State of Wyoming Department of
Transportation

FINAL REPORT
WY2104F

HUMAN MACHINE INTERFACE FOR CONNECTED VEHICLE: REQUIREMENTS, DEVELOPMENT AND ASSESSMENT

Principal Investigator
Mohamed M. Ahmed, Ph.D., PE
Williams and Person Professor & Wyoming Excellence Chair
Department of Civil and Architectural Engineering,
University of Wyoming

Authors
Mohamed M. Ahmed, Ph.D., PE
Sherif Gaweesh, Ph.D., PE
Biraj Subedi, MS
Omar Raddaoui, MS
Guangchuan Yang, Ph.D.

Department of Civil and Architectural Engineering,
University of Wyoming
1000 E. University Ave, Laramie, WY 82071
mahmed@uwyo.edu
Phone: 307-766-5550 Fax: 307-766-2221

October 2021

DISCLAIMER

Notice

This document is disseminated under the sponsorship of the Wyoming Department of Transportation (WYDOT) in the interest of information exchange. WYDOT assumes no liability for the use of the information contained in this document. WYDOT does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Quality Assurance Statement

WYDOT provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. WYDOT periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Copyright

No copyrighted material, except that which falls under the "fair use" clause, may be incorporated into a report without permission from the copyright owner, if the copyright owner requires such. Prior use of the material in a WYDOT or governmental publication does not necessarily constitute permission to use it in a later publication.

- Courtesy — Acknowledgment or credit will be given by footnote, bibliographic reference, or a statement in the text for use of material contributed or assistance provided, even when a copyright notice is not applicable.
- Caveat for Unpublished Work —Some material may be protected under common law or equity even though no copyright notice is displayed on the material. Credit will be given, and permission will be obtained as appropriate.
- Proprietary Information — To avoid restrictions on the availability of reports, proprietary information will not be included in reports, unless it is critical to the understanding of a report and prior approval is received from WYDOT. Reports containing such proprietary information will contain a statement on the Technical Report Documentation Page restricting availability of the report.

Creative Commons:

Technical Report Documentation Page

1. Report No. WY2104F	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Human Machine Interface for Connected Vehicle: Requirements, Development and Assessment		**5. Report Date** August 2020
		6. Performing Organization Code
7. Author(s) Mohamed Ahmed, Ph.D., P.E.- orcid.org/0000-0002-1921-0724 Sherif Gaweesh, Ph.D., P.E. - orcid.org/0000-0001-7977-6378 Biraj Subedi, M.S. – orcid.org/0000-0003-3683-574X Omar Raddaoui, M.S. – orcid.org/0000-0003-1956-2065-2065 Guangchuan Yang, Ph.D. – orcid.org/0000-0001-8150-489X		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Department of Civil & Architectural Engineering University of Wyoming 1000 E. University Avenue, Dept. 3295 Laramie, Wyoming 82071		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. RS04218
12. Sponsoring Organization Name and Address Wyoming Department of Transportation 5300 Bishop Blvd, Bldg. 6100 Cheyenne, WY 82009-3340		**13. Type of Report and Period Covered** Final Report October 2021
		14. Sponsoring Agency Code

