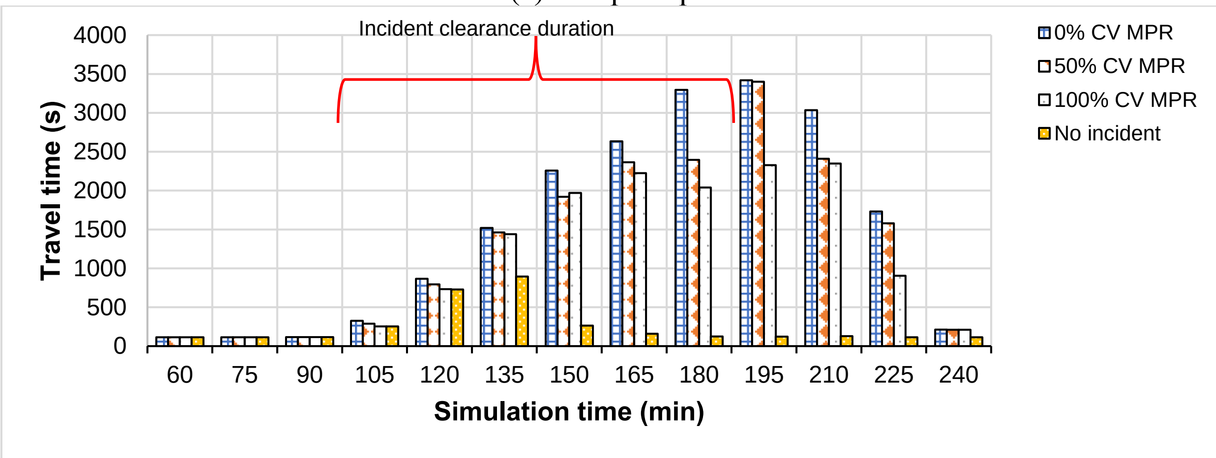
Figure 4-6: Travel time for 30 minutes incident clearance duration during the post-peak hour

Incidents with 90 Minutes Incident Clearance Duration

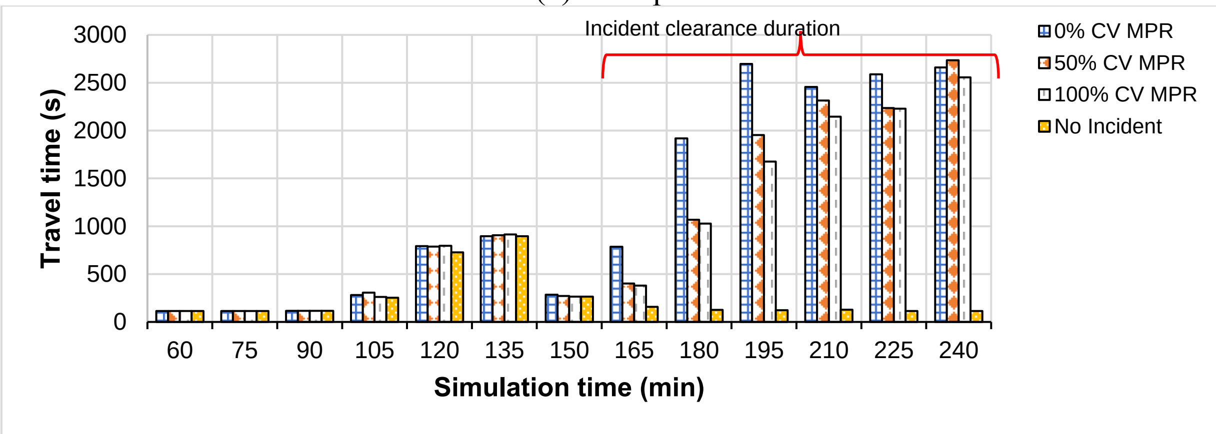
The travel time was extremely high on the freeway during without detour scenarios versus detours scenarios. Lane closures caused low speeds for vehicles on crash corridors, thus congesting the routes, as Figure 4-7 illustrates. Longer travel times were experienced when the incident occurred during the peak hour compared to the pre-peak hour.



(a) Pre-peak period



(b) Peak period

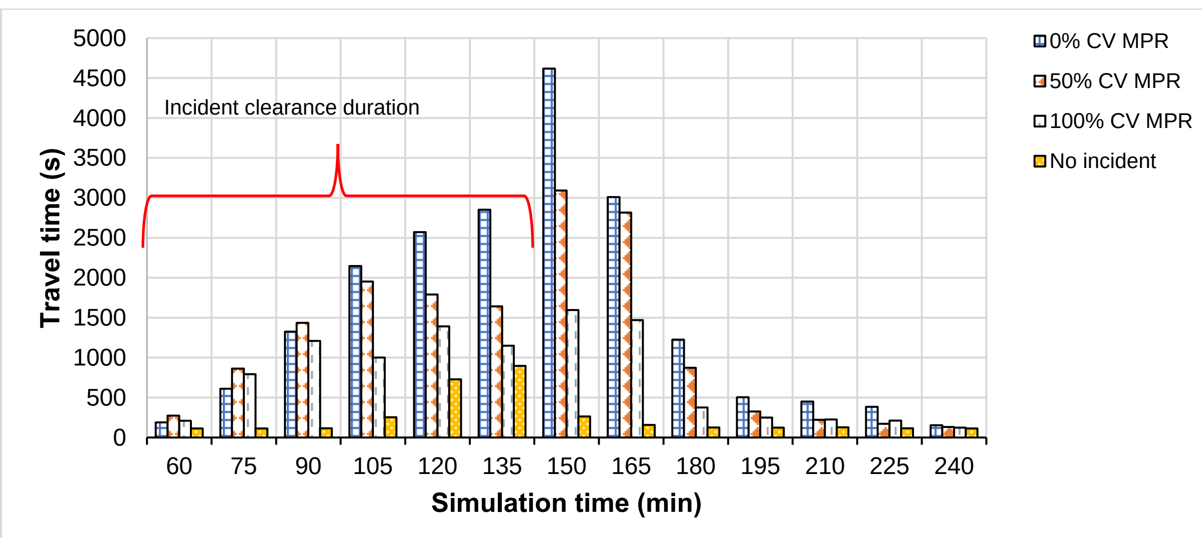


(c) Post-peak period

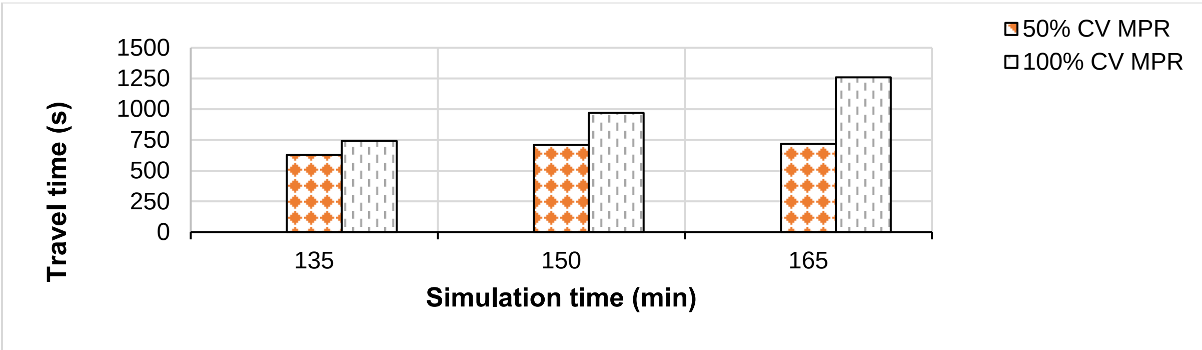
Figure 4-7: Travel time for 90 minutes incident clearance duration without detour strategy

For detour scenarios, the travel time on the freeway increased dramatically as the incident clearance duration increased to 90 minutes for all scenarios (0%, 50%, 100% CV MPRs). As a result, at higher CV MPRs, vehicles tremendously kept diverting to the alternative route. Indicating that detour operation has more potential for incidents duration greater than 30 minutes. For this purpose, the diversion strategy came into function, and vehicles were advised to divert with their respective CV MPRs. These findings resemble a study by Chou et al. (2011) that exploited the capacity of managed lanes in redirecting traffic around an incident.

