ANALYZING THE BENEFIT OF WIDESPREAD USE OF V2I COMMUNICATION FOR IMPROVING INCIDENT MANAGEMENT AT A CONGESTED URBAN CORRIDOR

A Thesis

by

JOSE GERARDO CAZARES

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Alireza Talebpour
Committee Members,	Yunlong Zhang
	Wei Li
Head of Department,	Robin Autenrieth

December 2017

Major Subject: Civil Engineering

ABSTRACT

The advent of connected vehicle technology provides the potential to reduce travel times along congested urban corridors. Not only that, this technology may also be useful for providing transportation agencies with assistance to manage incidents (e.g. lane closures due to an accident) in such a way that travelers will experience a decreased amount of delay. This project's goal is to understand and quantify the effectiveness of deploying Dedicated Short Range Communication (DSRC) technology for a specific mobility/safety application on an urban corridor by creating a queue-warning application. Effectiveness is determined by investigating the impacts that market penetration rates, rerouting strategies, and driver reaction times have upon the travel time reliability of an urban corridor. U.S. Highway 75 in Plano, TX is simulated and results of this investigation reveal that even without active reroute strategies, connected vehicles can reduce the average travel time during an incident with lane closures. As connected vehicles become increasingly prominent at market penetration rates of 30% and 50%, the average travel time for drivers on U.S. Highway 75 is reduced and remains relatively stable as market penetration rates continue to increase. As the reaction time of connected vehicle drivers decreased (due to drivers' awareness about the incident), there is a decrease in average travel time along the corridor, increased consistency in average travel times for higher market penetration rates, and increased similarity in the performance results of the five strategies used.

ACKNOWLEDGEMENTS

I would like to express my sincerest gratitude to my faculty advisor, Dr. Alireza Talebpour, for all of the guidance and support that he has provided me with throughout this project. His ambition and commitment to his work has been a great source of inspiration.

I wish to thank my committee members, Dr. Yunlong Zhang and Dr. Wei Li for taking the time to provide their input and sharing their wisdom with me. Their support and encouragement has provided me with further confidence in myself and in my work. I would like to thank the colleagues that I have met during my time here at Texas A&M University. Their kindness and friendship has made this experience all the more worthwhile.

I wish to express my thanks to the Transportation Research Board for peer-reviewing my submission, which included some of the work completed within this project, and granting me the opportunity to present at the 96th Annual Meeting in Washington, D.C. on January 2017.

I would like to thank my parents, Jose and Ana Maria, and my siblings, Anna, Yvette, and Erik, for all of the support and love that they have provided to me. It has truly been a great blessing to be a part of such a wonderful family.

Finally, I would like to express my deepest thanks to my best friend, Shireen. Her support, presence and love through both the happy and toughest of moments have kept me motivated to push forward.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Alireza Talebpour and Professor Yunlong Zhang of the Department of Civil Engineering and Professor Wei Li of the Department of Landscape Architecture and Urban Planning.

The data analyzed for Chapter IV was provided by Rajat Rajbhandari of the Texas A&M Transportation Institute.

All other work for the thesis was completed independently by the student.

Funding Sources

Graduate study was supported by a fellowship from Texas A&M University.

NOMENCLATURE

CV	Connected Vehicle
CVT	Connected Vehicle Technology
DMS	Dynamic Message Signs
DSRC	Dedicated Short Range Communication
GM	General Motors
MPR	Market Penetration Rate
NCV	Non-Connected Vehicle
NHTSA	National Highway Traffic Safety Administration
SUMO	Simulation of Urban Mobility
TT_{avg}	Average Travel Time
USDOT	United States Department of Transportation
US 75	United States Highway 75
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
V2X	V2V and V2I (collectively)

TABLE OF CONTENTS

Page

ABSTRACT ii

ACKNOWLEDGEMENTS iii

CONTRIBUTORS AND FUNDING SOURCES.....iv

NOMENCLATURE.....v

TABLE OF CONTENTS vi

LIST OF FIGURES..... viii

LIST OF TABLES ix

CHAPTER I INTRODUCTION 1

- Background.....1
- Problem Statement.....3
- Research Objective 4
- Thesis Organization.....5

CHAPTER II LITERATURE REVIEW.....6

- The Connected Vehicle: A Brief Definition and Description 6
- Microsimulation Modeling of Connected Vehicles 7
- Effects of Rerouting Strategies and Incident Management 8

CHAPTER III METHODOLOGY.....14

- Simulation of Urban Mobility (SUMO) 14

Site and Traffic Data 15
Modeling of Vehicles with No Communication Capabilities (Regular Vehicles) 16
Modeling of Vehicles with Communication Capabilities (Connected Vehicles) 18
Rerouting Strategies 19

CHAPTER IV DATA ANALYSIS AND RESULTS 25

Case 1: No Incident, No Rerouting (Base) 25
Case 2A: Incident, No Rerouting 27
Cases 2B-2F: Incident, Rerouting Active 33

CHAPTER V CONCLUSIONS AND RECOMMENDATIONS 37

Findings 38
Limitations 40
Future Research 41

REFERENCES 42

LIST OF FIGURES

Page

FIGURE 1. Map View of US 75 in Plano, Texas as Provided by Google Maps and the Network as Viewed in SUMO. 16

FIGURE 2. Summary of Rerouting Strategy Run Simultaneously with SUMO. 21

FIGURE 3. Reroute Path and Incident Location for Cases 2B through 2D.....................23

FIGURE 4. Reroute Path and Incident Location for Cases 2E and 2F. 24

FIGURE 5. Travel Time Distribution Frequencies for Different Market Penetration Rates of Connected Vehicles with Different Reaction Times. 26

FIGURE 6. Travel Time Distribution Frequencies for Different Market Penetration Rates of Connected Vehicles with Different Reaction Times When an Accident Occurs. 29

FIGURE 7. Travel Time vs Simulation Time (MPR 10%-30%). 32

FIGURE 8. Travel Time vs Simulation Time (MPR 50%-99%). 32

FIGURE 9. Average Travel Times for All Market Penetration Rates Pertaining to 2.0 sec Reaction Time.. 34

FIGURE 10. Average Travel Times for All Market Penetration Rates Pertaining to Reaction Time 35

LIST OF TABLES

Page

TABLE 1. Default Car-following Model Parameters in SUMO......................................18

CHAPTER I

INTRODUCTION*

Background

The automotive industry and academia both predict that connected vehicle technology will become increasingly widespread and ubiquitous in the coming years. Presently, vehicle manufacturers have announced their intentions to introduce Dedicated Short Range Communication (DSRC) devices in their vehicles in order to maximize safety benefits and have already begun development of their connected vehicle technologies *(1-3)*. The anticipated regulatory notice from the National Highway Traffic Safety Administration (NHTSA) intended to mandate such devices in all new vehicles is expected to place pressure on manufacturers and accelerate the introduction of DSRC devices *(4)*. Mindful of this, agencies at the state and local levels are now more invested in the prospect of deploying roadside DSRC devices for applications pertaining to both safety and mobility *(6-7)*. It is currently unclear how the extensive use of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) (collectively referred to as V2X) will influence the flow of traffic by virtue of having drivers receive up-to-date traffic information from roadside DSRCs. It is unknown, for example, how a driver traveling during the peak hour may react to obtaining real-time knowledge of an ongoing incident with lane closures downstream of their location on U.S. Highway 75 (US 75). There is a need, therefore, for a model capable of simulating how the drivers of connected vehicles

---

[*] Portions of this chapter were part of a paper submission by Cazares et al. (*44*) which was peer reviewed by the Transportation Research Board and presented at the 96th Annual Meeting in Washington, D.C.

may respond to a particular event (e.g. incidents, work zones) on highly congested urban corridors.

Connected vehicles are defined as those which possess the ability to communicate with other surrounding vehicles and infrastructure through the use of wireless technology *(5).* The potential benefits are predicted to include increases in driver safety and utilization of existing infrastructure, improved driving comfort, and enhanced convenience while reducing traffic congestion, travel time, and vehicle user costs *(5).* The United States Department of Transportation (USDOT) expects connected vehicles to provide safety, mobility, and environmental benefits thanks to V2X communication capabilities. Traffic congestion currently costs about $87.2 billion annually in the U.S. and results in an extra 4.2 billion hours of travel to its road users *(5).* It is generally proposed that information relayed from V2I through roadside DSRC devices is expected to assist in enhancing the way that transportation agencies manage their transportation systems. Connected vehicle technology (CVT) is predicted to result in improved operations that will stem from the unique components of V2X communications.

In recent years, various vehicle manufacturers have publicly expressed their support of including V2X communication capabilities in their newer vehicles. In 2014, General Motors (GM) announced that certain 2017 Cadillac models will offer “intelligent and connected” vehicle technologies *(1).* More specifically, the 2017 Cadillac will be equipped with V2V communication capabilities. GM expects V2V technology to be able to reduce traffic congestion and help lessen the impact of vehicle collisions. In 2015, Tesla Motors, Toyota and GM addressed a congressional subcommittee concerning the safety, security and driving benefits of connected vehicles. Vehicle manufacturing companies are beginning to move towards embracing connected vehicle technologies and it is predicted that one quarter billion connected vehicles will be traveling on US roads by 2020 *(6)*.

Problem Statement

Traditionally, microscopic traffic simulation models have been used to analyze the effects of various incidents on mobility in corridors by injecting response strategies using devices such as dynamic message signs (DMS) and lane control signals (*7-12*). However, such devices are limited by certain drawbacks. DMS, for example, may either overload drivers with information or lose driver trust by not providing any meaningful, accurate, timely and useful information (*9*). Additionally, DMS usefulness is affected by the number of travelers that see the messages, and while a DMS may be useful at one particular incident location, this may not be the case at a different location on a different day (*9*). With regards to lane control signals, the primary issue to consider is the compliance level of drivers required for effective operations (*10*). As noted previously by Wang et al, lane control may not be beneficial at low compliance levels or if the incident duration is long, and may require integration with other alternative management tools to be useful (*11*). The disadvantage of such devices, therefore, is that they are not pervasive enough and thus do not reach a large driver population at the same time (*12*).

On the other hand, given a high enough penetration rate, connected vehicle technology can be used to send lane- and geographic-specific messages to a large portion of traffic on a corridor. Should the NHTSA’s policy be passed, it is assumed that the number of vehicles with communication capabilities within the U.S. traffic stream will steadily increase. With drivers directly receiving messages to their vehicles concerning current traffic conditions, the visibility and pervasive limitations of current devices may no longer be an issue. Consequently, at a certain market penetration rate it may become possible to improve the efficiency of operations during incidents on a congested corridor.

Research Objective

The objective of this project is to characterize and quantify the effects of deploying a DSRC technology-based queue-warning application on travel time reliability in a congested urban corridor during peak hour traffic conditions. To achieve this objective, the following subtasks are to be performed:

- Adjust Intelligent Driver Model (IDM) parameters to model connected vehicles.
- Simulate an incident resulting in the closure of two freeway lanes.
- Develop Python scripts for various rerouting strategies to be implemented during the incident.
- Simulate various combinations of market penetration rates and driver reaction times.
- Discuss the variation in average travel times with respect to changing market penetration rates (MPRs) and driver reaction times; reduction in

average travel time for Non-Connected Vehicles (NCVs) and Connected Vehicles (CVs) will be the key performance measure used.

