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To the University of Wyoming:

The members of the Committee approve the Thesis of Eric Adomah presented on 12/19/2019.

Dr. Mohamed M. Ahmed, Chairperson

Dr. Ken Gerow, Outside Member

Dr. Milan Zlatkovic

APPROVED:

Anthony S. Denzer, Department, Division, or Program Chair, Department Head of Civil and Architectural Engineering.

Cameron H. G. Wright, College Dean/Provost

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Adomah, Eric, Safety Evaluation of Driver Behavior Adaptations in Connected Vehicle Environment Using Microsimulation Modeling, M.S., Department and Civil and Architectural Engineering, May,2020.

A major factor in traffic safety is driver behavior and adaptation to roadway systems. The variability in driver behavior expressed on a roadway may affect traffic safety in terms of exposure and risk. On a low volume road with relatively high speeds and large distance headways, there is bound to be high variability in driver behavior, in terms of the chosen desired speed. The associated fewer traffic interactions on low volume highways may lead to the lack of driver awareness to imminent dangers which can often result in multi-vehicle and severe crashes. Connected Vehicle (CV) technology upon full deployment is projected to improve driver behavior by increasing driver situational awareness. Connected Vehicle applications in the form of Traveler Information Messages (TIMs) in work zones and adverse through Infrastructure to Vehicle communications could decrease driver behavior variability.

This study is premised on the Wyoming Connected Vehicle Pilot Program sought to evaluate the effect the CV technology will have on the driving environment including mixed vehicle interaction of CV and non-CV vehicles using microsimulation modeling and a driving simulator based study. Microsimulation modeling using PTV VISSIM software provided the framework to evaluate the safety benefits associated with CV applications on the Wyoming I-80 corridor. Consequently, the overarching goal of the study was to 1) Quantify the effectiveness or impact of the Wyoming Connected Vehicle applications from a safety perspective on a rural roadway (Wyoming I-80) in a work zone and foggy weather conditions, 2) Identify the benefits of using driving simulator data for model calibration and validation, and 3) Evaluate how confounding

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factors such as the Market Penetration Rate of CV will impact the successful deployment and operations of the pilot project.

The study evaluated four different CV scenarios including 5, 15, 20, and 30 percent Market Penetration rate of CV plus a baseline scenario. The microsimulation model showed that the incorporation of CVs on the freeway would generally decrease traffic conflicts. Most conflicts occurred in the advance warning area of the work zone which had more than 50 percent of conflicts. However, the conflicts decreased as MPR increases, with a 21 percent reduction at 30 percent MPR in comparison with baseline conditions. Results also showed that the mean TTC increased as the market penetration rate increases. At the 30 percent MPR the mean TTC was 1.4 seconds as compared to a value of 0.61 seconds for baseline scenario which is a 53 percent increase in mean TTC. Regarding percentage change in PET risk, the risk decreased by 48 and 55 percent respectively in the 20 and 30 percent MPR compared to 13 percent in the baseline scenario. The 30 percent MPR of CV is important to the Wyoming CV pilot because the focus of the pilot is on heavy trucks that comprise 30 percent of the traffic composition. Hence, the full MPR of connected trucks has the potential to substantially reduce the crash risk at work zones.

Moreover, for a low volume rural highway, the effect of CV MPR will not be explicitly translated in the driver behavior except during high MPRs. At the 20 and 30 percent MPRs, CVs showed the capability to enhance speed behavior through speed harmonization in the work zone. Findings indicated that the standard deviation of speed significantly decreased as MPR of CVs increased. The standard deviation of speed is higher in the advance warning area and the upstream section as drivers continue to drive in the foggy conditions compared to other sections of the work zone.

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SAFETY EVALUATION OF DRIVER BEHAVIOR ADAPTATIONS IN CONNECTED VEHICLE ENVIRONMENT USING MICROSIMULATION MODELING

By

Eric Adomah

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DEDICATION

This research work is dedicated to the Almighty God who holds all knowledge and to everyone who has been part of my life journey.