Moreover, as the incident clearance duration increased to above 30 minutes, travel time on the diversion route is greater at 100% CV MPRs than the 50% CV MPRs scenario, as Figures 4-8, 4-9 and 4-10 (b) illustrate. The reason could be that at greater CV MPRs, most vehicles receive the message to divert, thus increasing travel time on the diversion route. However, the travel time on the diversion route remained lower than that on the freeway.

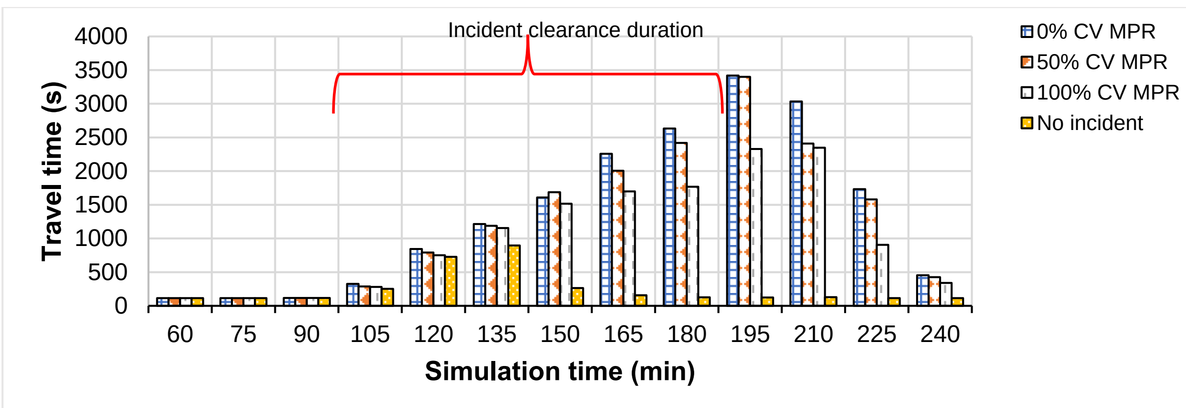


(a) Freeway

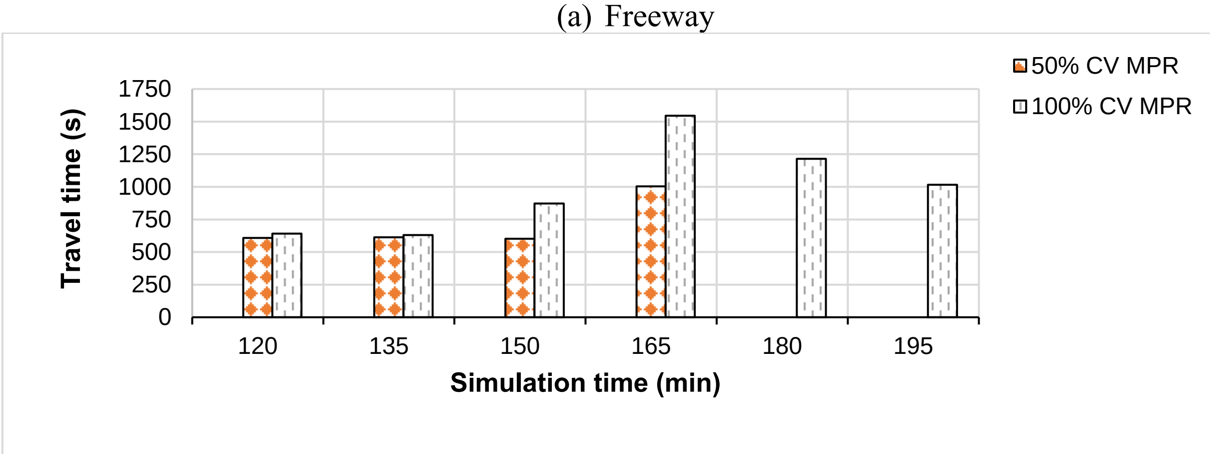


(b) Diversion route

Figure 4-8: Travel time for 90 minutes incident clearance duration during the pre-peak hour with detour strategy

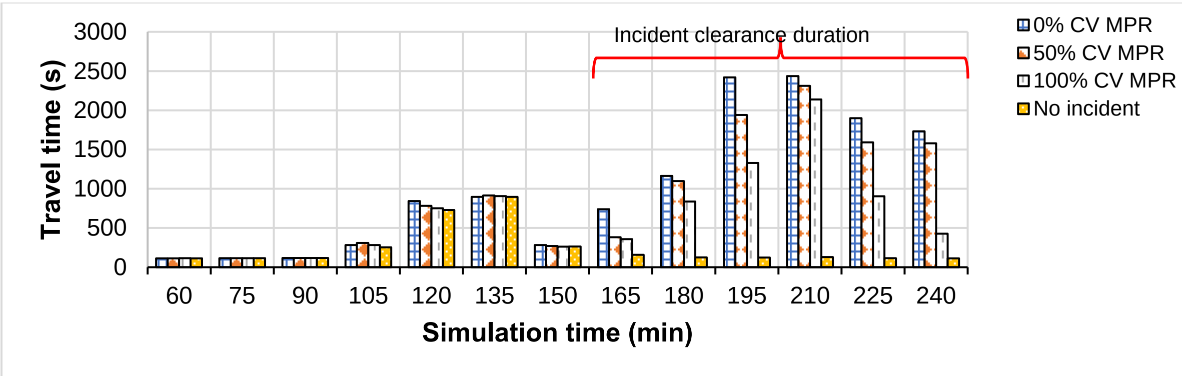


(a) Freeway

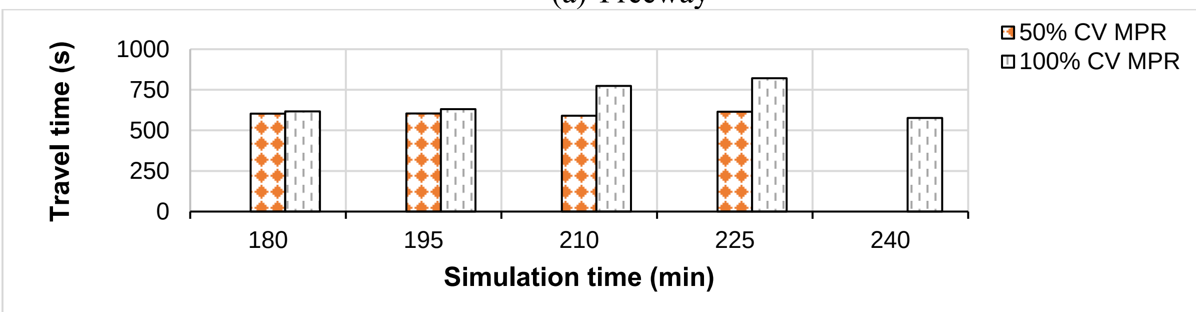


(b) Diversion route

Figure 4-9: Travel time for 90 minutes incident clearance duration during peak hour with detour strategy