- Draw conclusions regarding the potential impact of the queue-warning application and connected vehicles upon the urban corridor.

Thesis Organization

This thesis consists of four chapters following the introduction. Chapter II provides a review of the literature pertaining to past studies on the modeling of a connected vehicle environment and real-time incident management. Chapter III discusses the methodology used within the study. Specifically, this chapter describes the simulator (Simulation of Urban Mobility (SUMO)), the characteristics of the simulated environment, the logic behind how connected vehicles and non-connected vehicles were modeled, the simulated cases and the Python script used for rerouting. Chapter IV analyzes the data output by SUMO and provides details on the results using the provided data. Chapter V provides the study’s conclusions and outlines future research directions.

CHAPTER II

LITERATURE REVIEW*

This chapter is organized into three sections and presents a review of the extensive amount of work that has gone into investigating V2X communications and its effects on traffic operations. Initially, a review on the definition of connected vehicles is provided in the first section. The following section discusses the findings of previous investigations which utilized microsimulation to model a connected environment. The third section reviews the previous literature investigating effects of rerouting strategies and incident management in a connected environment. A short portion of the third section is dedicated to discussing how this particular project differs and builds on the previous works discussed in this chapter.

The Connected Vehicle: A Brief Definition and Description

Literature currently establishes definitions for the types of connected vehicles and also identifies each group's respective characteristics (*13-15*). As mentioned in the previous chapter, two types of communications exist for connected vehicles: V2V and V2I. The first type allows for the transmission of detailed information between vehicles currently traveling within the traffic stream. Depending on the MPR at any given time and the communication range of each vehicle, a driver in a V2V-enabled vehicle may be able to obtain information from the vehicles which immediately precede or follow them

---

[*] Portions of this chapter were part of a paper submission by Cazares et al. (*44*) which was peer reviewed by the Transportation Research Board and presented at the 96th Annual Meeting in Washington, D.C.

as well as from a number of vehicles at positions located further upstream or downstream *(13-15)*. V2I communication, on the other hand, provides drivers with information related to changes in the driving environment. Such information may include changes to the speed limit, work zones, weather conditions, downstream incidents and lane closures etc. *(13-15)*. The combination of these two forms of communication, referred to as V2X, can provide drivers the opportunity to formulate more strategic decisions and partake in better-informed maneuvers.

Microsimulation Modeling of Connected Vehicles

A significant amount of effort has gone into utilizing car-following models to create simulations which can accurately recreate a connected environment *(15-21)*. Wang et al. *(16)* developed an improved safe distance model (SDM) which makes use of the V2V communication technology available within vehicles. The proposed model is capable of revealing what a CV's status is at any given time, and the study's results suggest that the reduced safe distances seen between leader and follower may be caused by up-to-date traffic information lowering the reaction times of drivers *(16)*. Jin et al. *(17)* proposed a general bidirectional control framework which is derived from the ability of CVs to obtain information from not only leading vehicles but from following vehicles as well. The results of this study indicate that backward communication may be useful for alleviating congested traffic conditions in addition to stabilizing the traffic flow *(17)*. For vehicles equipped with connected cruise control (CCC), Jin and Orosz *(18)* used microscopic simulation to model car-following dynamics. According to their findings, the introduction of a few CCC-equipped vehicles into the traffic stream engendered string stability within a platoon which would otherwise be string unstable *(18)*. Furthermore, a significant decrease in driver reaction times was observed *(18)*. Talebpour et al. *(15, 19 and 20)* presented an acceleration framework which made use of different car-following models each containing different assumptions in order to simulate vehicle types with different communication capabilities. They quantified and analyzed the impact of CV technology and autonomous vehicles on a simple roadway segment's efficiency. It was found that higher MPRs could potentially produce higher breakdown flows and densities, a reduction in the likelihood of breakdown *(20)*, and increased the traffic flow's string stability*(15)*. Goodall et al. *(21)* presented an algorithm which they used the behavior of CVs to predict the location of NCVs. With only 10% of all vehicles communicating, the proposed algorithm was capable of determining the location of 30% of all vehicles traveling in the same lane *(21)*. When partnered with a preexisting algorithm designed for ramp metering, performance was significantly improved at low MPRs and maintained at higher MPRs. They noted that due to dependence on interactions between vehicles, the estimated positions were only accurate either at roadway segments which were congested or at locations downstream of such congested segments *(21)*.

Effects of Rerouting Strategies and Incident Management

Numerous researchers have tested various approaches for examining the potential effectiveness of rerouting strategies and their impact on drivers traveling within a connected environment. Both academia and practitioners alike have placed an emphasis on understanding the impact that rerouting strategies could have upon incident management. Abdulhai and Look *(22)* were among the first to investigate the consequences of using dynamic route guidance systems with regards to both safety and travel time. Their study's results reveal that the average travel time of vehicles within a transportation network will typically decrease as the MPR of equipped vehicles increases *(22)*. Lee and Park later went on to conduct their own study while inserting an incident into their transportation network model *(23)*. Their findings conclude that V2X-based rerouting strategies can result in significant travel time reductions, competing strategies do not subtract from overall performance, and increased MPRs could potentially produce greater benefits *(23)*.

In the years following the aforementioned initial studies, Kattan et al. *(24)* examined the potential benefits of V2V communications when present during an incident by measuring not only the probability of occurrence of secondary collisions but also any travel time changes which occurred within their modeled network. Their results indicate that V2V communications can effectively improve both safety and the travel time experienced by drivers while moving through a network experiencing moderate and high congestion levels *(24)*. Improvements in safety conditions at severe congestion levels, however, come at the cost of increased travel time for drivers. Mei et al. *(25)* created a simulation model for the purpose of understanding the impacts that V2V communications may have upon traffic network operations which use a combination of dynamic route diversion and variable speed limits in the event of a severe incident occurring within a network. Their results indicated evidence of sensitivity to both MPR levels and various control strategies *(25)*. Yeo et al. *(26)* developed model for observing the likely impacts that V2V alert messages (as well as the lack thereof) may have on driver response to freeway incidents with lane closures. The Next-Generation Simulation (NGSIM) oversaturated freeway flow model and an adjusted version of that same model were utilized to represent NCVs and CVs respectively. The study's results indicate that increasing market penetration rates may lead to an increase in avoidance of unnecessary lane changes and allows for the traffic stream to sustain higher flow rates *(26)*. Rim et al. developed an approach for using V2X communications to estimate individual lane-level travel times (L^{2}TT) *(27)*. Based on their observations, they concluded that with MPRs of 20% and higher it becomes possible to obtain mean absolute relative error values between 6%-8% *(27)*. However, they did make note that there was still a need for more research before V2X technology could reach a point where it could transmit traffic information with minimized travel time errors to drivers.

Paikari et al. *(28 and 29)* have more recently investigated the benefits of having CVs present during an incident occurring on a model of a real-world freeway. The study's results seemed to point towards a consistent travel time reduction as the MPR of CVs increased *(28 and 29)*. Depending on demand, the average travel times were found to improve by as much as 44% while the MPR was at a value of 40% *(29)*. Pan et al. *(30)* studied five different congestion-responsive rerouting strategies and their effectiveness at reducing travel time. The study concludes that implementing a proper rerouting strategy could improve the average travel time by as much as 4.5 times (*30)*. Though results do indicate benefits of rerouting vehicles, the approach focuses primarily on congestion mitigation rather than responding to an incident, and the simulations were run on grid networks containing signalized intersections which cannot elucidate upon how freeway conditions may be affected. Olia et al. *(31)* analyzed the impacts of providing drivers of CVs with real-time routing guidance and warning messages while an incident is present within a simulated network. It was found that when compared to a base case with only NCVs, drivers of CVs may experience a travel time reduction of up to 37% when the MPR value was at 50% *(31)*. However, MPRs beyond 50% may not necessarily perform as well as a result of changes in traffic conditions occurring much more quickly. Furthermore, increased discrepancies between the predicted and actual travel time are detrimental to the performance at higher MPRs within the simulated environment *(31)*. Although real-time traffic information can decrease the travel time experienced on congested major routes while resulting in a simultaneous rise in travel times on minor routes, both NCVs and CVs will typically experience overall decreased travel times. Smith et al. *(32)* implemented a rerouting strategy within an artificial grid network and on grid-like, real-world networks extracted from Los Angeles and New York City. Their networks contained several simulated incidents, and the strategy which they proposed were found to yield reduced travel times (*32*). More specifically, their strategy resulted in an average travel time reduction of 53% of what was experienced in a case without the strategy's implementation. Smith et al. conclude that as an accident's duration increases, the greater the benefits of rerouting become *(32)*. Backfrieder et al. *(33)* developed a unique predictive congestion minimization in combination with an A*-based router algorithm for the purpose of locating, predicting, and avoiding traffic congestion through the utilization of real-time traffic information collected via V2X communications. In scenarios which modeled both artificial and real-world networks, the best case resulted in the rerouting strategy providing a 71.8% decrease in travel time compared to scenarios where the strategy was disabled *(33)*. Dowling et al. *(34)* tested an approach which used speed harmonization in conjunction with an advanced queue-warning system. The study used both microscopic simulation and a localized field test to analyze their proposed approach. Their simulation implemented percentages of CVs ranging from 10% to 50% which would represent the number of drivers responding to the strategies. Ultimately, this study limited their simulation to only observing the effects of speed harmonization due to lack of information to simulate how drivers would realistically react to a queue warning system. The results of the study found that the number of speed drops was reduced while the reduced amount of shockwaves came at the cost of mean speed *(34)*, but lacked any commentary regarding changes to the average travel time.

Studies that previously examined freeway incident impacts on travel time *(23 and 27-29)* may be compared to the methodology and objectives presented in this paper. Lee et al. examined two incidents occurring within a hypothetical network containing a freeway *(23)* using an extensive number of simulations under a variety of conditions (i.e., different MPRs and reroute strategies). However, the study did not investigate the impact of driver reaction times on travel time, which is something presented in this paper. Although the study presented by Rim et al. *(27)* indicates that increased connected vehicle MPRs can improve estimated travel time reliability, it only states that travel time may be expected to be reduced rather than determining actual travel time reductions for the studied MPRs, which is something that is presented in this paper. Paikari et al. *(28 and 29)* state that their proposed rerouting strategy could provide significantly lower travel times during freeway incidents. However, their studies presented the results of testing MPRs no higher than 50% *(28 and 29)* due to finding negative impacts on travel times at higher MPRs. This paper investigates a larger range of MPRs to better understand how exactly larger MPRs affect travel times in combination with different driver reaction times. As with *(23)*, *(28-29)* did not investigate the impact of driver reaction times on travel time.

CHAPTER III

METHODOLOGY*

This chapter provides a description of the methodology used within the study and is divided into five sections. The first section is dedicated to presenting the details regarding the simulator (SUMO). The second section describes the characteristics of the location and traffic data used within the simulation. The third and fourth sections describe the logic behind how connected vehicles and non-connected vehicles were modeled. The fifth section discusses the simulated cases and the Python script used for rerouting vehicles during a simulated incident.