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LIST OF ACRONYMS

Acronym	Description
ARTS	Advanced Rural Transportation Systems
API	Application Programming Interfaces
AV	Autonomous Vehicle
CVI	Connected Vehicle Infrastructure
CV	Connected Vehicle
CVO	Commercial Vehicle Operations
CDBA	Continuous Driver Behavior Adjustment
DSRC	Dedicated Short-range Communications
FHWA	Federal Highways Administration
FCW	Forward Collision Warning
HMI	Human-Machine Interface
I-80	Interstate 80
ITS	Intelligent Transportation Systems
IVI	Intelligent Vehicle Initiative
MAPE	Mean Absolute Percentage Error
MPR	Market Penetration Rate
NHTSA	National Highway Traffic Safety Administration
PET	Post Encroachment Time
RSU	Roadside Unit
SSAM	Surrogate Safety Assessment Model
SMoS	Surrogate Measure of Safety
TTC	Time-to-Collision
TIM	Traveler Information Message
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WHO	World Health Organization
WYDOT	Wyoming Department of Transportation

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CHAPTER ONE: INTRODUCTION

1.1 Background

Transportation systems have evolved throughout time, from the 18^{th} century when mechanization became an integral component of the industrial revolution and human advancement to new paradigms in connected and autonomous vehicles. The Transportation system elements including road environment, infrastructure, vehicles continue to be vital for a productive society. In an economic sense, quality transportation systems are vital to a country's economic growth. However, maintaining traffic safety and mobility remains a significant concern in the transportation field. Road crashes annually claim nearly 1.25 million lives, with a projected global cost of USD 518 billion, according to the World Health Organization (WHO)(World Health Organisation, 2015). The NHTSA 2018 annual report on crashes indicated a total of 33,654 fatalities across all states in the US. Concerning the state of Wyoming, a value of 21.23 fatalities per 100,000 population has been recorded compared to 11.40 national value making traffic safety an urgent concern for the state (National Highway Traffic Safety Administration, 2019).

A major factor in traffic safety is driver behavior and adaptation to roadway systems. Studies have estimated that drivers account for about 94 percent of all road crashes (Singh, 2018). The variability in driver behavior expressed on a roadway may affect traffic safety in terms of exposure, risk, and consequence, as described by (Nilsson, 2004a). Driver behavior adaptation to new technologies and safety features has been a subject that researches seek to gain more knowledge. A synthesis of the literature has shown that adverse weather conditions and work zones are factors that increase variabilities in driver behavior, thereby increasing crash risk. Adverse weather conditions, including reduced visibility, snowy and rainy conditions present unusual patterns in driver behavior, thus leading to an increase in crash risk. A ten-year National Highway Traffic

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Safety Administration (NHTSA) data analyzed from 2007 to 2016, revealed that on average, 21 percent of annual crashes are weather-related, and 16 percent of all fatal crashes are weather-related(Federal Highway Administration., 2019). A study in Canada revealed that traffic collisions increased by 75 percent, corresponding to 45 percent in related injuries due to precipitation compared to normal conditions (Andrey et.al, 2003), making adverse weather experienced on roadways a global concern.

Furthermore, driver behavior and adaptation to changing roadway conditions and lane restrictions like a work zone remain critical to roadway safety. With most DOTs committed to maintenance and rehabilitation strategies, work zones continue to be predominant in our roadway system. Although there are guidelines and technologies for active management of work zones, they still pose a risk to drivers and workers. A comparison of severity and crash frequency between work zones to non-work zones indicated that the presence of work zones increases the likelihood of crash occurrence by 16.8 percent on highways (Garber and Woo, 1990; Kapitanov, 2017). The total number of work zone related crashes increased to 96,626 in 2015, culminating in 25,484 injuries and 642 fatalities (Federal Highway Administration, 2018). One primary concern in work zone active management is how to decrease the variability in driver speed behavior in the work zone.

Given these concerns, the FHWA has initiated several Intelligent Transportation Systems (ITS) based research programs (United States Department of Transportation, 2019). One such area involves the implementation of CV technology. This new paradigm shift is expected to annually prevent 439,000 to 615,000 crashes at full Vehicle-to-Vehicle (V2V) communication adoption (National Highway Traffic Safety Administration, 2016). Connected Vehicles (CV) Infrastructure to Vehicle (I2V) technology provides real-time information including work zone and weather

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information that will allow drivers to become more aware of their surrounding traffic conditions, thereby, enhancing driver behavior. However, to adequately assess the full benefits of CV technologies during the deployment and operational stage, it is imperative to proactively test the system.

Unfortunately, traditional methodologies are limited by the lack of real-world data. Therefore, there is a need for a comprehensive simulation framework to model driver behavior in a connected driving environment. In comparison with the traditional approaches that require a large sample size of traffic performance data under the CV environment, a well-calibrated microsimulation model can accurately and quickly test various CV strategies. The accurate and robust modeling of connected transportation environment, including driver behavior adjustments in such systems, is essential for designing, planning, and managing connected transportation systems. Also, since a microsimulation model can control for the confounding factors that may affect system performance, this provides a more credible environment for the comparison of system performance between the Pre- and Post-deployment periods. As such, driver behavior adaptation to CV applications and their effect on road safety and mobility can be accounted for in developing more efficient transportation management strategies.