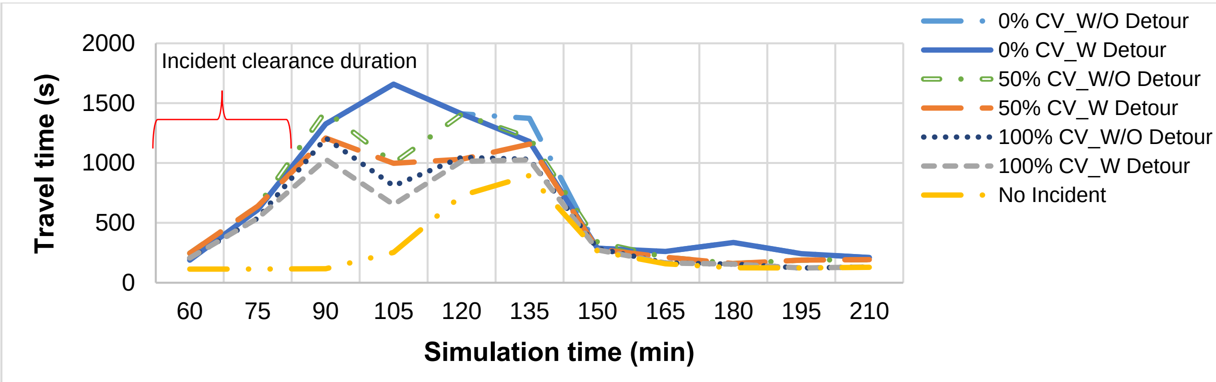
(a) Freeway



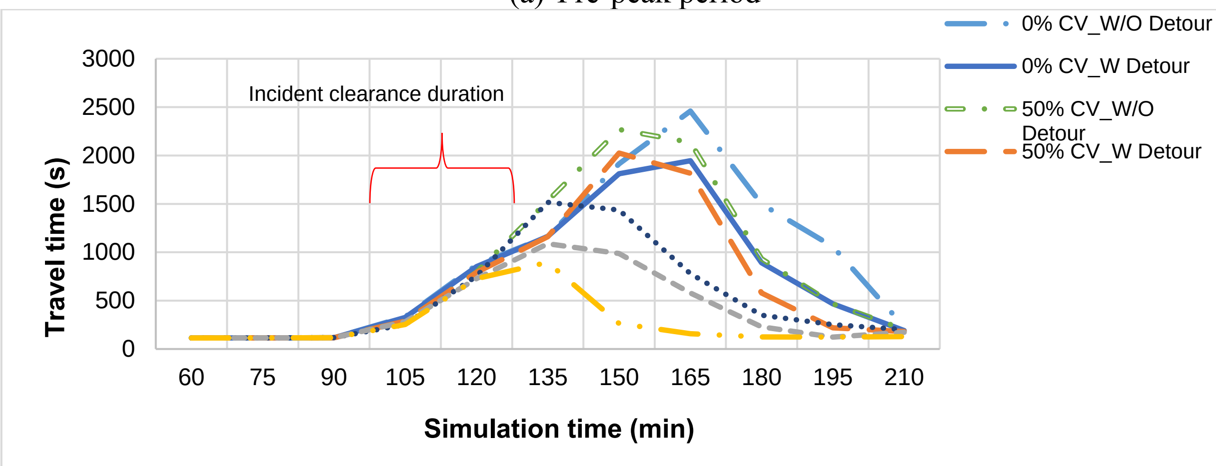
(b) Diversion route

Figure 4-10: Travel time for 90 minutes incident clearance duration during the post-peak hour with detour strategy

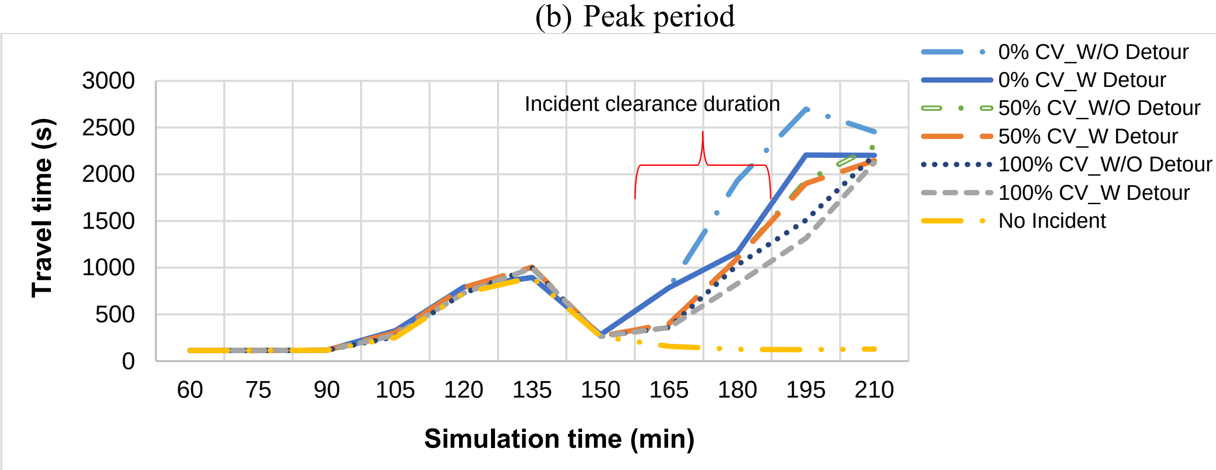
As explained in the methodology, conventional vehicles were coded to divert. However, they did not comply with the message, possibly due to the small percentage assumed, leading to a lack of cooperation between vehicles in the network. Additionally, the outcome mimics the reality that route guidance information provided by VMS is just a kind of suggestion message, and it has no mandatory effect on drivers. For this purpose, drivers could comply with the VMS or not. Meanwhile, the 0% CV MPRs scenarios had negligible travel times on the freeway between detour and without detour scenarios. Generally, detour advisory scenarios experienced less congestion compared to without-detour strategy scenarios, as shown in Figures 4-11 and 4-12. Thus, showing the importance of detour strategy in relation to CVs when an incident occurs on the freeway.