15. Supplementary Notes
Project Champion: Vince Garcia

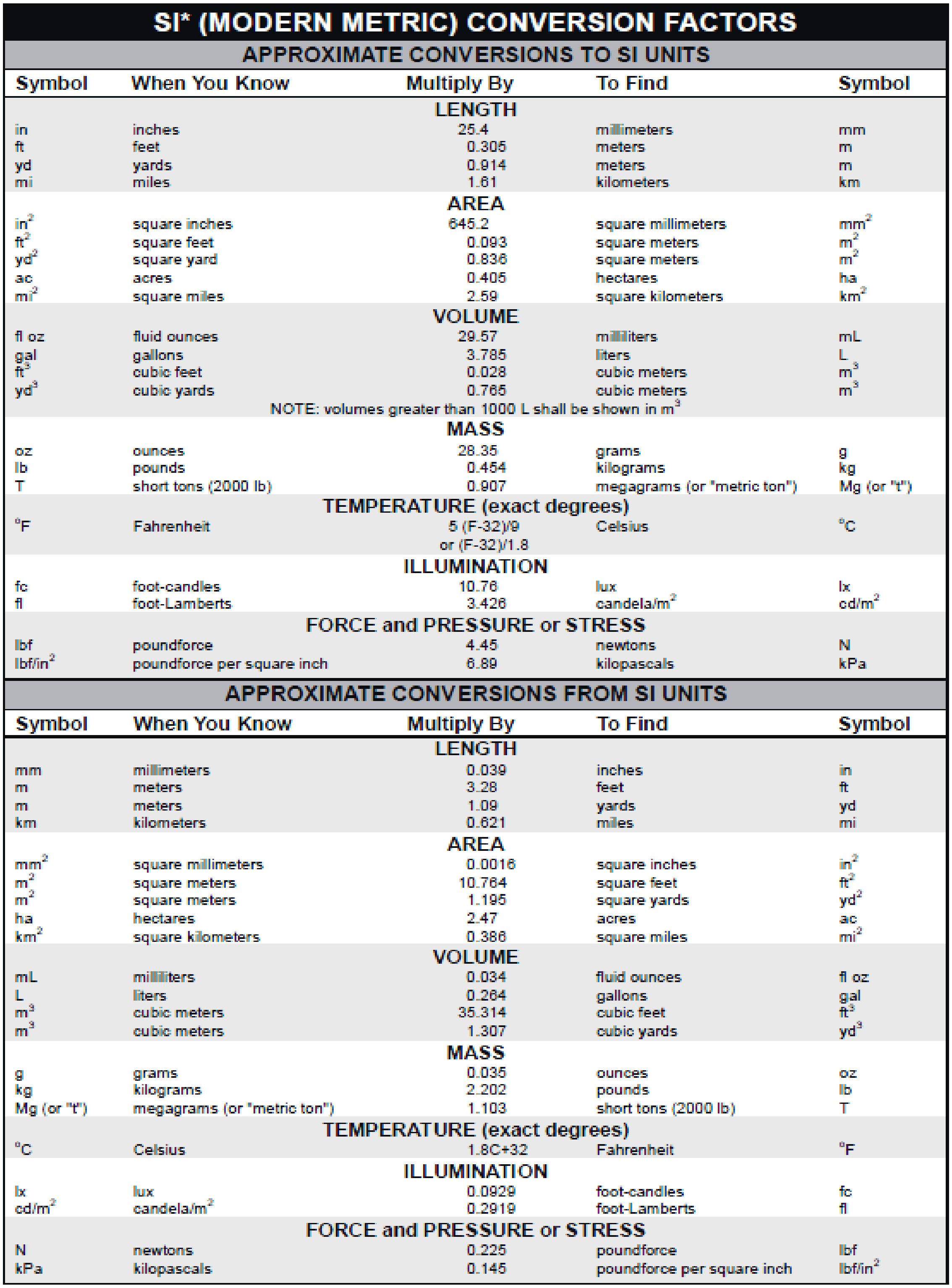
16. Abstract

The Connected Vehicle Pilot project was deployed on Interstate 80 corridor in Wyoming with the goal of promoting safety and mobility for road users with a focus on commercial vehicles, Highway patrol, and winter maintenance vehicles. One of the key components of the Wyoming department of transportation (WYDOT) CV pilot is the Human Machine Interface (HMI) that delivers real-time geo-specific Basic Safety Messages (BSM) and Traveler Information Messages (TIMs) to the drivers. However, some potential safety issues of transportation emerging technology stem from the fact that most CV applications rely on HMI, leading to the possibility of distracted driving. This study aims to develop a well-designed HMI that has the potential to provide drivers with proactive decision-making supports by minimizing distraction. In order to achieve this, the stakeholders of the Wyoming CV Pilot were interviewed, E-training modules were developed, and driving simulator testbeds were designed keeping in mind the needs, preferences and regulations of the stakeholders. Twenty professional truck drivers, as well as ten highway troopers from the Wyoming Highway Patrol participated in this study. The results suggested that exposure to CV notifications has promising safety benefits manifested in improved driver behavior and better response to upcoming hazardous events. Furthermore, both the weather and work zone notifications gained high approval from the participants in terms of usefulness and ease of understanding. Nonetheless, little to moderate distraction was introduced from the WYDOT CV Human Machine Interface notifications. Recommendations to the modalities and HMI design were implemented by the WYDOT.