Simulation of Urban Mobility (SUMO)

For this study, modeling of all cases was performed using the Simulation of Urban Mobility (SUMO) program (*35*). Developed in 2001 by the Institute of Transportation Systems at the German Aerospace Center, SUMO is an open-source microscopic traffic simulation platform. SUMO allows for the modeling of a range of road configurations as simple as a four-legged signalized intersection and as complex as a city-wide network. SUMO's time-discrete simulations may be viewed in the included graphical user interface and can generate outputs including travel time, segment speed, segment density, and emissions. The program suite includes a road network importer, a demand generator capable of utilizing a variety of input sources (i.e. OD matrices, traffic

---

[*] Portions of this chapter were part of a paper submission by Cazares et al. (*44*) which was peer reviewed by the Transportation Research Board and presented at the 96th Annual Meeting in Washington, D.C.

counts, etc.), and a control interface known as TraCI (*36*) which allows the user to make instantaneous changes during a simulation run. In particular, Python may utilize TraCI commands within user-created scripts to interact with SUMO in a specific manner, as is done in this study and discussed in a later section within this chapter. All simulations were run using SUMO version 0.26.0.

Site and Traffic Data

A microscopic simulation was constructed in order to observe the effectiveness of a specific mobility application on a 3 mile segment of U.S. Highway 75 (US 75) in Plano, Texas. Running north-south, the roadway network includes freeway segments, frontage roads and two signal-controlled diamond interchanges. The network consists of seven off-ramps, seven on-ramps, and contains no more than six lanes and no less than four lanes. Figure 1 provides a map view as well as a SUMO view of the network. Vehicular volume for morning peak hour has been provided by the Texas A&M Transportation Institute. The simulation will run the provided data for a one-hour time period taking place at 7-8AM during a weekday.

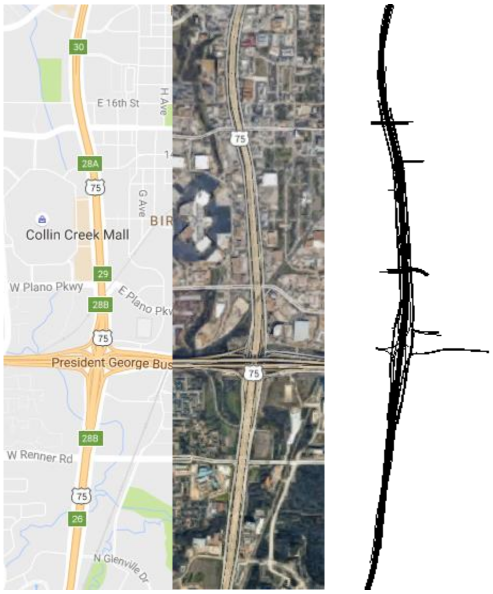


FIGURE 1. Map View of US 75 in Plano, Texas as Provided by Google Maps (left, middle), and the Network as Viewed in SUMO (right).

Modeling of Vehicles with No Communication Capabilities (Regular Vehicles)

Drivers of regular vehicles do not receive information from any external source (i.e. other vehicles, roadside devices). SUMO's default car-following model, a modified version of the Krauss model, is used to simulate regular vehicles. The model allows vehicles to drive as fast as possible while avoiding collisions as long as the leader breaks within leader/follower maximum acceleration/deceleration bounds *(35*). The follower will attempt to remain behind the leader at a distance and speed that allows the follower to adapt to the leader's deceleration. The model's default parameters within SUMO are listed in Table 1. The model's safe speed is formulated by:

$$v_{safe}(t) = v_l(t) + \frac{g_n(t) - g_{des}(t)}{\tau_b + \tau} \quad (1)$$

where v_l is the leading vehicle's speed, τ represents the driver's reaction time, τ_b is a time scale denoted by $\tau_b = \frac{v_f(t)+v_l(t)}{2b}$, b is the driver's deceleration, $g_{des}(t)$ is the desired gap given by $g_{des}(t) \geq v_n(t)\tau$, and $g_n(t)$ is the gap between a pair of vehicles at time t and is found by:

$$g(t+\Delta t) = g(t) + \Delta t\big(v_l(t+\Delta t)\big) - v_f(t+\Delta t) \tag{2}$$

with v_f representing the following vehicle's speed. It is possible that the safe speed is larger than the maximum speed allowed on the road segment or larger than the speed the vehicle is capable of accelerating to in the next time step. The desired speed is therefore calculated using the following equation:

$$v_{des}(t) = \min[v_{max}, v(t) + a(v)\Delta t, v_{safe}(t)] \tag{3}$$

The target vehicle's speed is then found using:

$$v(t+\Delta t) = \max[0, v_{des}(t) - \eta] \tag{4}$$

where η is a stochastic error term for driver imperfection that is set to zero. This equation confirms that the following vehicle does not move backwards against the traffic flow.

TABLE 1. Default Car-following Model Parameters in SUMO. (Note that Minimum Gap for IDM is not a default value. This value is calculated at every time step of the simulation for each vehicle.)

	Maximum Acceleration, a_{max} (m/s^2)	Maximum Deceleration, b_{max} (m/s^2)	Maximum Speed, V_{max} (m/s)	Minimum Gap [m]	Acceleration Exponent, δ	Driver Reaction Time, τ (sec)
Krauss	2.6	4.5	70	2.5	-	1.0
IDM	0.73	1.67	120	-	4	0.5

Modeling of Vehicles with Communication Capabilities (Connected Vehicles)

Drivers of CVs have the ability to receive/send information from/to other vehicles and roadside devices. CV drivers are more aware of the driving environment. As previously mentioned by Talebpour *(15)*, a deterministic car-following model is acceptable for simulating connected vehicle behavior. From current available models, the Intelligent Driver Model (IDM) developed by Treiber et al. *(38)* is capable of providing enhanced realism without sacrificing different congestion dynamics *(39)*. By taking into account parameters including desired acceleration, desired gap size, and comfortable deceleration, this model is capable of simulating collision-free conditions. Following the assumptions proposed by Talebpour *(39)*, the IDM can be used to simulate environments in which connected vehicles with active communication features are present. The model's default parameters within SUMO are listed in Table 1 while the acceleration formula is given by:

$$a^f = a_{max}\left[1 - \left(\frac{v_f(t)}{v_0}\right)^{\delta} - \left(\frac{s^*(v,\Delta v)}{s}\right)^2\right] \tag{5}$$

where a_{max} is the maximum acceleration of the following vehicle, a^f is the follower's current acceleration, $v_f(t)$ is the follower's current speed, v_0 is the follower's desired speed, s is the current distance between the following and leading vehicles, s^* is the desired distance, and δ is an acceleration exponent. The desired distance is determined by:

$$s_f^*(v, \Delta v) = s_0^{(f)} + T_f v_f(t) + \frac{v_f(t)\Delta v}{2\sqrt{a_{max} b}} \tag{6}$$

where $s_0^{(f)}$ is the jam distance, T_f is the safe time headway, and b is the desired deceleration.

The various MPRs were simulated by changing the percentage of vehicles abiding by the IDM. Additional features of this model include the assumption of lower reaction times (50% that of regular vehicles) and safe spacing between the follower and leader vehicle *(39).* For this study, the safe time headway of IDM vehicles are changed within SUMO to a range between 0.5 and 2 seconds. From this point on, the term Connected Vehicle (CV) will refer to a vehicle which obeys the IDM within SUMO.

Rerouting Strategies

To determine and understand the effectiveness of deploying DSRC technology along the corridor, this study implements five rerouting strategies which take advantage of real-time information provided by the roadside devices. Chen et al. *(41)* previously pointed out that routing compliance rate is highest when drivers receive reliable, predicted real-time information. Additionally, Muizelaar and van Arem *(42)* determined that the traffic information content most preferred to be received by drivers is advice regarding the fastest route to their destination. Combining the previous literature findings with the concept borrowed from Elfar et al. *(43)* regarding market penetration rate reflecting the percentage of CVs receiving and complying with instructions, rerouting strategies are created on Python scripts which are then run simultaneously with SUMO.

The scripts first determine the occupancy of the lanes on the segment on which the incident occurs. In order to model realistic, rubbernecking behavior, the lanes adjacent to the incident will have reduced speeds as the queues grow on the blocked lanes. The script then collects the travel time on the freeway and compares it to the travel time on the frontage road. When the travel time on the freeway becomes greater than on the frontage road, vehicles receive the prompt to reroute from the freeway to the frontage road. The flow chart in Figure 2 summarizes the scripts.

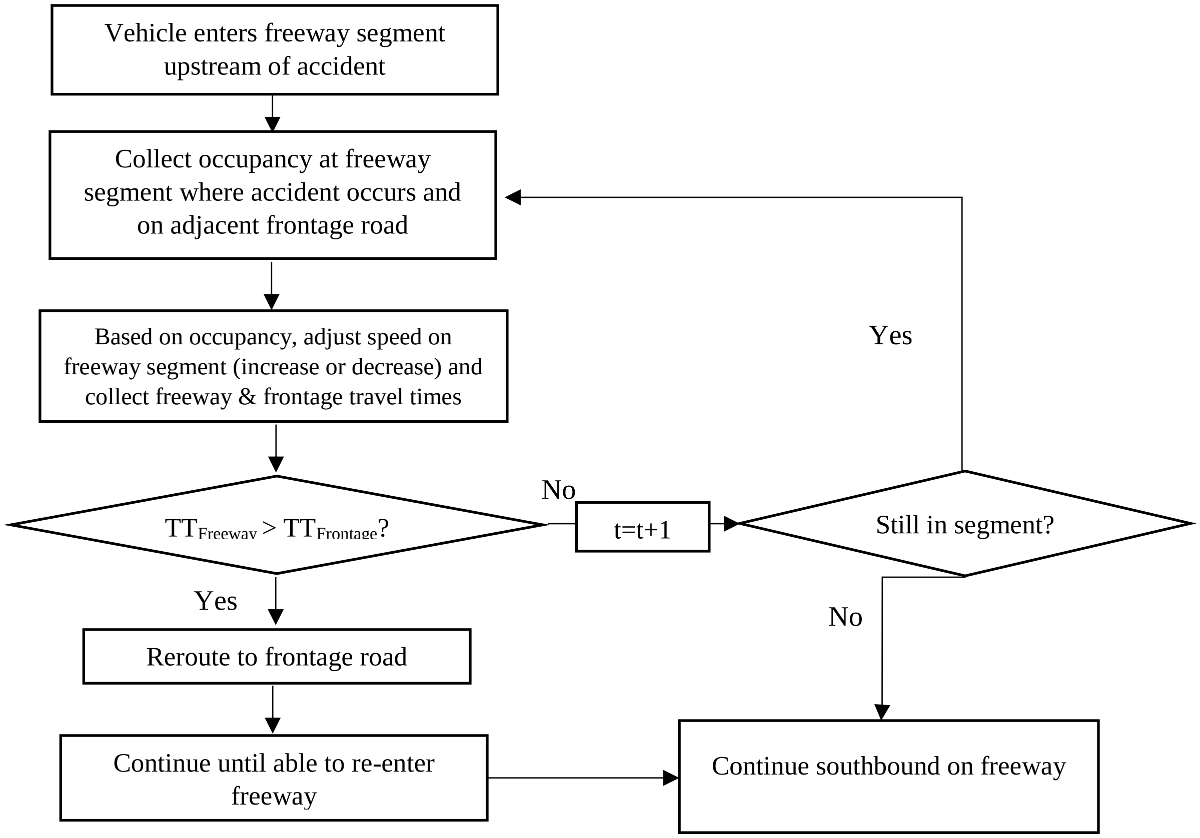


FIGURE 2. Summary of the Rerouting Strategy Run Simultaneously with SUMO.