(a) Pre-peak period

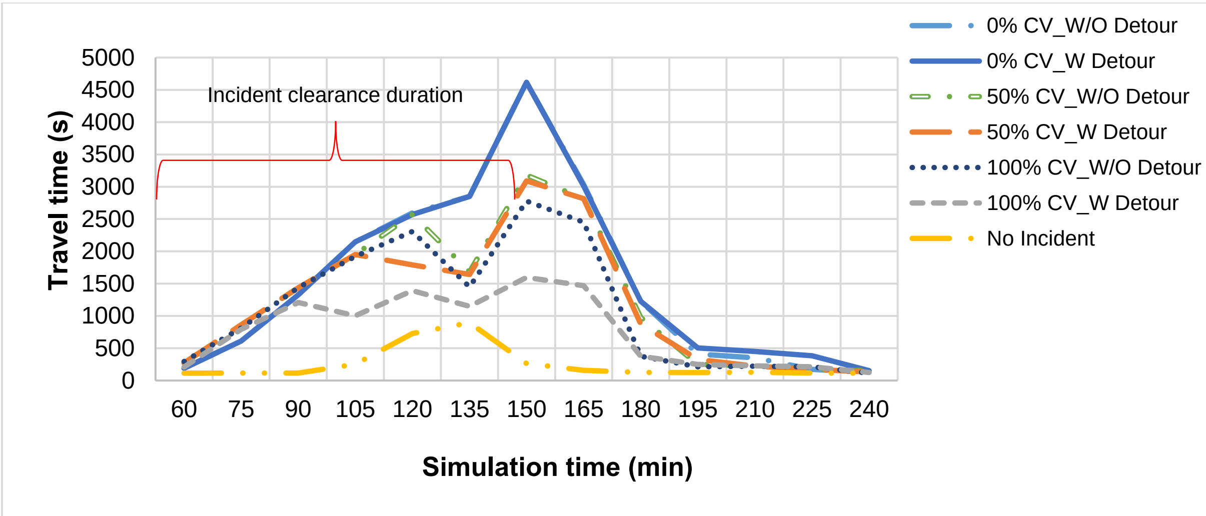


(b) Peak period

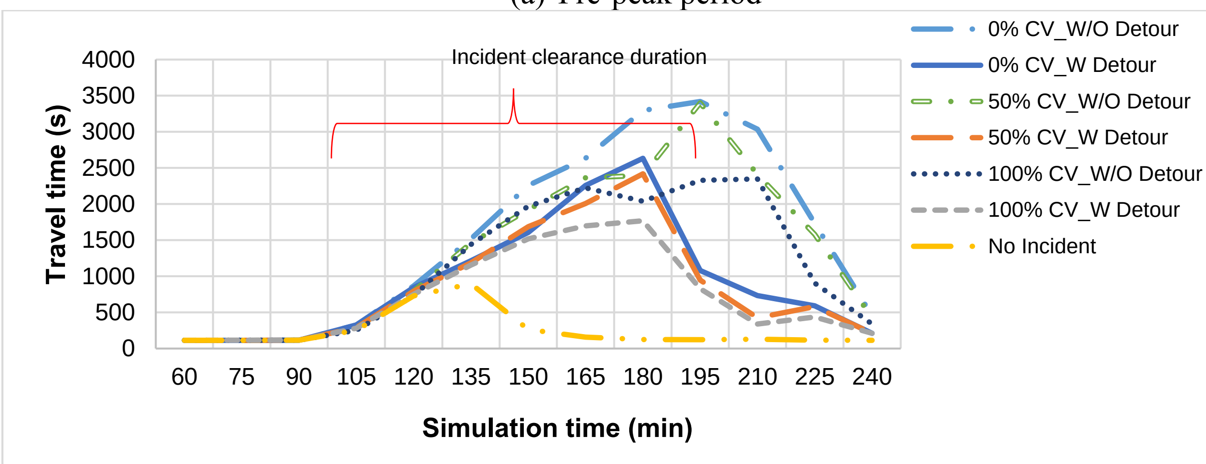


(c) Post-peak period

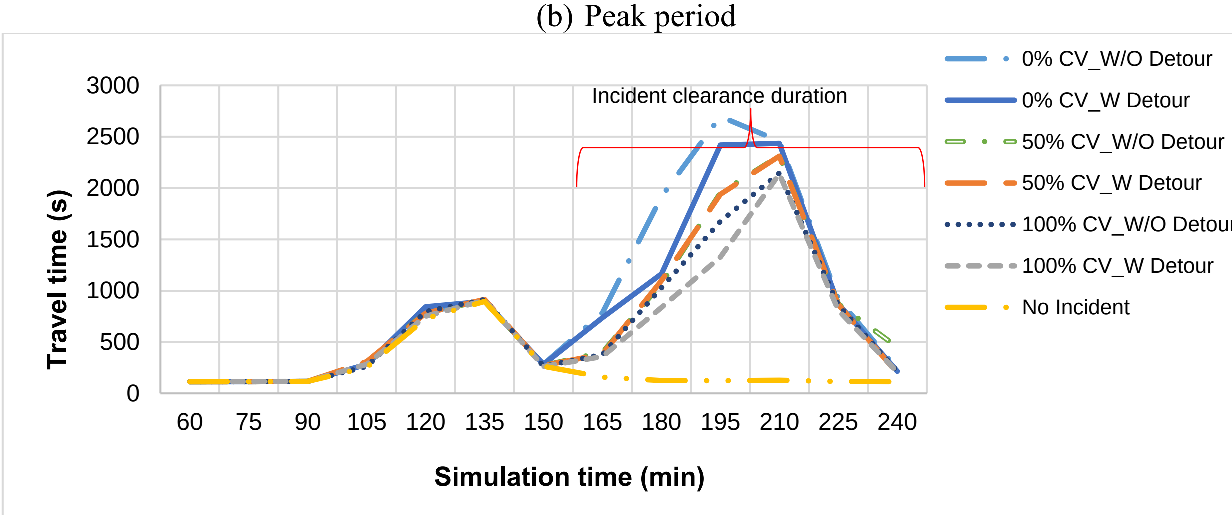
Figure 4-11: Comparison of travel time on the freeway between with detour and without detour strategy at 30 minutes incident clearance duration



(a) Pre-peak period



(b) Peak period



(c) Post-peak period

Figure 4-12: Comparison of travel time on the freeway between with detour and without detour strategy at 90 minutes incident clearance duration

4.2.2 Conflict Results for With/Without Detour Strategy

Incidents with 30 Minutes Incident Clearance Duration

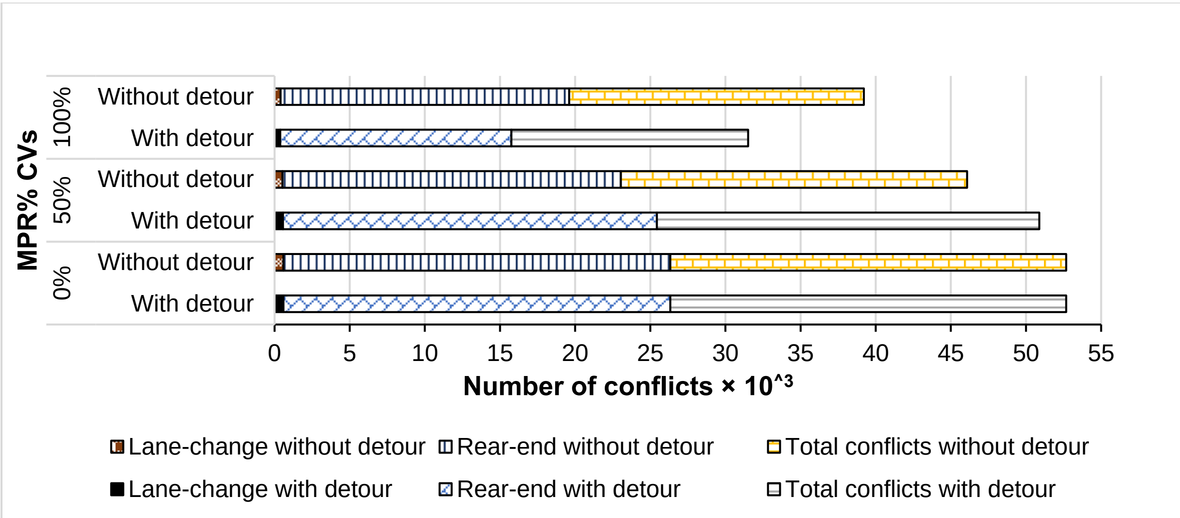
The blocking of two lanes disrupted the traffic on a high-speed facility, i.e., freeway, which resulted in long queues, creating many stop-and-go situations for vehicles. The total number of conflicts was more significant for without detour scenarios than with detour scenarios, as Figure 4-13 illustrates.