17. Key Words Human Machine Interface, Driving Simulator, HMI, Highway Patrol, Truck, Eye-tracking, Vehicle Dynamics		**18. Distribution Statement** This document is available through the National Transportation Library and the Wyoming State Library. Copyright @2018. All rights reserved, State of Wyoming, Wyoming Department of Transportation, and University of Wyoming.	
19. Security Classification (of this report) Non-Classified	**20. Security Classification (of this page)** Non-Classified	**21. No. of Pages** **168**	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized

METRIC CONVERSION FACTORS



SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

Acronym	**Description**
3D	Three Dimensions
AAM	Alliance of Automobile Manufacturers
ABS	Antilock Braking System
ADAS	Advanced Driver Assistance Systems
ANOVA	Analysis of Variance
BSM	Basic Safety Messages
CDL	Commercial Driver License
CI	Confidence Interval
CMV	Commercial Motor Vehicle
CV	Connected Vehicles
DN	Distress Notification
DOF	Degrees of Freedom
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
F	Levene’s Statistics Value
FARS	Fatality Analysis Reporting System
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GPS	Global Positioning System
HMI	Human Machine Interface
I2V	Infrastructure to Vehicle
I-80	Interstate 80
IoT	Internet of Things
IRB	Institutional Review Board
IT	Information Technology
IVIS	In-vehicle Information Systems
LCM	Lane Change Merge
LEO	Law Enforcement Officers
LEP	Limited English Proficiency
MDT	Mobile Data Terminal
mph	miles per hour
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
OBU	On-board Unit
p	Probability
PC	Personal Computer
RSU	Road Side Unit

Acronym	**Description**
SAE	The Society of Automotive Engineers
SMoS	Surrogate Measure of Safety
SWIW	Spot Weather Impact Warning
t	t-statistics Value
TIM	Traveler Information Messages
TMC	Traffic Management Center
TTC	Time to Collision
U	Mann-Whitney test Value
US	United States
UX	User Experience
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	vehicle-to-everything
VSL	Variable Speed Limits
WCS	World Coordinate System
WHP	Wyoming Highway Patrol
WYDOT	Wyoming Department of Transportation
WZ	Work Zone
WZW	Work Zone Warning
χ	Chi-squared Test Value

CHAPTER 1. EXECUTIVE SUMMARY

The United States (US) is entering a new era of disruptive, yet innovative mobility, bringing the vision of safer and smarter transportation closer to reality. Driven by advances in automotive technologies along with the collection, communication, and analysis of real-time data, vehicles are becoming at the heart of the connected world and the digital user experience. Connected Vehicles (CV) are those that are equipped with applications, services and technologies that connect vehicles wirelessly to its surrounding. This connection allows for exchange of important messages that could help in enhance the safety and mobility of traffic. The surrounding areas may include other similarly equipped vehicles, roadside devices, pedestrians or other transportation systems. The data and messages obtained from these vehicles can have vast applications, including traffic safety and efficiency, infotainment, parking assistance, weather assistance, improved vehicle location and global positioning system (GPS), roadside assistance, etc.

To show case and initiate the real-world implementation of CV technology in the United States, USDOT selected three pilot deployments located at Tampa, FL, Wyoming, and New York City, NY. These pilots are tailored to meet the unique transportation needs of each of the regions. The Wyoming CV Pilot is deployed on the 402-mile stretch of Interstate 80 (I-80) corridor at the south part of Wyoming. Around 400 heavy vehicles, 35 highway patrol vehicles, snowplows, and other Wyoming Department of Transportation (WYDOT) fleet vehicles will be equipped with this technology, as well as 75 roadside units will be installed throughout the I-80 corridor to provide infrastructure communication capability.

The core of CV safety applications lies in the increased driver situational awareness of potential hazards. A robust Human Machine Interface (HMI) not only communicates information beneficial to the safety of the drivers, but also safeguards against potentially adverse impacts drivers may experience. This study acts on finding requirements for the Wyoming CV Pilot's end users, and developing a safe and efficient HMI based on the requirements and assessing any potential distraction from the installation of this technology in the cab of the drivers vehicle may introduce.