The simulation scenarios are placed under two major categories: with and without initiation of rerouting strategies. Both categories contain cases where the reaction time of connected vehicle drivers is either 0.5, 1.0, 1.5, or 2.0 seconds. Literature suggests that CVs have the potential to reduce driver reaction times due to having the ability to receive traffic information in real-time *(14, 15, 19, and 39)*, and this paper investigates how the change in reaction time can potentially impact travel time. For each reaction time, there are cases with different percentages of CVs making up the traffic stream. The percentages of connected vehicles used are 0, 10, 25, 30, 50, 75, 90 and 99%. Each simulation was run using 10 random seeds. In total, 2,240 unique simulations were run.

Case 1

The first case simulates the existing traffic conditions using the provided traffic data for the morning peak hour. In this case, all range of MPRs and reaction times are tested. The results of this case are used as a baseline for the average travel time attainable under typical traffic operation conditions.

Case 2A

Case 2A is the first case in which an incident is inserted into the corridor. The incident blocks the two leftmost lanes on a southbound segment of US 75 downstream of the off-ramp to Renner Rd. The incident begins at the second minute of the simulation’s run and is cleared after 35 minutes, lasting a total of 33 minutes. The southbound direction was selected since it handles the most traffic during the selected hour. Like Case 1, Case 2A simulated all ranges of MPRs and reaction times. The potential effectiveness of CVs will be evaluated by not only comparing the change in travel time within typical traffic conditions, but also by comparing the changes that are seen while an incident is present.

Cases 2B through 2F

Cases 2B through 2F build upon Case 2A by introducing various rerouting strategies. The first strategy (strategy B) updates vehicles on current downstream travel times when they are 336 m (1102 ft) upstream of the accident. This is Case 2B. The second strategy (strategy C) combines the first with a warning to vehicles on the leftmost lane prompting them to change to the adjacent lane during the accident. The third strategy (strategy D) operates identically to the second, with the modification of prompting the two leftmost lanes to switch to the nearest unblocked lane. The cases using strategies C and D are referred to as Case 2C and Case 2D, respectively. Strategies B-D utilize the only eligible alternate route: exiting via the off-ramp to Renner Rd, traveling on a short segment (approximately 900 ft) of US 75 Frontage Rd, and reentering via the on-ramp prior to Renner Rd. Figure 3 provides a visual representation of the reroute path and incident location.

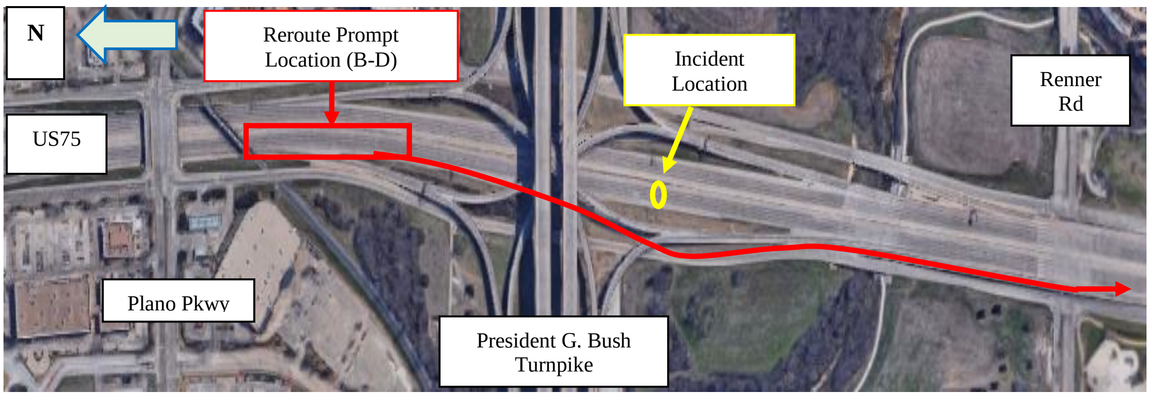


FIGURE 3. Reroute Path and Incident Location for Cases 2B through 2D.

The fourth strategy (strategy E) modifies the first by providing a warning 1609 m (5280 ft) upstream of the accident, and its respective case is referred to as Case 2E. The fifth strategy (strategy F) provides a "staggered" warning throughout the freeway upstream of the accident. At 1609 m, 1309 m, 1009 m, and 336 m upstream of the accident the fifth (leftmost), fourth, third, and second (adjacent to rightmost) lanes, respectively, are provided with current travel times and may choose to reroute. This case is referred to as Case 2F. For strategies E and F, in addition to the alternate route in strategies B-D, a second route exists: exiting via the off-ramp to Plano Parkway, continuing through the intersection of Plano Pkwy at US 75 Frontage Rd, and back onto the freeway via the on-ramp prior to Renner Rd. Figure 4 provides a visual representation of the reroute path and incident location.

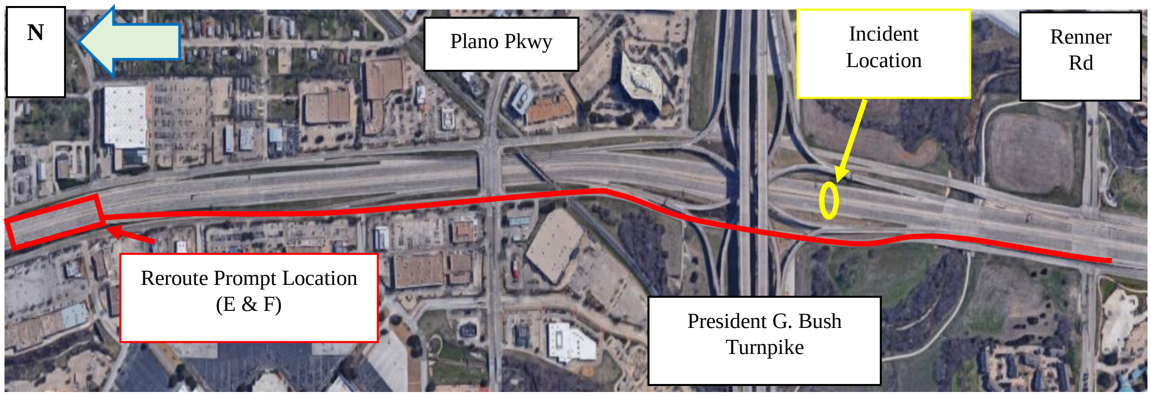


FIGURE 4. Reroute Path and Incident Location for Cases 2E and 2F.

CHAPTER IV

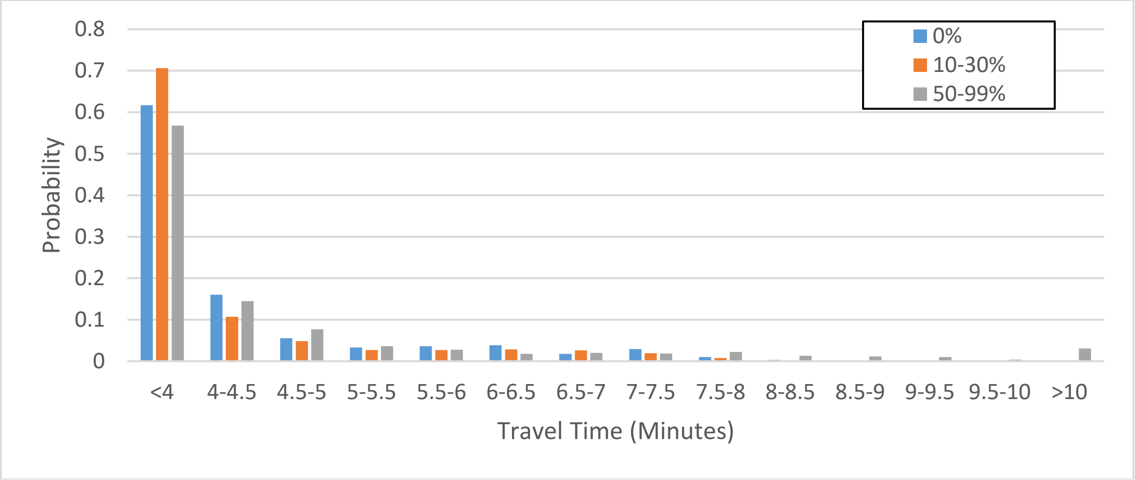
DATA ANALYSIS AND RESULTS*

Case 1: No Incident, No Rerouting (Base)

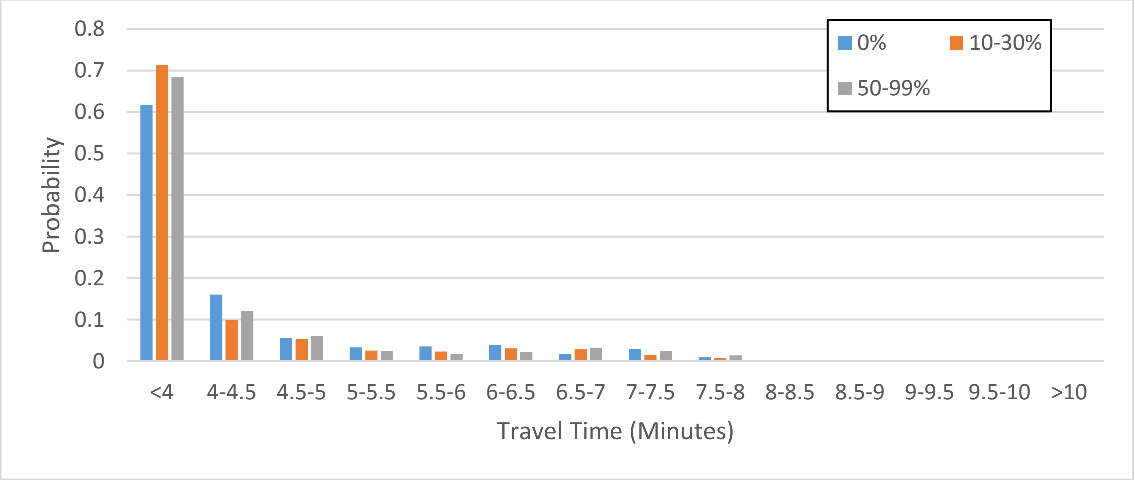
This case modeled an environment with various MPRs of CVs. Reaction times of 0.5, 1.0, 1.5, and 2.0 seconds were considered when modeling CVs. Figure 5 shows the travel time distributions for this first case, with the average travel time (TT_{avg}) being approximately 4 minutes. The results indicate that the probability of vehicles traveling through the freeway in 4 minutes or less increases as reaction time of CV drivers decreases. Moreover, except for the 0.5 second reaction time scenario, improvement in travel time is minimal at MPRs above 30%. However, as reaction time decreases, MPRs beyond 30% begin to provide improved performance. Similar results were found by Talebpour et al. (40) using a different traffic modeling framework.

---

[*] Portions of this chapter were part of a paper submission by Cazares et al. (*44*) which was peer reviewed by the Transportation Research Board and presented at the 96th Annual Meeting in Washington, D.C.