Rear-end Conflicts

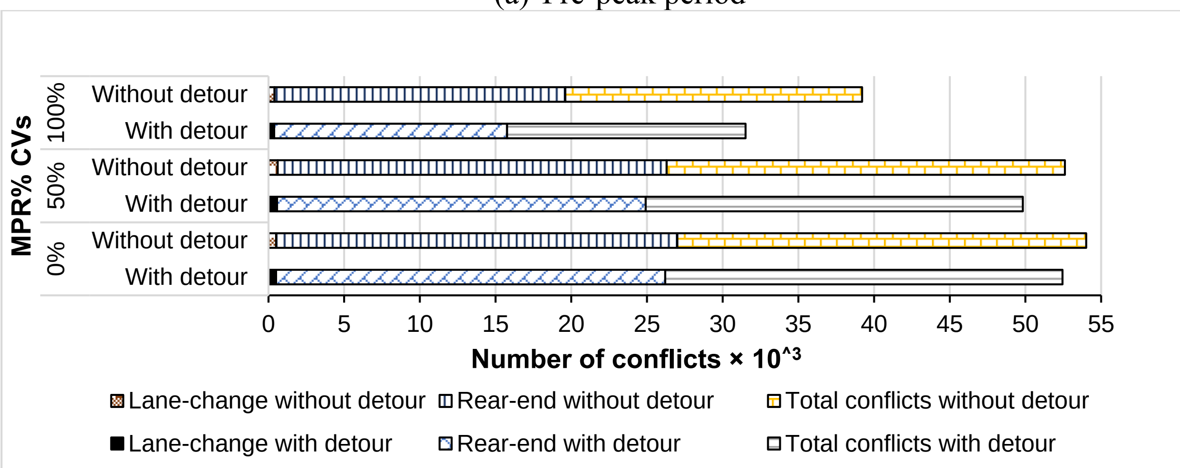
Reduction in rear-end conflicts was observed when the detour advisory was disseminated under the increased penetration of CVs, as shown in Table 4-3, possibly due to the decrease in traffic approaching the incident scene after the detour advisory. Moreover, early speed and lane-change advisories to CVs help drivers adjust their driving behavior as they approach the scene.

Lane-change Conflicts

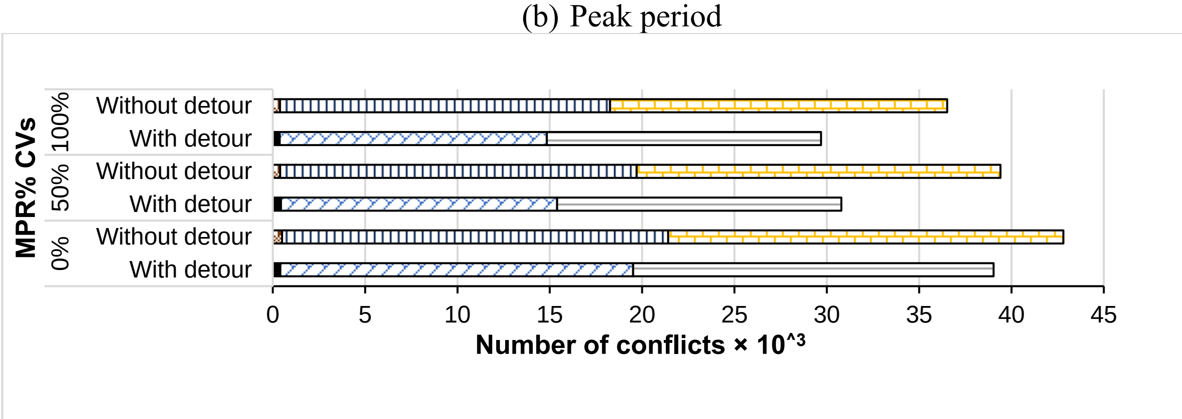
For all the morning peak scenarios (pre-peak, peak, post-peak), lane-change conflicts were observed for scenarios with the detour advisory than those without the advisory. The reason could be that the CVs changed lanes to access the detour. In all the analyzed scenarios, fewer lane-change conflicts were observed than rear-end conflicts, as shown in Figure 4-13.



(a) Pre-peak period



(b) Peak period



(c) Post-peak period

Figure 4-13: Conflict results between with detour and without detour strategy at 30 minutes incident clearance duration for AM peak hour

At 100% CV MPR, results indicate a reduced number of total conflicts of up to 24% and 14% for with and without detour advisory, respectively, at peak hours, as illustrated in Table 4-3. For pre-and post-peak scenarios, with 100% CV MPR, the results indicated a reduced number of total conflicts of up to 40% and 26% for with and without detour advisory, respectively. A consistent trend in conflict decline was observed for every 50% increment of CV composition.

Table 4-3: Conflict change in percent for detour and without detour strategy at 30 minutes incident clearance duration

DETOUR ADVISORY (30 MIN)						
	AM Pre-peak Hour		AM Peak Hour		AM Post-peak Hour	
	Total Conflicts		Total Conflicts		Total Conflicts	
	Initial Composition		Initial Composition		Initial Composition	
%CVs	0	50	0	50	0	50
50	-3.41%		-21.12%		-5.06%	
100	-40.18%	-38.07%	-23.94%	-3.57%	-39.96%	-36.76%
	Rear-end Conflicts		Rear-end Conflicts		Rear-end Conflicts	
%CVs	0	50	0	50	0	50
50	-3.39%		-21.78%		-5.29%	
100	-40.30%	-38.20%	-24.31%	-3.22%	-40.19%	-36.85%
	Lane-change Conflicts		Lane-change Conflicts		Lane-change Conflicts	
%CVs	0	50	0	50	0	50
50	-4.43%		10.12%		5.61%	
100	-35.26%	-32.26%	-6.67%	-15.25%	-28.97%	-32.74%

WITHOUT DETOUR ADVISORY (30 MIN)						
	AM Pre-peak Hour		AM Peak Hour		AM Post-peak Hour	
	Total Conflicts		Total Conflicts		Total Conflicts	
	Initial Composition		Initial Composition		Initial Composition	
%CVs	0	50	0	50	0	50
50	-12.52%		-7.96%		-2.61%	
100	-25.57%	-14.92%	-14.70%	-7.33%	-27.41%	-25.47%
	Rear-end Conflicts		Rear-end Conflicts		Rear-end Conflicts	
%CVs	0	50	0	50	0	50
50	-12.56%		-7.65%		-3.04%	
100	-25.42%	-14.71%	-14.51%	-7.42%	-27.53%	-25.26%
	Lane-change Conflicts		Lane-change Conflicts		Lane-change Conflicts	
%CVs	0	50	0	50	0	50
50	-10.56%		-20.63%		19.96%	
100	-32.03%	-24.00%	-22.82%	-2.75%	-21.15%	-34.27%

Conflict reduction (green)   Conflict increase (red)

Incidents with 90 Minutes Incident Clearance Duration

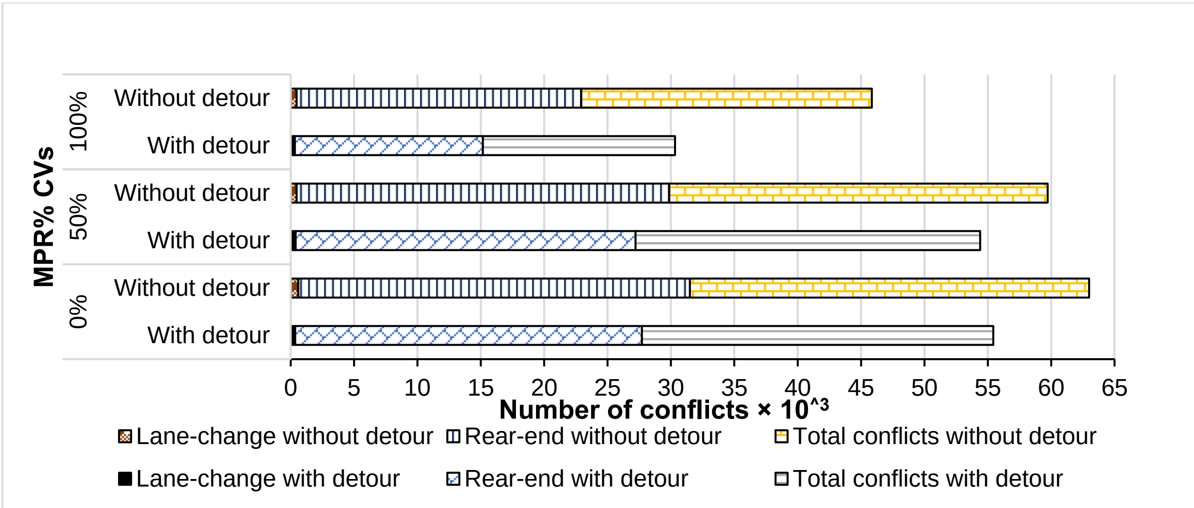
The trend is similar with 30 minutes incident clearance duration. The total number of conflicts was more significant without detour scenarios than with detour scenarios, as Figure 4-14. A consistent trend in conflict decline was observed for every 50% increment of CV composition except during the post-peak scenarios, where the total number of conflicts seemed to increase between 0% CV MPRs and 50% CV MPRs. The reason could be at 50% CV MPRs there is confusion between conventional and connected vehicles leading to a lack of cooperation between vehicles.