To achieve these objectives, two high fidelity driving simulators, housed at the University of Wyoming WyoSafeSim Lab, were used. The simulators included a truck cab simulator, modeled after a 2000 Sterling AT9500 18-wheeler semi-trailer and an open cab passenger car, modeled after a 2004 Ford Fusion. Professional truck drivers recruited by WYDOT and troopers from

Wyoming Highway Patrol (WHP) participated in the study. The driving simulator testbeds were developed to mimic the driving environment in the Wyoming I-80 corridor. The scenarios included all the CV applications, such as infrastructure to vehicle (I2V) work zone, I2V situational awareness, vehicle to vehicle (V2V) forward collision warning (FCW), distressed vehicle notification, and others. Vehicle dynamics data was obtained directly from the SimObserver system and Eye-tracking data were obtained from the SmartEye Tracking system installed on the simulator. All the data were collected throughout the comprehensive experimental framework. Additionally, extensive post-drive questionnaire surveys were also employed to gather drivers' qualitative opinions regarding the readability, clarity, interpretability, accessibility, and ease of handling the HMI. An E-training module was also developed specific to the different user groups that aimed at providing all information relevant to the Wyoming CV pilot, different applications of the CV pilot, and appropriate responses to the CV warnings.

Truck drivers were invited and recruited to conduct the first phase of the study, in which the truck simulator was used. For this phase, two scenarios were tested, a baseline (non-CV) scenario with the HMI deactivated and the second with the HMI activated to communicate the CV warnings. Comparisons were done between the two scenarios based on the driving performance, vehicle dynamics data, as well as eye-tracking data. Overall, findings from this study revealed that exposure to the CV weather and WZW has promising safety benefits manifested in early and smoother braking, lower speed variability, and early lane merge. The participants also approved the CV warnings in terms of ease of understanding and usefulness for the real-world application. The eye-tracking analyses showed that the glances induced by the CV HMI warnings are within the typical range of in-vehicle devices. The CV weather notifications did not seem to introduce any distraction. However, it was observed that the CV WZ notifications might have induced significant visual/cognitive demand to the drivers, likely due to the display of multiple small-sized WZW displayed in a short period. Based on this study, although the CV scenario with the HMI enable performed better, it was observed that it might be better to test different modalities of communicating the messages so the drivers can effectively perceive and extract information from the HMI in a timely fashion.

The second phase of the study focused on Highway Patrol Troopers. The car simulator was used for this study, in which multiple upgrades were performed to the exiting cab to mimic highway and patrol cars. Different equipment in a highway cab, such as the Mobile Data Terminal (MDT), radio, and siren were installed in the simulator to make it more realistic. The driving simulator testbeds were changed entirely, and were made more complex to be in line with the highway patrol driving environment and regular daily tasks. It incorporated high-speed driving, accident scenes, communication between dispatch and troopers, as well as tasks for introducing cognitive workload. Four different modalities were tested for this study, a baseline (no CV-warning), enlarged icons with voice, enlarged icons with beeps, and small icons with beeps. From the vehicle dynamics data, it was found that the participants had better results with the CV technology being enabled. However, no significant difference was found between the different CV modalities. From the eye-tracking data, however, it was observed that the participants had much lesser distraction when provided with enlarged icons with beeps.

CHAPTER 2. INTRODUCTION

The United States is entering a new era of disruptive technology, yet innovative mobility, bringing the vision of safer and smarter transportation closer to reality. Driven by advances in automotive technologies, along with the collection, communication, and analysis of real-time data, vehicles are becoming the heart of the connected world and the digital user experience. Public agencies, technology industry, automobile manufacturers, and academic and research institutions have assumed an instrumental role in leveraging connected and automated driving solutions to tackle the 21st century transportation challenges, and bring new business opportunities to the market place [1].

CV technology has become a prime trend in the automotive and transportation sectors. CV technology leverages wireless communications between vehicles, the infrastructure, and other connected devices to inform drivers about various types of safety-beneficial information [2]. In an effort to spur CV technology maturity and deployment, the USDOT launched the first wave of CV Pilots, in 2015, in three locations, namely New York City, NY, Tampa, FL, and Wyoming [3]. The Wyoming Department of Transportation (WYDOT) CV Pilot is being deployed over a 402-mile rural freeway corridor of Wyoming's Interstate 80 (I-80). The Pilot consists of equipping 400 trucks with CV technology along with 75 roadside units, throughout the I-80 corridor [3].