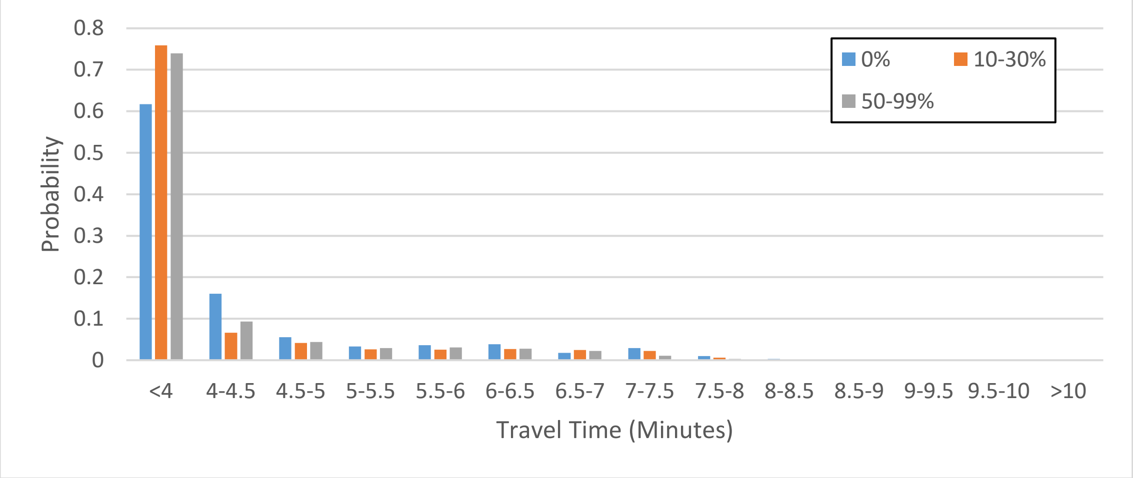


(a)

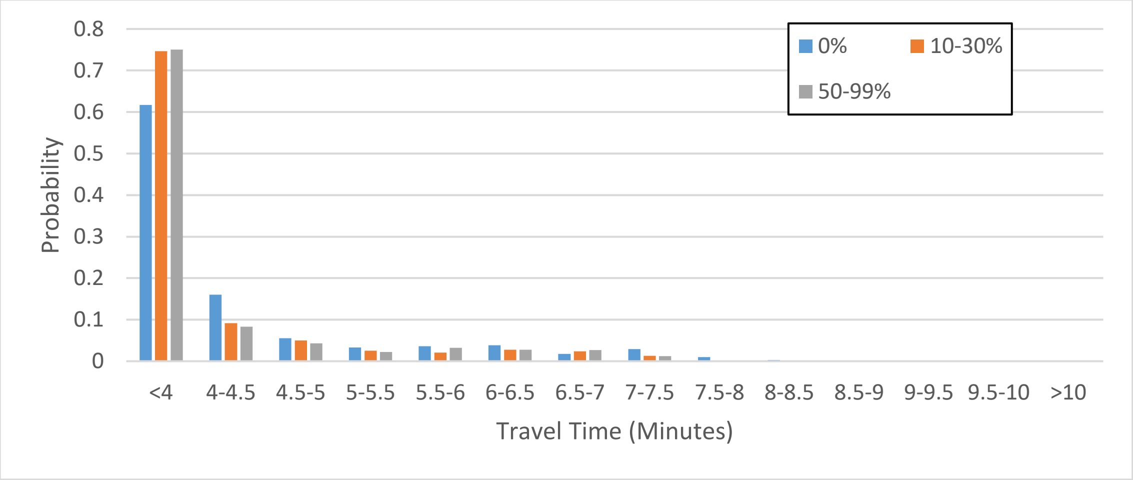


(b)

FIGURE 5. Travel Time Distribution Frequencies for Different Market Penetration Rates of Connected Vehicles with Different Reaction Times, (a) 2 seconds, (b), 1.5 seconds, (c) 1 second, and (d) 0.5 second.



(c)



(d)

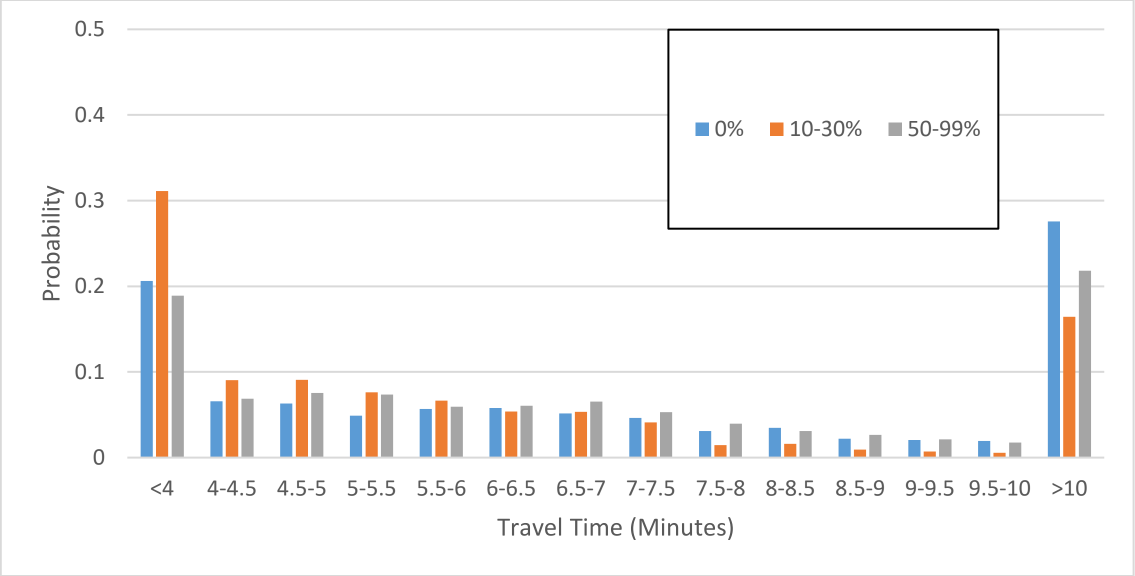
FIGURE 5. Continued.

Case 2A: Incident, No Rerouting

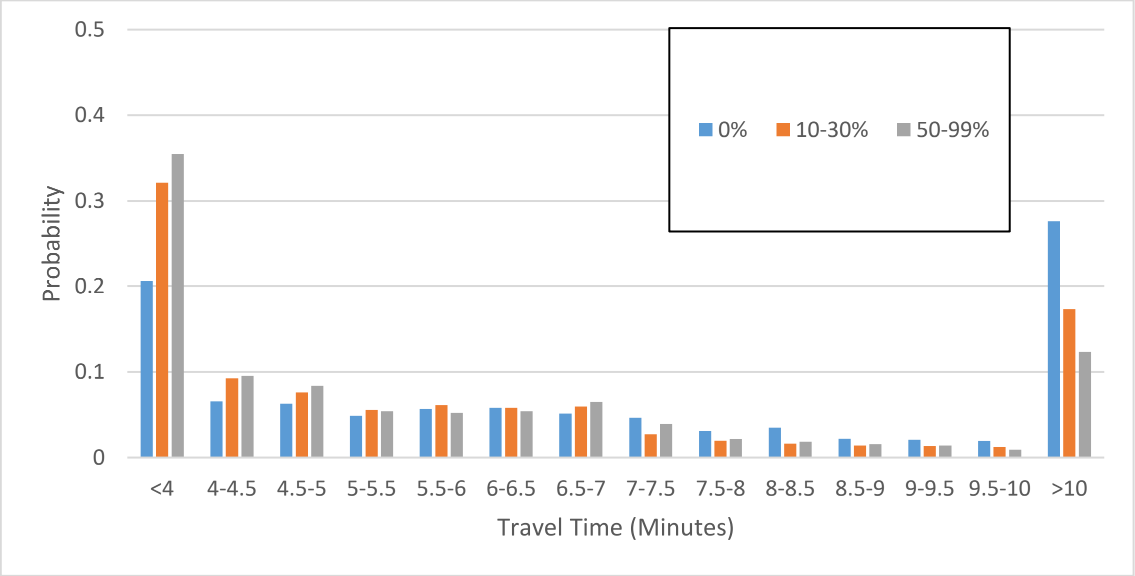
The second simulation case also modeled various penetration rates. Differing from the first, an incident was inserted at a four-lane southbound segment of the US 75, resulting in the closure of the two leftmost lanes for 33 minutes. Rerouting strategies remained inactive for this case. Figure 6 shows resulting travel time distributions for each market penetration rate at each tested reaction time. The TT_{avg} for vehicles at 0%

MPR is slightly over 10 minutes, with a substantial number of travelers experiencing over 10 minutes on a trip that is ideally 4 minutes long on average.

The results indicate that, as seen previously in Case 1, the probability that drivers will experience travel times at or below 4 minutes increases as the reaction time decreases. Furthermore, MPRs below 50% show enhanced performance with 2 seconds reaction time, while MPRs above 50% provided more ideal performance for all lower reaction times. Particularly, the 50%-99% MPR range where CVs each operate with a 0.5 second reaction time allowed 49.5% of CVs to experience travel times below 4 minutes despite the closure of two lanes. All tested reaction times and MPRs provide travelers with a reduced probability of traveling over 10 minutes. Based on the results of Case 1 and Case 2A alone, it is possible for travelers to benefit from V2I capabilities even without rerouting strategies in place, with notable benefits being obtained even at lower market penetration rates during an incident.

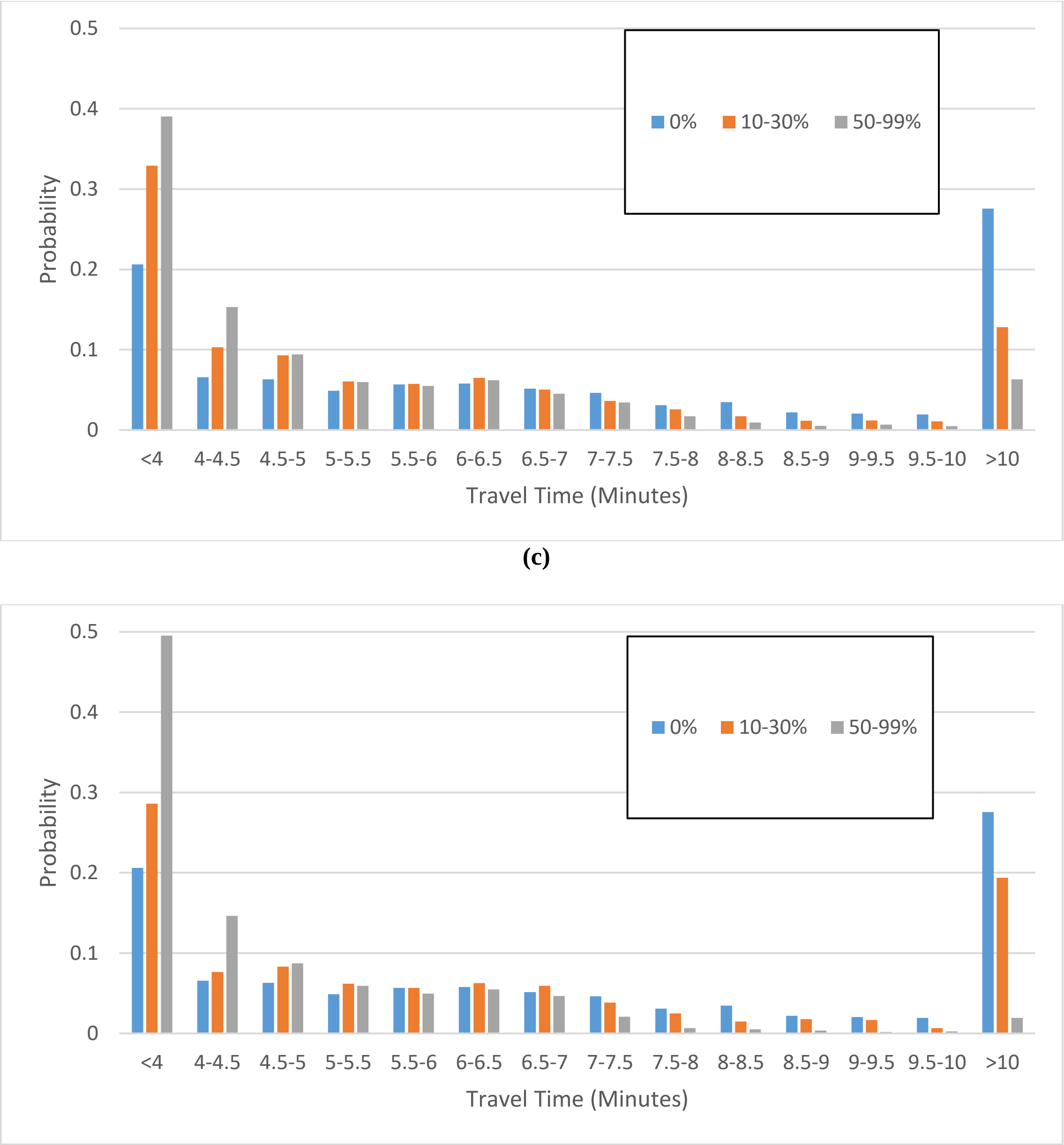


(a)