1.2 Overview of Wyoming Connected Vehicle Pilot Program

Interstate 80 in Wyoming is a major freight corridor connecting the east and west in the U.S. One major characteristic of the corridor is the high truck volume which ranges from 30 to 55 percent of the total volume and can rise to as much as 70 percent during seasonal peaks. The elevations on the I-80 corridor in Wyoming are all above 600ft, with the highest point reaching 8640ft above sea level at Sherman Summit.

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In 2015, Wyoming was among the three states selected by the USDOT to pilot CV applications to improve safety and mobility on a 402-mile Interstate 80 (I-80) corridor. CV applications developed for the pilot program are pertinent to related conditions faced on I-80 in Wyoming. Systems and applications developed in the pilot will improve the situational awareness of drivers of connected vehicles. The components of the pilot system will include: 1) 75 roadside units (RSUs) with Dedicated Short-Range Communication (DSRC) that can transmit advisories and alerts to equipped vehicles along I-80, 2) CV applications that utilize vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) DSRC technologies, 3) Equip and operate a set of vehicles that are expected to be regular users of I-80, with on-board units (OBU) with DSRC connectivity. CV technology will enable communication of alerts and advisories regarding various road conditions to drivers. Also due to some new developments with the Federal Communications Commission (FCC), the deployment will include satellite communications. Phase 1(planning) of the pilot project was concluded by WYODOT in September 2016. The deployment Phase 2 (deployment) and Phase 3 (demonstration) are scheduled concurrently which began September 2018 (Gopalakrishna et al., 2016; Kitchener et al., 2018).

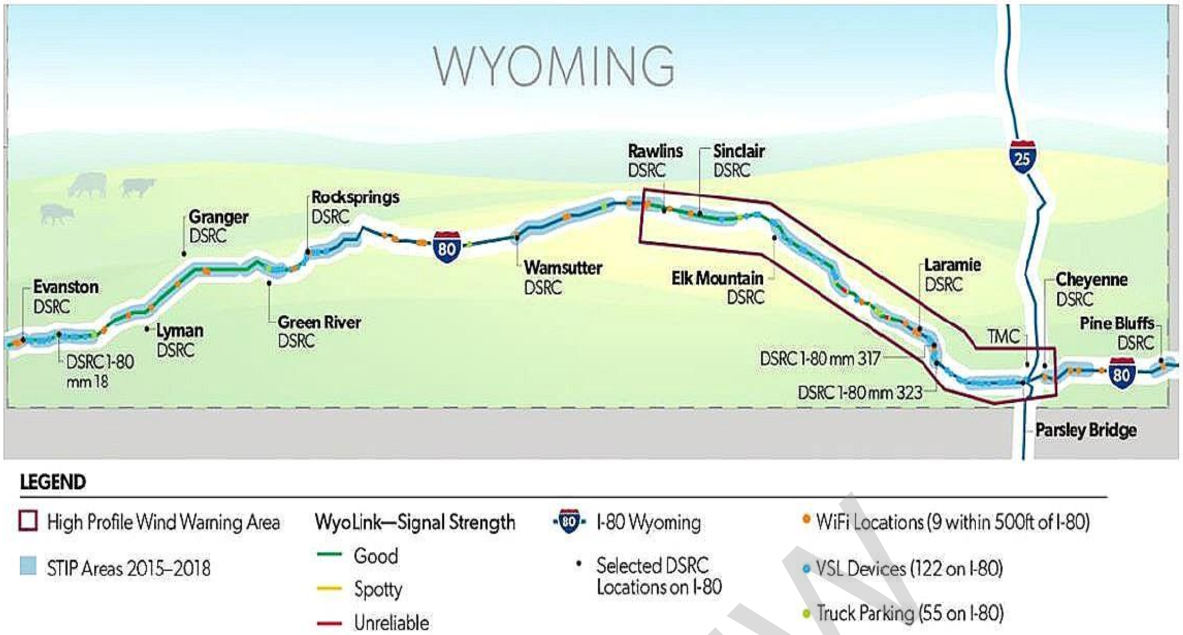

Figure 1. 1: Scope of Wyoming CV pilot deployment program (WYDOT, 2019)

1.3 Problem Statement

Wyoming I-80 corridor is affected by adverse winter weather events such as low visibility from blizzard, icy road surface, blowing snow for significant parts of the year, which resulted in fatalities, extended closures, and substantial economic loss (Wyoming Department of Transportation, 2019). Crash rates in winter (mid-October to mid-April) have also been found to be 3 to 5 times as high as the summer crash rates. Notwithstanding this, reduced visibility presented by foggy conditions poses an increase in crash risk in the summer and mostly in work zones. The expected benefits of the project revolve around objectives of improving safety, mobility, and productivity of the users of I-80 in Wyoming and neighbor states (Ahmed, M., Gopalakrishna, D., Garcia, 2016). These benefits are directly dependent on the CV applications that will be developed during the Wyoming CV Pilot; V2I applications in the form of Traveler Information Messages (TIMs) sent to vehicles, which will increase the situational awareness of drivers thereby warning them of imminent dangerous roadway conditions.