The inclement weather conditions in I-80 induce a large number of accidents each year. In 2018 alone, 13,792 crashes occurred involving 20,959 vehicles, in Wyoming. Out of these 13,792 crashes, 2,047 crashes were due to ice/frost conditions, 921 were due to snow, and 867 due to wet conditions [4]. This shows that nearly 30 percent of all accidents are due to adverse road/weather conditions [4]. The winter crash rate has been found to be 3to 5 times higher compared to summer, on I-80 [5]. Apart from the adverse weather, driver distraction is another chief cause of accidents. A study by NHTSA showed that in 2009, 5,474 people died on US roadways, and an estimated 448,000 were injured in motor vehicle crashes that were reported to have involved distracted driving. The study also indicated that secondary task distraction contributed to over 22 percent of all the crashes and near-crashes documented during the study period [6]. Law Enforcement Officers (LEO), particularly highway patrol troopers, are greatly distracted due to the number of secondary tasks that they perform an regular daily basis [7]. They are required to attend and respond to emergency cases at high speeds, while performing secondary tasks. The complicated and tense driving conditions causes a great deal of cognitive workload.

Heavy truck traffic, on the I-80, corridor reaches as high as 50 percent during seasonal peaks, coupled with one of the most challenging road and adverse weather conditions in the nation, often make travel conditions hazardous for motorists [3]. In addition, multiple-vehicle collisions or pile-up crashes are not uncommon on Wyoming's roadways. One of the prominent recent pileups occurred on April 16, 2015. About 70 vehicles piled up following a heavy snow storm on I-80 between Laramie and Cheyenne, WY, resulting in multiple injuries [8].

In light of the recurrent challenging road and weather conditions, and the heavy truck traffic on the I-80 corridor, a suite of freight-focused CV applications is being implemented to improve the safety and reliability of the traffic on the corridor streamline, when challenging road and weather conditions exist [3]. The suite of CV applications consists of the FCW application, the I2V situational awareness application, relaying information about incidents, road closures, speed restrictions, parking information, along with other traveler information, and the work zone warning (WZW) application, providing navigation guidance at work zones, as shown in Figure 1. In addition, the suite includes the spot weather impact warning (SWIW) application alerting drivers about geo-specific weather and road conditions, shown in Figure 2, as well as the distress notification application that allows vehicles to broadcast distress notifications and request assistance [3].

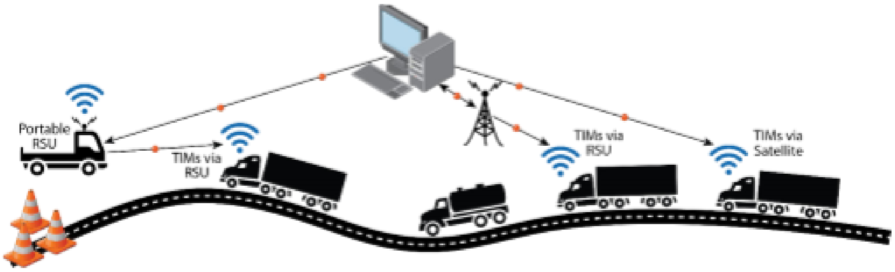


Figure 1 Work Zone Warning Application Process. Source: [9]

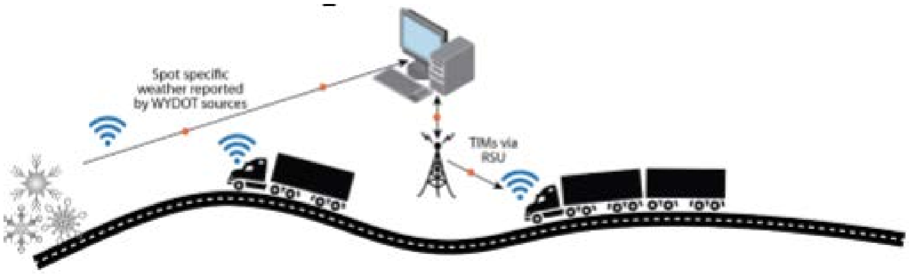


Figure 2 Spot Weather Impact Warning application process. Source: [9]

The multiple CV applications for the pilot deployment are communicated with the motorists via an in-vehicle display system called HMI. The HMI is designed to be an additional standalone system equipped on the vehicle dashboard. The HMI for commercial trucks and WYDOT maintenance vehicles was considered a 10-inch screen tablet, while a regular cell phone will be used with highway patrol. It is known that the in-vehicle environment of trucks, snow plows, and highway patrol is already crowded and challenging. Adding an HMI might provide distraction to the drivers. This study focuses on assessing the impact of the CV HMI and evaluating its safety benefits. Additionally, it provided insight about the best design practices that could help in developing HMIs.