(b)

FIGURE 6. Travel Time Distribution Frequencies for Different Market Penetration Rates of Connected Vehicles with Different Reaction Times When an Accident Occurs, (a) 2 seconds, (b), 1.5 seconds, (c) 1 second, and (d) 0.5 second.



(c)

(d)

FIGURE 6. Continued.

The change in travel time over the simulation run was recorded. Figure 7 compares the average results obtained from the range of reaction times which were tested for MPRs between 10% and 30%. As mentioned previously, the incident begins at

2 minutes into the simulation's run and ends after 35 minutes. For a case simulating only NCVs (reaction time 2.0 seconds), the travel time beings to steadily increase after eight minutes of blockage for the remainder of the incident's duration. The largest travel time occurs at 34 minutes into the simulation (32 minutes after the lanes become blocked) with a value of 16.5 minutes. Simulation of varying reaction times for connected vehicles reveals that even when drivers maintain reaction times of 2.0 seconds, the maximum travel time will remain under ten minutes. Additionally, as reaction times decrease from 2.0 seconds to 0.5 second, the amount of time during which travel times over 6 minutes are experienced is reduced by 18 minutes. Furthermore, the recovery time after the lanes are cleared becomes shorter with decreasing reaction time.

Figure 8 compares the average results obtained from the range of reaction times which were tested for MPRs between 50% and 99%. For this range of MPRs, simulation of all but one of the tested reaction times resulted in travel times no greater than 6 minutes. Two observations are made regarding the results displayed in Figure 6. Firstly, although the results from runs using reaction times of 2.0 seconds indicate a successful reduction in experienced travel time, it fails to perform as well after the lanes have been cleared. Secondly, the results from 0.5 second reaction time runs experience minimum effects to none at all from the incident. The results displayed in Figures 7 and 8 help to support the earlier claim which stated that it is possible for travelers to gain some benefit from V2I capabilities even without implementing any rerouting strategies.

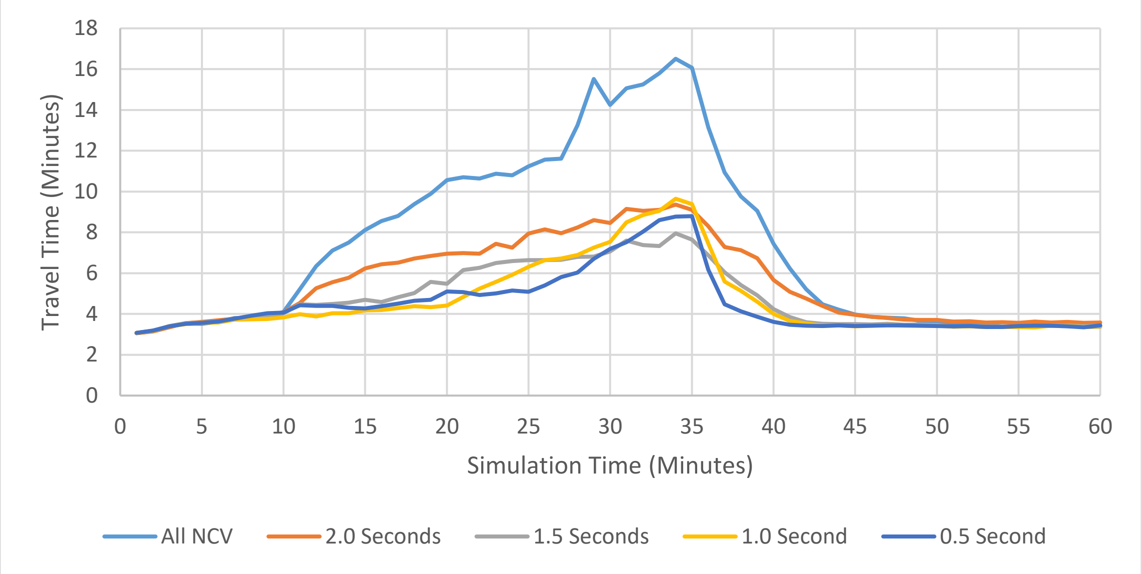


FIGURE 7. Travel Time vs Simulation Time (MPR 10%-30%).

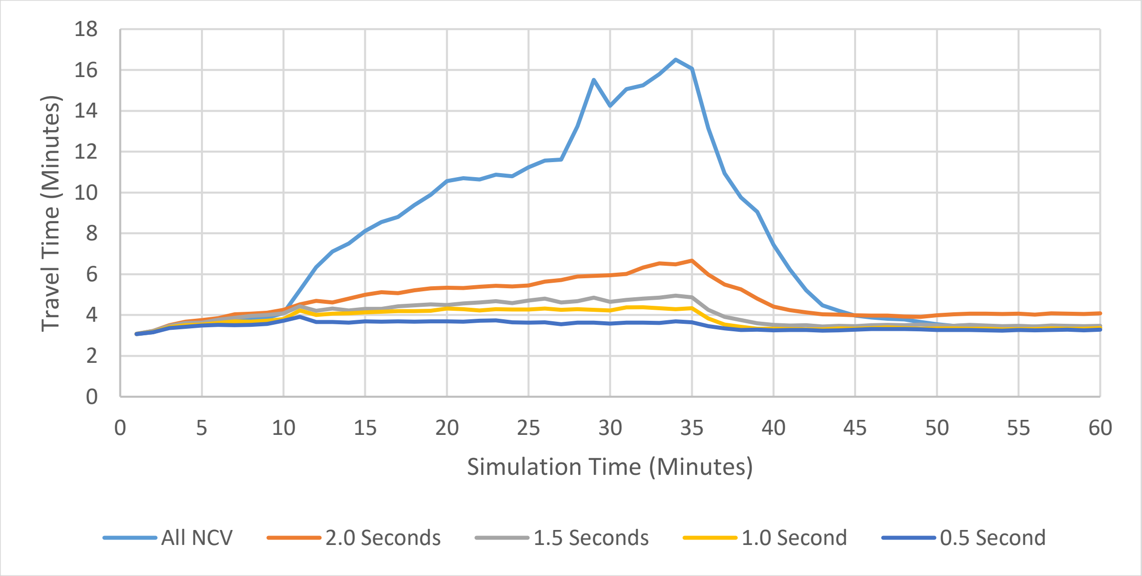


FIGURE 8. Travel Time vs Simulation Time (MPR 50%-99%).

Cases 2B-2F: Incident, Rerouting Active

The five rerouting strategies are implemented during the incident. Figure 9 shows the TT_{avg} values of Case 1 and Cases 2A-F using a reaction time of 2.0 seconds. The results indicate that strategies C and D (warning at 336 m upstream of the incident, with prompted lane changes for the leftmost and two leftmost lanes, respectively) yield the lowest TT_{avg} for CVs. While these strategies also reduce the TT_{avg} for NCVs compared to Case 2A, these values did not drop below 7 minutes, with the exception of strategy C at 75% MPR. With regards to the greatest decrease in TT_{avg} for NCVs, strategy E (warning at 1609 m upstream of the incident) performed best, decreasing TT_{avg} to just over 5 minutes at 99% MPR. There does not appear to be any substantial benefits to be gained from increasing MPRs past 25% as previously suggested by Paikari *(27 and 28)*. A trend worth noting is the increase in average travel time for all vehicles during normal conditions (the blue line below the rest). This was observed to occur as a result of the lane changing behavior of CVs. The parameters of the lane changing models for all vehicles were left unchanged and not examined in this study.