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Improved Driver behavior adaption through speed harmonization as well as a reduction in speed variations at work zones and adverse weather conditions could be a direct indication of the benefits of the CV system. However, modeling driver behavior and behavior adaptation to a new system are challenging as humans are complex entities in roadway systems and patterns in driver behavior are stochastic. From a broader perspective, it is imperative to access the operational benefits of CV technology in terms of safety. Simulation frameworks could, however, be an appropriate means to gain valuable insights into driver behavior adaptation to CV technology. Consequently, insights into the benefits of the implementation of the Wyoming CV pilot until real-life CV data become available, including the minimum significant Market Penetration Rate (MPR) to make CV beneficial can be quantified.

1.4 Research Approach and Modelling Framework

Simulation frameworks through microsimulation and driving simulator scenario modeling present a robust and effective platform to evaluate the safety and mobility benefits of CV applications. This thesis combined two simulation frameworks:1) driving simulator and 2) microsimulation modelling to evaluate driver behavior adaptations in a CV environment. In practice, driver speed adjustments in a CV environment from a driving simulator experiment is imputed in microsimulation models through a calibration process. Driver behavior models in microsimulation are based on the car following and lane changing behavior.

Furthermore, to quantify the safety impact of CVs during adverse weather conditions and work zones, the Surrogate Safety Assessment Model (SSAM) (Pu and Joshi, 2008) was used to evaluate the potential inherent conflicts induced by traffic interactions from the microsimulation model. The most used methods for safety performance assessment in simulation modeling have been

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based on the Surrogate Measure of Safety (SMoS). In this case, the Time-to-Collision, Post Encroachment Time (PET), and Modified Deceleration Rate to Avoid Crash (MDRAC) were predominantly used. Analysis of Variance (ANOVA) and t-tests was also used to compare the means of speeds for different CV scenarios.

1.5 Research Objectives

The objectives of the thesis are as follows:

- To quantify the effectiveness or impact of Connected Vehicle applications from safety and mobility perspectives on a rural roadway (Wyoming I-80) in a work zone and adverse weather conditions.
- To examine the benefits of Analysis, Modeling, and Simulation (AMS) to analyze driver behavior under a CV environment involving mixed vehicular traffic to determine the minimum CV penetration rate to gain safety benefits of the Wyoming Pilot Program.
- Explore the benefits of using driving Simulator data to internally calibrate and validate microsimulation models.

1.6 Research Tasks

- Effectively using Microsimulation modeling and Surrogate Safety Assessment to analyze the safety benefits of a CV ; minimum CV market penetration rate to have significant benefits
- Understanding driver behavior in a CV environment in rural work zones and adverse weather conditions using microsimulation modeling.

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1.7 Contributions

For a successful deployment of CV technology and, subsequently, its' ubiquitous influence on transportation systems, it is imperative to understand the pre and post effects of such disruptive technology. CV warning applications were tested in both adverse weather conditions and work zones. A methodology to quantify the effect of driver behavior in the CV environment in work zones and foggy weather conditions was developed with the help of data from a driving simulator study to calibrate CV behavior in VISSIM.

Overall, the analysis and evaluation of driver behavior adjustments in response to CV messages using microsimulation models provided insights into the safety and mobility impacts of CV deployment on a challenging rural roadway such as the I-80 in Wyoming. The analysis provided preliminary knowledge on the minimum Market Penetration Rate (MPR) to which we can expect significant safety benefits of CV warning applications on a rural highway.

1.8 Thesis Structure

The organization of this thesis is as follows: Chapter 2 provides a review of the literature on the latest advancements in CV technology. The chapter also introduces the role human factors and behavior play in roadway safety. The section also continues by synthesizing previous studies on microsimulation modeling in evaluating driver behavior in the CV environment and some traffic conflict techniques. Chapter 3 presents the simulation framework for achieving the thesis objectives. The chapter outlines the data acquisition and extraction processes. Also, a detailed description of the microsimulation procedure is described. It also presents the different driver behavior modeling approaches used in VISSIM. Chapter 4 investigate the effect of real-time Traveler Information Messages on speed harmonization in adverse weather conditions. Chapter 5