Rear-end Conflict

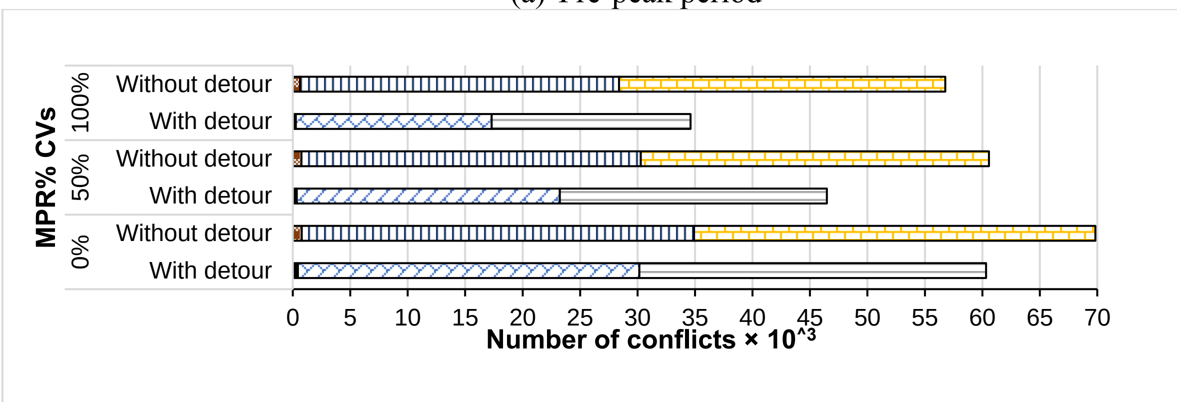
Rear-end conflicts were more prominent in 90 minutes of incident clearance duration than 30 minutes. The percent change in conflicts was above 40% for all analyzed morning periods. As mentioned above, rear-end conflicts seemed to increase between 0% and 50% CV MPRs during the post-peak scenarios with and with the detour strategy.

Lane-Change Conflicts

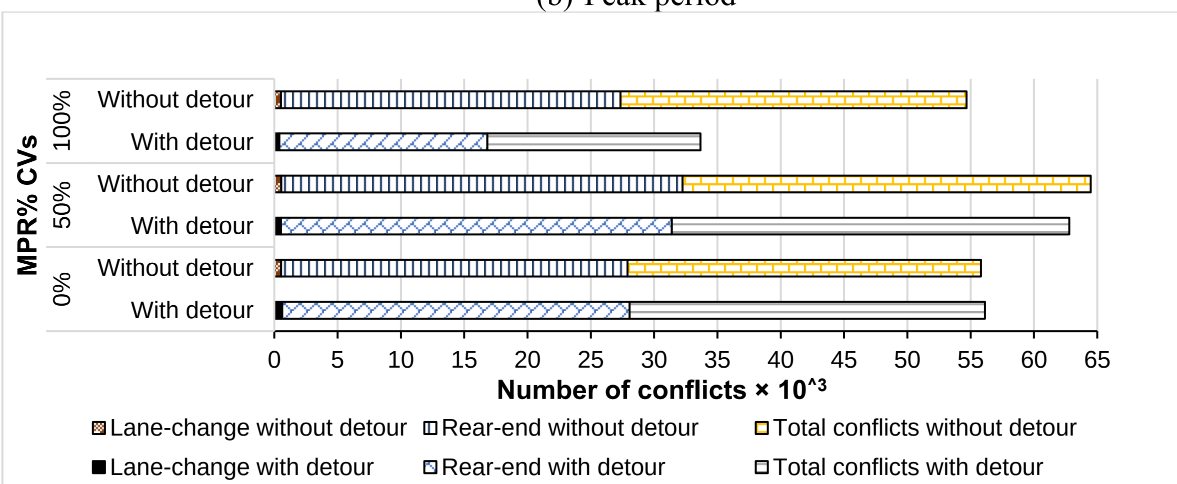
At 100% CV MPRs fewer conflicts were observed for scenarios with the detour advisory than those without the advisory. This situation was different during 30 minutes incident clearance duration. The reason could be increased incident clearance duration time; thus, the vehicles were stuck in the queue that even some CVs failed to make a lane-changing movement to access the detour. In all the scenarios, fewer lane-change conflicts were observed than rear-end conflicts, as shown in Figure 4-14.



(a) Pre-peak period



(b) Peak period



(c) Post-peak period

Figure 4-14: Conflict results between with detour and without detour strategy at 90 minutes incident clearance duration for morning peak hour

At 100% CV MPR, results indicate a reduced number of total conflicts of up to 43% and 19% for with and without detour advisory, respectively, as illustrated in Table 4.4. For pre-peak scenarios, with 100% CV MPR, the results indicated a reduced number of total conflicts of up to 45% and 27% for with and without detour advisory, respectively.

Table 4-4: Conflict change in percent for detour and without detour strategy at 90 minutes incident clearance duration

	DETOUR ADVISORY (90 MIN)					
	AM Pre-peak Hour		**AM Peak Hour**		**AM Post-peak Hour**	
	Total Conflicts		**Total Conflicts**		**Total Conflicts**	
	Initial Composition		Initial Composition		Initial Composition	
%CVs	0	50	0	50	0	50
50	-1.86%		-22.96%		11.87%	
100	-45.29%	-44.25%	-42.63%	-25.54%	-40.03%	-46.40%
	Rear-end Conflicts		**Rear-end Conflicts**		**Rear-end Conflicts**	
%CVs	0	50	0	50	0	50
50	-2.01%		-23.00%		12.50%	
100	-45.80%	-44.69%	-42.68%	-25.55%	-40.13%	-46.78%
	Lane-change Conflicts		**Lane-change Conflicts**		**Lane-change Conflicts**	
%CVs	0	50	0	50	0	50
50	9.89%		-20.18%		-15.52%	
100	-5.93%	-14.40%	-39.68%	-24.43%	-35.52%	-23.67%
	WITHOUT DETOUR ADVISORY (90 MIN)					
	AM Pre-peak Hour		**AM Peak Hour**		**AM Post-peak Hour**	
	Total Conflicts		**Total Conflicts**		**Total Conflicts**	
	Initial Composition		Initial Composition		Initial Composition	
%CVs	0	50	0	50	0	50
50	-5.20%		-13.27%		15.55%	
100	-27.21%	-23.22%	-18.71%	-6.27%	-2.03%	-15.21%
	Rear-end Conflicts		**Rear-end Conflicts**		**Rear-end Conflicts**	
%CVs	0	50	0	50	0	50
50	-4.89%		-13.48%		15.81%	
100	-27.33%	-23.59%	-18.69%	-6.03%	-2.01%	-15.39%
	Lane-change Conflicts		**Lane-change Conflicts**		**Lane-change Conflicts**	
%CVs	0	50	0	50	0	50
50	-21.07%		2.58%		2.58%	
100	-21.40%	-0.42%	-2.76%	-5.21%	-2.76%	-5.21%

(Green) Conflict reduction; (Red) Conflict increase

4.3 Statistical Analysis Results

To assess the effects of the CV technology on freeway safety, the variable of interest was the number of critical TTC values recorded during a simulation run. As stated earlier, the ANOVA test was used to determine whether any of the group means are different from the overall mean of the data by checking the variance of each group against the overall variance of the data. The null hypothesis was that the hypothesized mean for TTC values at CVs MPRs are equal. The alternative hypothesis was that the mean for TTC values between groups is not equal.