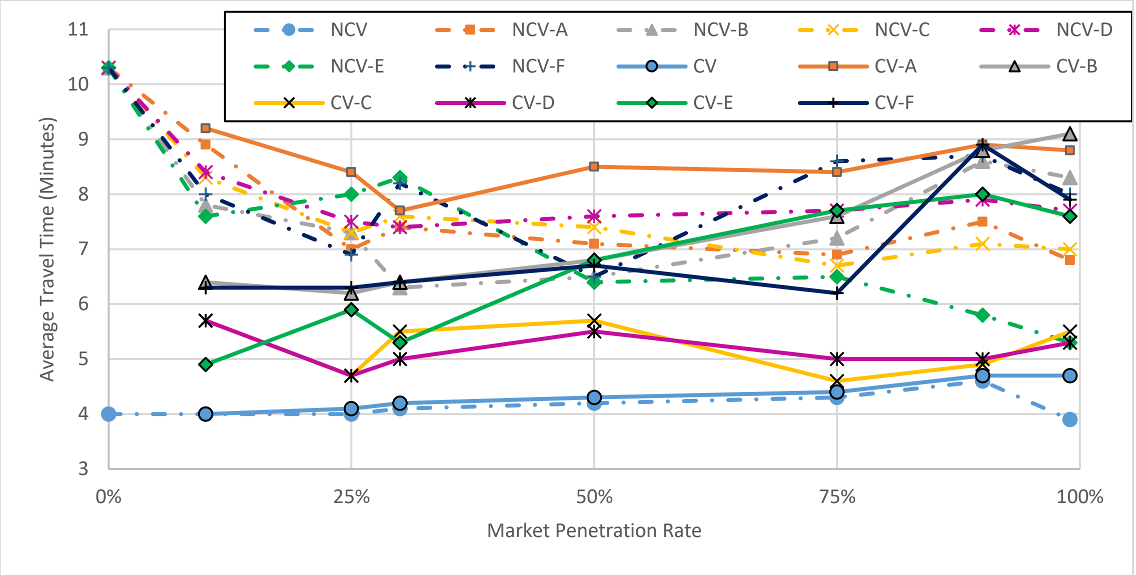
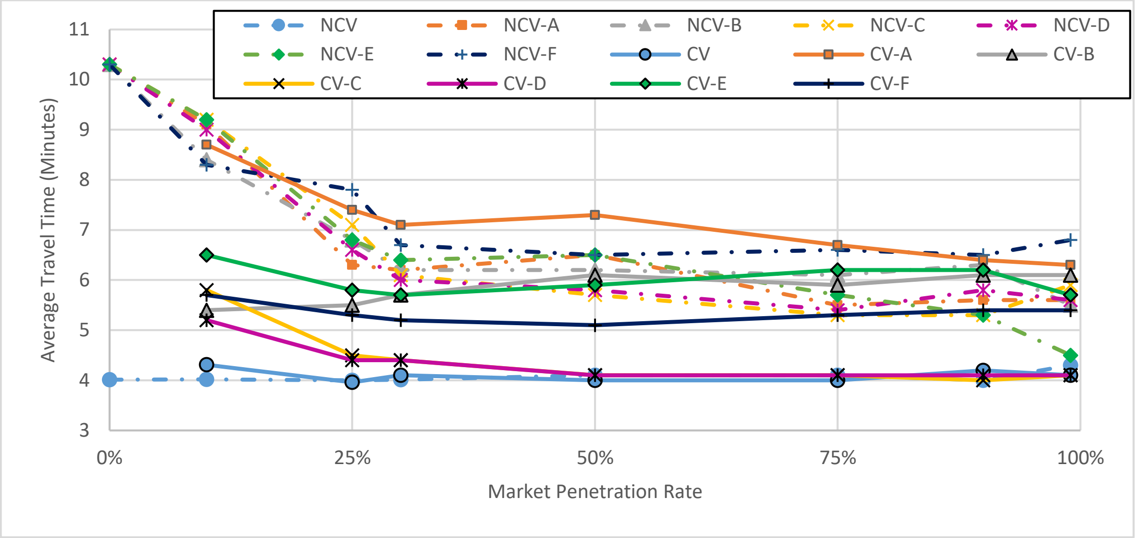
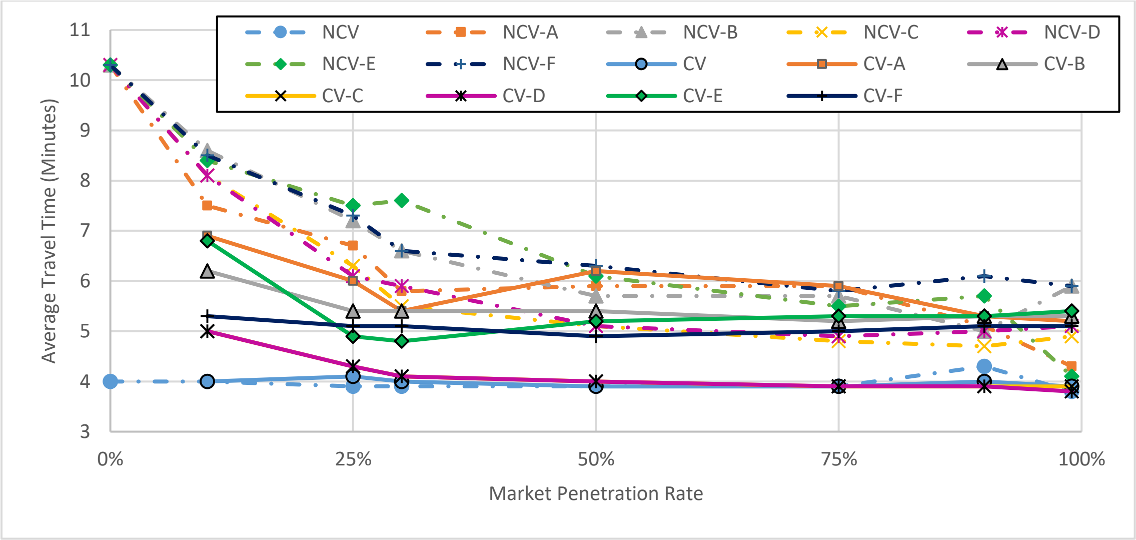


FIGURE 9. Average Travel Times for All Market Penetration Rates Pertaining to 2.0 sec Reaction Time. NCV, NCV-A, B, C, D, E, and F refer to Non-Connected Vehicles (Case 1), Non-Connected Vehicles (Case 2A, B, C, D, E, and F) respectively. Similarly, CV, CV-A, B, C, D, E, and F refer to Connected Vehicles (Case 1), Connected Vehicles (Case 2A, B, C, D, E, and F) respectively.

The TT_{avg} vs MPR for 1.5, 1.0, and 0.5 reaction times are shown in Figure 10. Unlike the sporadic TT_{avg} pattern seen for strategies using reaction times of 2.0 seconds, TT_{avg} values for reaction times of 1.5 seconds and lower generally decrease until reaching 30% MPR. Rates beyond 30% typically maintain a consistent TT_{avg} which may only change again at 90% or 99% MPR. For the three different reaction times, strategies C and D once again provided the lowest TT_{avg} values for CVs. Unlike what was seen previously, strategies C and D also resulted in the lowest TT_{avg} for NCVs. At 99% MPR, however, strategy E once more provided the lowest TT_{avg} for NCVs. Overall, as reaction time decreases the TT_{avg} tends to decrease, the performances of the rerouting strategies become increasingly similar, and NCV TT_{avg} can be halved of what is experienced during an accident.

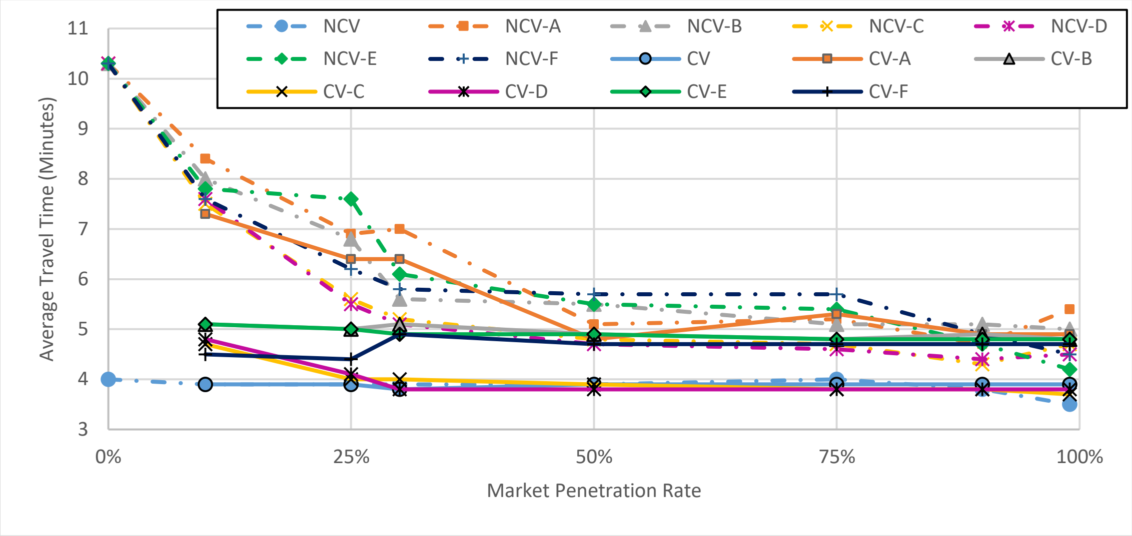


(a)



(b)

FIGURE 10. Average Travel Times for All Market Penetration Rates Pertaining to Reaction Time, (a) 1.5 sec Reaction Time, (b) 1.0 sec Reaction Time and (c) 0.5 sec Reaction Time. Abbreviations are same as for Figure 9.



(c)

FIGURE 10. Continued.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS*

This study utilized microscopic simulations to predict how the introduction of connected vehicles and DSRC technology may impact an existing urban corridor using actual traffic volume data during a morning peak hour. This study investigated the effectiveness of a queue-warning application by making use of various market penetration rates, reaction times, and rerouting strategies on connected vehicles. Building upon the findings in previous literature, this study assumes that the market penetration rate reflects the percentage of connected vehicles receiving and complying with instructions. In addition, the literature has suggested that connected vehicle technology may be able to potentially reduce driver reaction times from being able to obtain real-time traffic information. The effect of this claim upon travel time has been investigated within this paper.

Within this study, the open-source simulation program SUMO was used to test various cases for the evaluation of the queue-warning application. Outputs from the simulations included travel time distribution, travel time vs simulation time, and average travel time vs market penetration rate. By creating travel time distributions and by comparing the changes in travel time over the simulation's run, it is possible to observe the effects that both market penetration rate and reaction time have on travelers during a

---

[*] Portions of this chapter were part of a paper submission by Cazares et al. (*44*) which was peer reviewed by the Transportation Research Board and presented at the 96th Annual Meeting in Washington, D.C.

simulated incident. Furthermore, by comparing the average travel time to the market penetration rate, conclusions may be drawn regarding combined effects of various market penetration rates, driver reaction times, and rerouting strategies upon the travel time through the corridor.

This chapter presents a summary of the results and findings of the study. Next, limitations of the study are discussed. Finally, directions for future research are provided.

Findings

This study's results indicate that even without rerouting strategies being implemented, connected vehicle technology can potentially reduce the average travel time during an incident. Observation of the changes in travel time over the simulation's run time reveals that it is possible to achieve lower travel times even with low market penetration rates and larger reaction times during an incident. Moreover, as the presence of connected vehicles becomes more prominent at penetration rates of 30% and 50%, the average travel time for travelers on a corridor such as US 75 can be expected to decrease and possibly reach average travel time values within a minute of non-incident conditions for market penetration rates beyond 30%. Simulation of connected vehicles with lower reaction times were also performed and the results displayed a decrease in average travel time along the freeway corridor. As reaction times decreased, the performance of rerouting strategies became increasingly similar, and the average travel time values of non-connected vehicles could potentially be halved of what is experienced during an incident.

Comparisons between the various implemented rerouting strategies have been made. For all tested reaction times, Strategies C (combination of rerouting and lane change from leftmost lane) and D (combination of rerouting and lane change from two leftmost lanes) yielded the lowest average travel times for drivers of connected vehicles. Additionally, when connected vehicle drivers are assumed to have reaction times of 2.0 seconds, Strategies C and D were the only strategies that did not increase significantly at higher market penetration rates. The results of Strategies C and D reveal two details which will be discussed. Firstly, warning drivers and providing the suggestion to reroute immediately upstream of the incident (within 336 m or 1102 ft) can provide lower average travel times than warning them further upstream. Second, when compared to Strategy B, which did not include any suggested lane changes during the simulated incident, the results clarify the impact of creating a queue-warning application which is capable of suggesting lane changes to drivers in addition to alternate routes when necessary.

With respect to non-connected vehicles, average travel times may be reduced even at a market penetration rate of 10% and with connected vehicle driver reaction times of 2.0 seconds. The average travel times of non-connected vehicles tended to be lower when connected vehicles abided by Strategies C and D for all market penetration rates except at the largest market penetration rate tested. At 99%, non-connected vehicles experience greatly reduced average travel time when connected vehicles abide by Strategy E where they are warned further upstream than in Strategies C and D. This trend is observed through all tested reaction times, with its cause not yet being fully understood.