Null Hypothesis: H_0: $\mu1 = \mu2 = \mu3 = \mu4 = \mu5$

Alternative hypothesis: H_1: The mean TTC differs for at least two of the CV MPRS

The turkeyHSD checked the difference between groups thus;

H_1:$\mu1 \neq \mu2$ or $\mu1 \neq \mu3$ or $\mu1 \neq \mu4$ or $\mu1 \neq \mu5$ or $\mu2 \neq \mu3$ or $\mu2 \neq \mu4$ or $\mu2 \neq \mu5$ or $\mu3 \neq \mu4$ or $\mu3 \neq \mu5$ or $\mu4 \neq \mu5$

Where $\mu1, \mu2, \mu3, \mu4, \mu5$ = mean TTC value at i % CV MPRs (*i=0%, 25%, 50%, 75%, and 100%)*

This study considered a 95% confidence level (α= 0.05). The results did not indicate significant differences between the average TTC values between 0% CV composition and 25% CV composition for AM and PM periods, as shown in Tables 4-5 and 4-6 below. However, at higher market penetration rates, the results were statistically significant.

Among the analyzed scenarios with different CV MPRs (0%, 25%, 50%,75%, and 100%), the mean TTC of CV MPRs less than 25% were not statistically significant. Thus, it indicates that the risk of rear-end and lane-change conflicts can decrease when CV MPRs are higher than lower and when collision warnings are disseminated early to give drivers enough response time. This observation is consistent with the previous study, which also observed an insignificant decrease in

total conflicts for MPR of less than 10% (Yang et al., 2020). Also, Rahman et al. (2019) stated 30% CV MPR as the minimum MPR for significant safety benefits in terms of surrogate measures of safety in CV approaches. On the other hand, when the CV MPR was greater than 25%, there were remarkable reductions in the total conflicts as the CV MPR increased.

Table 4-5: Results for TTC values based on the detour strategy (AM period)

Scenarios	**CV Composition**	**Pre-peak**		**Peak**		**Post-peak**	
		Mean diff.	***P*-value**	**Mean diff.**	***P*-value**	**Mean diff.**	***P*-value**
With detour (30 min incident clearance duration)	50-0%	-0.364	*0.125*	0.957	0.000	0.493	0.012
	100-0%	0.428	0.052	1.569	0.000	0.580	0.002
	100-50%	0.792	0.000	0.612	0.029	*0.086*	*0.852*
Without detour (30 min incident clearance duration)	50-0%	-0.399	0.072	0.826	0.000	-0.563	0.025
	100-0%	*0.093*	*0.883*	1.585	0.000	1.2	0.000
	100-50%	0.492	0.033	0.758	0.000	*0.275*	*0.408*
With detour (90 min incident clearance duration)	50-0%	0.647	0.001	0.596	0.001	0.563	0.001
	100-0%	0.882	0.000	1.178	0.000	0.526	0.008
	100-50%	*0.235*	*0.272*	0.582	0.000	*-0.037*	*0.972*
Without detour (90 min incident clearance duration)	50-0%	0.611	0.002	0.596	0.001	0.727	0.000
	100-0%	0.620	0.001	1.522	0.000	0.812	0.000
	100-50%	*0.010*	*0.998*	0.925	0.000	*0.085*	*0.855*

Note: Italic values present statistical insignificance; Mean diff. illustrates the difference of mean

Generally, for scenarios with detour advisory, a significant reduction was observed in the transition from 0% to 50% CVs and 0% to 100%. Both without and with detour strategy scenarios displayed statistical significance for peak periods, as illustrated in Table 4-5. However, the conflict results between 50% and 100% CV MPRs were not statistically significant for the post-peak period. During 30 minutes incident scenarios, statistical significance was observed between 0% and 50% CV MPRs; however, the same CV MPRs were statistically significant during 90 minutes incident clearance duration.

Table 4-6: Summary of results for TTC values based on one lane blockage

Scenarios	CV Composition	Pre-peak		Peak		Post-peak	
		Mean diff.	***P*-value**	**Mean diff.**	***P*-value**	**Mean diff.**	***P*-value**
OLB (AM)	25-0%	*-0.231*	*0.698*	0.967	0.000	0.815	0.002
	50-0%	0.549	0.050	2.189	0.000	1.252	0.000
	75-0%	0.966	0.000	1.639	0.000	2.220	0.000
	100-0%	1.171	0.000	2.623	0.000	2.349	0.000
	50-25%	*-0.005*	*1.000*	1.222	0.000	*0.437*	*0.330*
	75-25%	1.197	0.000	0.673	0.000	1.405	0.000
	100-25%	1.402	0.000	1.656	0.000	1.534	0.001
	75-50%	1.202	0.000	-0.549	0.006	0.968	0.001
	100-50%	1.407	0.000	1.618	0.000	1.097	0.053
	100-75%	0.845	0.011	1.501	0.000	0.702	0.016
OLB (PM)	25-0%	0.528	0.000	0.829	0.000	0.528	0.000
	50-0%	0.783	0.000	1.512	0.000	0.783	0.000
	75-0%	0.865	0.000	2.111	0.000	0.718	0.000
	100-0%	0.976	0.000	2.571	0.000	0.543	0.052
	50-25%	*0.205*	*0.871*	0.683	0.001	*0.255*	*0.461*
	75-25%	0.580	0.005	1.282	0.000	0.726	0.000
	100-25%	0.731	0.002	1.742	0.000	0.543	0.052
	75-50%	0.675	0.026	0.599	0.009	0.726	0.000
	100-50%	0.848	0.030	0.616	0.018	0.549	0.050
	100-75%	0.936	0.049	0.537	0.000	0.712	0.039
ILB (AM)	25-0%	*0.396*	*0.474*	*0.019*	*1.000*	1.505	0.000
	50-0%	1.299	0.000	0.521	0.045	0.702	0.016
	75-0%	1.539	0.000	1.282	0.000	1.807	0.000
	100-0%	1.220	0.001	2.127	0.000	2.127	0.000
	50-25%	0.903	0.026	0.503	0.082	1.533	0.000
	75-25%	1.143	0.005	1.263	0.000	1.412	0.000
	100-25%	1.347	0.008	2.109	0.000	1.827	0.000
	75-50%	1.287	0.014	0.760	0.003	1.104	0.001
	100-50%	1.533	0.000	1.606	0.000	0.594	0.044
	100-75%	1.412	0.000	0.845	0.011	0.715	0.010
ILB (PM)	25-0%	*0.151*	*0.956*	0.537	0.000	0.673	0.000
	50-0%	0.848	0.030	0.652	0.000	0.702	0.016
	75-0%	0.936	0.049	1.117	0.000	1.807	0.000
	100-0%	0.528	0.000	1.268	0.000	2.623	0.000
	50-25%	0.783	0.000	*0.115*	*0.936*	1.222	0.000
	75-25%	0.865	0.000	0.580	0.005	1.505	0.000
	100-25%	0.976	0.000	0.731	0.002	1.656	0.000
	75-50%	0.594	0.042	0.465	0.057	1.104	0.001
	100-50%	0.715	0.009	0.616	0.018	-0.549	0.006
	100-75%	2.127	0.000	0.675	0.026	0.967	0.000

Note: Italic values present statistical insignificance; Mean diff. illustrates the difference of mean

4.4 Summary and Results Comparison

It is worth noting that this study extends the previous theses done by Soloka (2019) and Monyo (2020). These studies share the same study site and data and analyzed CVs' benefits at various MPRs scenarios. However, these studies assumed a 100% driver's compliance rate with advisory messages. The present study covers this gap by presenting conflicts resulting from the scenarios by incorporating the driver's compliance behavior and comparing the findings with the study mentioned above. Table 4.7 summarizes the percent reduction in total conflicts between these previous studies and the present one.