Limitations

The limitations of this study are as follows:

- No consideration was given to the effect of the signalized diamond interchanges upon the rerouting strategies. In reality, without a way of providing vehicles with real-time information regarding traffic signal timings, it is possible that the suggested route may not provide any travel time savings, depending on what point in the signal's cycle the vehicle arrived.
- Lane changing behavior within SUMO was not considered. It is likely that the lane changing behavior of each vehicle type used could potentially affect the results based on their respective parameters.
- The simulation did not use actual connected vehicle data. Thus, the results of this study are at best approximations of potential behavior of connected vehicles.
- Connectivity is assumed within the simulation. A network simulator was not utilized to create actual connections to vehicles and roadside devices. Therefore, the possibility of dropped communication is ignored.

- 100% compliance of all connected vehicles to the rerouting strategies is assumed. In actuality, not all drivers will heed the suggestion provided to them.

Future Research

This study could be enhanced by conducting future work that touches upon the following details:

- Including a vehicle platooning system such as cooperative adaptive cruise control. A system which can maintain speed and distance to a leading vehicle while also providing the driver with up-to-date information about their environment may be worthwhile of investigation.
- The simulation of variable speed limits in combination or independent of the rerouting strategies presented in this study. Connected vehicle technology provides the potential to reach a larger portion of drivers than variable message signs.
- The inclusion of autonomous vehicles within the simulation. With autonomous vehicles being predicted to enter the traffic stream in the upcoming years, it would be advantageous for agencies and researchers alike to further understand the expected effects they may have.

REFERENCES

1. Ford Motors. Ford Teams With Pivotal To Speed Development of Connected Car Experiences Capitalizing On New Ford Sync Connect *https://media.ford.com/content/fordmedia/fna/us/en/news/2015/12/15/ford-teams-with-pivotal-to-speed-development-of-connected-car.html*. Accessed Jul. 28, 2016.
2. Korosec, K. (2016) Toyota Is Turning This City Into a Giant Connected Car Experiment http://fortune.com/2016/04/14/toyota-connected-car-experiment/. Accessed Jul. 27, 2016.
3. General Motors. Cadillac to Introduce Advanced 'Intelligent and Connected' Vehicle Technologies on Select 2017 Models http://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2014/Sep/0907-its-overview.html. Accessed Jul. 27, 2016.
4. Federal Register. Federal Motor Vehicle Safety Standards: Vehicle-to-Vehicle (V2V) Communications Federal Register Vol. 79, No. 161, Accessed Jul. 28, 2016.
5. United States Department of Transportation. *Automated and Connected Vehicles: Current State of the Practice*, Accessed Jul. 27, 2016
6. Gartner. Gartner Says By 2020, a Quarter Billion Connected Vehicles Will Enable New In-Vehicle Services and Automated Driving Capabilities *http://www.gartner.com/newsroom/id/2970017*. Accessed Jul. 28, 2016
7. Mounce, J. M., G.L. Ullman, G. Pesti, and V Pezoldt. Guidelines for the evaluation of dynamic message sign performance. No. FHWA/TX-07/0-4772-1, 2007.

8. Krumnow, M. and A. Kretschmer. Real-Time Simulations Based on Live Detector Data–Experiences of Using SUMO in a Traffic Management System." *Simulation of Urban MObility User Conference*. Springer Berlin Heidelberg, 2013.

9. Rathi, V. Assessment of impact of dynamic route guidance through variable message signs. Diss. Massachusetts Institute of Technology, 2007.

10. Schaefer, L., J. Upchurch, and S. A. Ashur. An evaluation of freeway lane control signing using computer simulation. *Mathematical and Computer Modelling* 27.9, 1998, pp. 177-187.

11. Walton, C. M., K. Persad, Z. Wang, K. Svicarovich, A. Conway, and G. Zhang. Arterial Intelligent Transportation Systems—Infrastructure Elements and Traveler Information Requirements (No. FHWA/TX-10/0-5865-1), 2009.

12. Wang, Y., Chang, H., & Ioannou, P. A. (2009). Lane Change Guidance for Freeway Incident Management. *IFAC Proceedings Volumes*, *42*(15), 7-11.

13. Samad, T., and Annaswamy, A. M. The Impact of Control Technology. *IEEE Control Systems Society*, 2011.

14. Dey, K. C., A. Rayamajhi, M. Chowdhury, P. Bhavsar, and J. Martin. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication in a heterogeneous wireless network–Performance evaluation. *Transportation Research Part C: Emerging Technologies*, *68*, 2016, pp. 168-184.

15. Talebpour, A., and H. S. Mahmassani. Influence of Autonomous and Connected Vehicles on Stability of Traffic Flow. *Transportation Research Board 94th Annual Meeting*. No. 15-5971, 2015.

16. Wang, H., W. Quan, Y. Wang, and X. Liu. Modeling of Safe Driving Distance on the Basis of Vehicle-to-Vehicle Communication. *Transportation Research Record: Journal of the Transportation Research Board*, (2381), 2013, pp. 28-35.
17. Jin, P., D. Yang, B. Ran, M. Cebelak, C. Walton. Bidirectional Control Characteristics of General Motors and Optimal Velocity Car-Following Models: Implications for Coordinated Driving in a Connected Vehicle Environment. *Transportation Research Record: Journal of the Transportation Research Board*, (2381), 2013, pp. 110-119.
18. Jin, I. G. and G. Orosz. Dynamics of connected vehicle systems with delayed acceleration feedback. *Transportation Research Part C: Emerging Technologies*, 2014, pp. 46-64.
19. Talebpour, A., H. S. Mahmassani, and S. Hamdar. Multiregime Sequential Risk-Taking Model of Car-Following Behavior: Specification, Calibration, and Sensitivity Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, (2260), 2011, pp. 60-66.
20. Talebpour, A. and H. S. Mahmassani. Modeling Acceleration Behavior in a Connected Environment. In *Midyear Meetings and Symposium Celebrating 50 Years of Traffic Flow Theory, Portland OR*, 2014.
21. Goodall, N. J., B. Smith, B. Park. Microscopic estimation of freeway vehicle positions from the behavior of connected vehicles. *Journal of Intelligent Transportation Systems*, *20*(1), 2016, pp. 45-54.

22. Abdulhai, B. and H. Look. Impact of Dynamic and Safety-Conscious Route Guidance on Accident Risk. *Journal of Transportation Engineering*, *129*, 2003, pp. 369-376.

23. Lee, J., and B. Park. Evaluation of route guidance strategies based on vehicle-infrastructure integration under incident conditions. *Transportation Research Record: Journal of the Transportation Research Board*, (2086), 2008, pp. 107-114.

24. Kattan, L., M. Moussavi, B. Far, C. Harschnitz, A. Radmanesh, and S. Saidi. Evaluating the potential benefits of vehicle to vehicle communication (V2V) under incident conditions in the PARAMICS model. *Proceedings of the 13th International IEEE Conference on Intelligent Transportation, Madeira, Portugal* (Vol. 9), 2010.

25. Mei, B., H. Hu, N. Rouphail, and J. J. Lee. Simulation model for studying impact of vehicle-to-vehicle wireless communications on traffic network operations. *Transportation Research Record: Journal of the Transportation Research Board*, (2189), 2010, pp. 107-115.

26. Yeo, H., S. Shladover, H. Krishnan, and A. Skabardonis. Microscopic traffic simulation of vehicle-to-vehicle hazard alerts on freeway. *Transportation Research Record: Journal of the Transportation Research Board*, (2189), 2010, pp. 68-77.

27. Rim, H., C. Oh, K. Kang, and S. Kim. Estimation of lane-level travel times in vehicle-to-vehicle and vehicle-to-infrastructure-based traffic information system. *Transportation Research Record: Journal of the Transportation Research Board*, (2243), 2011, pp. 9-16.

28. Paikari, E., L. Kattan, S. Tahmasseby, and B. Far. Modeling and simulation of advisory speed and re-routing strategies in connected vehicles systems for crash risk and travel time reduction. *Electrical and Computer Engineering (CCECE), 2013 26th Annual IEEE Canadian Conference on*, 2013, pp. 1-4.
29. Paikari, E., S. Tahmasseby, and B. Far. A simulation-based benefit analysis of deploying connected vehicles using dedicated short range communication. *2014 IEEE Intelligent Vehicles Symposium Proceedings*, 2014, pp. 980-985.
30. Pan, J., I. S. Popa, K. Zeitouni, and C. Borcea. Proactive vehicular traffic rerouting for lower travel time. *IEEE Transactions on vehicular technology* 62.8, 2013, pp. 3551-3568.
31. Olia, A., H. Abdelgawad, B. Abdulhai, and S. N. Razavi. Assessing the potential impacts of connected vehicles: mobility, environmental, and safety perspectives. *Transportation Research Board 93rd Annual Meeting* (No. 14-2348), 2014
32. Smith, D., S. Djahel, and J. Murphy. A SUMO based evaluation of road incidents' impact on traffic congestion level in smart cities. *Local Computer Networks Workshops (LCN Workshops), IEEE 39th Conference*. IEEE, 2014.
33. Backfrieder, C., G. Ostermayer, C. F. Mecklenbräuker. Increased Traffic Flow Through Node-Based Bottleneck Prediction and V2X Communication, 2016
34. Dowling, R., B. Nevers, A. Jia, A. Skabardonis, C. Krause, and M. Vasudevan. Performance benefits of connected vehicles for implementing speed harmonization. *Transportation Research Procedia* 15, 2016, pp. 459-470.

35. Behrisch, M., L. Bieker, J. Erdmann, and D. Krajzewicz. SUMO–simulation of urban mobility: an overview. *Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation*. ThinkMind, 2011.

36. Wegener, A., Piórkowski, M., Raya, M., Hellbrück, H., Fischer, S., & Hubaux, J. P. (2008, April). TraCI: an interface for coupling road traffic and network simulators. In *Proceedings of the 11th communications and networking simulation symposium* (pp. 155-163). ACM.

37. Krauss, S. Microscopic modeling of traffic flow: Investigation of collision free vehicle dynamics. Doctoral dissertation, Universitat zu Koln, 1998

38. Treiber, M., A. Hennecke, and D. Helbing. Congested traffic states in empirical observations and microscopic simulations. *Physical Review E,62*(2), 1805, 2000

39. Talebpour, A. Modeling driver behavior in a connected environment: Integration of microscopic traffic simulation and telecommunication systems, Doctoral dissertation, Northwestern University, 2015.

40. Talebpour, A., H. S. Mahmassani, and F. E. Bustamante. Modeling Driver Behavior in a Connected Environment: Integrated Microscopic Simulation of Traffic and Mobile Wireless Telecommunication Systems. *Transportation Research Board 95th Annual Meeting*. No. 16-2540. 2016.

41. Chen, P., K. Srinivasan, and & Mahmassani, H. S. Effect of information quality on compliance behavior of commuters under real-time traffic information. *Transportation Research Record: Journal of the Transportation Research Board*, (1676), 1999, pp. 53-60, 1999.

42. Muizelaar, T. and B. van Arem. Drivers' preferences for traffic information for nonrecurrent traffic situations. *Transportation Research Record: Journal of the Transportation Research Board*, pp. 72-79, 2007.
43. Elfar, A., A. Talebpour, and H. S. Mahmassani. Analyzing Queue Warning in Connected Environment: A Micro Simulation Approach. In *Transportation Research Board 95th Annual Meeting* (No. 16-4841), 2016.
44. Cazares, J. G., Talebpour, A., & Rajbhandari, R. Analyzing the Benefit of Widespread use of V2I Communication for Improving Incident Management at a Congested Urban Corridor (No. 17-05164), 2017.