Table 4-7: Percent reduction of total conflicts

Scenario	Percent Reduction in Total Conflicts (Peak Hour)		
	Soloka (2019)	Monyo (2020)	Present Study
Outer Lane Blockage (AM)	96.2	96.2	95.2
Outer Lane Blockage (PM)	86.6	70.0	81.4
Inner Lane Blockage (AM)	N/A	94.9	62.7
Inner Lane Blockage (PM)	N/A	79.5	80.0
Two outer lane blockage with detour (30 min incident clearance duration)	N/A	19.7	23.9
Two outer lane blockage without detour (30 min incident clearance duration)	N/A	15.6	14.7
Two outer lane blockage with detour (90 min incident clearance duration)	N/A	N/A	42.6
Two outer lane blockage without detour (90 min incident clearance duration)	N/A	N/A	18.7

While Soloka (2019) had a scenario of only OLB, Monyo (2020) added scenarios of ILB and two-lane blockages with 30-minutes incident duration. This study analyzed detour strategy when two outer lanes are blocked at an increased incident clearance duration of 90 minutes. In addition, the previous two studies performed statistical analysis considering the mean difference between the average TTC values between 0% CV MPR and a succeeding percentage of CV compositions. In contrast, this study finds the mean difference between the average TTC values

between various CV MPRs. Since the penetration of CVs is still low and increasing gradually at this stage, it is essential to know the significance of each incrementing step.

The morning period during OLB scenarios showed a significant difference in total conflicts as the CVs MPRs increased. Although this observation is consistent with the results observed in the previous study by Monyo (2020), the number of total conflicts in all scenarios was greater in the present study than the total conflicts obtained during the previous study. This observation may be attributed to the driver's compliance rate effect considered in the present study. Moreover, the percent change in total conflicts was higher in OLB than ILB scenarios for pre-peak and peak hours, as shown in Table 4-1. The results from both studies follow the same trend that the OLB scenarios resulted in more conflicts than the ILB. Post-peak hours resulted in fewer total conflicts than pre-peak and peak hours in all scenarios. Generally, the number of total conflicts decreased roughly linearly as the market penetration of CVs increased from 0% to 100%.

While a previous study by Monyo (2020) had a reduction in the number of conflicts of up to 71% and 64% for with and without detour advisory, respectively, during pre and post-peak scenarios, this study obtained a reduction of up to 40% and 26%. The difference in percentage change may be due to the effect of compliance rate, which was one of the limitations of the previously mentioned study. Moreover, changes compared to versions before Vissim 2020. During vehicle simulation, the driving behavior for which the attribute *'Observe adjacent lanes' or 'standstill distance for static obstacles'* is selected can lead to simulation results that differ from those of earlier versions. In the recent VISSIM version, the vehicle no longer moves as far to the left as possible in situations where the minimum lateral distance to vehicles on both adjacent lanes cannot be maintained simultaneously.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

CV technology is becoming more prominent, with innovative features from the automotive industry, such as Tesla, Audi, and BMW. Safety is one of the objectives of the developing technologies that would navigate the transportation network, coupled with increased research on exploring benefits that come with the implementation of CV technology. However, most microsimulation studies do not consider the human factor in CV modeling by assuming that drivers comply 100%. This study sought to cover the gap in knowledge by incorporating drivers' compliance rate in the varying CV MPRs of 0%, 25%, 50%, 75%, and 100% while exploring the effect of CV technology deployment on traffic safety improvement on a freeway during incidents and diversion strategies implementation.

This study used a calibrated VISSIM model to simulate the operational features of CVs. Various simulation scenarios were designed to mimic the typical conditions of Florida's Turnpike traffic based on field-collected traffic flow data. The simulated results from this study point out that the number of conflicts decreased with the increase of TTC, showing a decreasing conflict trend with the rise of CV MPR. Generally, the number of total conflicts decreased roughly linearly as the market penetration of CVs increased from 0% to 100%.

Among the analyzed scenarios with different CV MPRs, as the CV MPR increased, remarkable reductions resulted in the total number of conflicts. It was also observed that incidents that block the outer lane result in more traffic conflicts than incidents that block the inner lane. It could be due to less restriction to merge and diverge maneuvers when the inner lane is closed, unlike the outer lane. Also, the rear-end conflicts were more prominent than the lane-change conflicts, probably because the freeway is a high-speed facility, so drivers may not find enough time to react to the incident ahead of their path. Overall, the analysis showed that more conflicts

were observed in the PM period compared to the AM peak period. In all scenarios, post-peak hours resulted in fewer conflicts than pre-peak and peak hours, probably due to less traffic volume.

The finding also indicates that more congestion and conflicts were observed when two lanes were closed, unlike single lanes. The detour advisory was significant for an incident that blocked multiple lanes than single-lane closures. The speed of queue formation was a function of the analysis period when the incident occurred. Thus 90 minutes of incident duration had more conflicts than 30 minutes. Moreover, the detour strategy was more helpful when the incident clearance duration lasted more than 30 minutes. This information may help the incident management process prepare for detour strategies based on the severity of the incident at hand. Various studies have researched models to determine the severity of an incident and incident clearance duration prediction (Sullivan, 1997; Valenti et al., 2010; Xu et al., 2013). Furthermore, at higher CV MPRs, the detour strategy seemed to lessen travel time on the freeway, and more minor conflicts were observed, thus improving safety on the freeway.

The statistical analysis showed that the difference in the average TTC surrogate measure used in deriving conflicts was significant at higher CV MPRs above 25% CV MPR for single lane blockage scenarios, thus, indicating that the CV applications can improve traffic safety. Generally, the number of total conflicts decreased roughly linearly as the market penetration of CVs increased from 25% to 100%.

Yet, the actual safety performance of CVs is still not precise since, at this stage, the penetration of CVs is still low. It might take a long to collect sufficient real-world traffic performance data for assessment.

Recommendations for Future Work

TTC is only one of many surrogate measures to determine traffic safety. Future studies may consider other network surrogate safety measures. Moreover, future research is needed on drivers' behavioral response to critical safety messages, as sharing traffic information is only helpful if the driver is likely to comply. In real life, not all drivers who receive the message will substantially change their driving behavior (increase awareness/decrease aggressiveness). Thus, while microscopic simulation models have some limitations in analyzing driver behavior and compliance rates, driver simulator studies can investigate these factors. Also, the zero scenario used as a base case situation in this study was microsimulation-based. Future studies may consider validating the zero scenario by using a driving simulator. Again, the study site was limited to a network corridor that did not include intersections. Future studies may consider extending the network.

Despite the advantages of travel time to model drivers' decision to divert, it is not the only factor affecting a driver's route choice. Different determinants such as environmental components, human characteristics, and real-time information may influence driver's route choice with varying trip purposes. However, there is uncertainty with drivers' perceptions of travel time, which varies by drivers' value of time, familiarity, and trip purpose. Future studies should seek to incorporate more route attributes in route choice models and develop spatial behavioral theories that can be applied to study route choice. Field experiments, in which the behavior of travelers driving in real networks and performing actual travel tasks with and without information services is monitored, appear to be a promising future research direction.

As the CV technology is still being developed, the proposed driving behaviors of CV technologies are not calibrated within a real-world road network. The total market penetration of

those CV technologies might not be accomplished in the immediate future. Thus, an integrated traffic flow including conventional and CVs is expected. With this in mind, the interaction between CV technologies and conventional vehicles is mainly unknown. Thus, it advances the understanding of the impacts of CVs by conducting a comprehensive CV safety evaluation using traffic microsimulation.

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