CHAPTER 3. LITERATURE REVIEW

CV technology could be looked at as a connected network where equipped-vehicles can talk to other equipped-vehicles, the infrastructure, and other connected devices [2]. With the exchange of information taking place in real-time between the multiple ends, equipped vehicles are able to acquire information and build awareness of the surrounding traffic environment. Safety-wise, in case of an impending potential hazard, CV technology enables drivers to receive advance notifications about potential hazards, and thus, calling them to take the appropriate precautionary action [2]. Besides improving safety, CV technology could be harnessed to serve a wide array of utilities, such as improving mobility and traffic operations, in addition to advancing sustainability [9].

3.1 General

According to National Highway Traffic Safety Administration (NHTSA) (2017), there had been 37,461 traffic fatalities on the US roads in 2016, 12 percent of which are due to crashes involving large truck [10]. A report published by NHTSA (2015) highlights that drivers are for the most part responsible for 94 percent of all crashes taking place. Of this percentage, 41 percent of crashes are due to recognition errors, and 33 percent due to decision errors [11]. In this regard, CV technology is expected to elevate drivers' situational awareness through real-time safety warnings and feedback communicated individually to the equipped drivers, should a hazardous situation occur. With this in mind, it is estimated that CV technology has the potential to cut down unimpaired vehicle crashes by 81 percent [9]. On another level, traffic management applications on freeways have the potential to reduce crashes related to winter weather conditions by up to 25 percent [12].

Primarily, three fundamental forms of wireless connectivity (i.e. V2V, V2I, and V2X) are likely to exist in a CV environment. V2V communications allow equipped vehicles to talk to one another. By exchanging vehicle data (position, speed, heading, acceleration, etc.), known as Basic Safety Messages (BSM), at a rate of 10 times per second, vehicles can build a geo-specific awareness of the surrounding environment in real-time [13] [9]. In case of potential hazards, CVs issue in-vehicle warnings to the individual drivers [13] [9].

Vehicle-to-Infrastructure (V2I) communications enable a two-way exchange of information between the equipped-vehicles and the infrastructure-dedicated road side units (RSU) [14] [9].

Vehicles can transfer information collected from the driving environment to the RSUs while the latter can communicate information to the equipped vehicles that will be beneficial for the equipped drivers [14] [9].

As vehicles continue to merge within the internet of things (IoT), in-vehicle technologies are becoming integral to the users' experiences. A myriad of connected driving safety and infotainment systems are expected to sweep the market in the coming years enabled by the vehicle-to-everything (V2X) communications. V2X primarily establishes direct communications between the CV and the broad cyber-physical environment (e.g., pedestrians, smart homes, devices, infrastructure, etc.) [15].

CV technology leverages a myriad of systems and processes taking place behind the scenes to enable the operations of the technology:

- Wireless communications present the backbone of a connected vehicle environment [9]. Currently, a huge debate is ongoing on whether dedicated short-range communications (DSRC), or 5G communications (a subsequent version of 4G), should take over the market as the primary medium for CV communications [16]. It is noteworthy that the WYDOT CV Pilot is currently based on DSRC-enabled communications [3]. DSRC operates under a frequency band of 75 MHz at the 5.9 GHZ band [9]. DSRC is optimal for V2V and V2I for several reasons: first, it offers high speed and low latency communications with data exchange delays in the order of 0.02s, thus satisfying all the latency requirement for in-vehicle safety warning systems [9]. For example, to ensure optimal functionality of the lane change warning application, a maximum latency of 0.1s is needed, a requirement that DSRC can satisfy [9]. Second, DSRC signals can only span a short range in the order of 300 m. This short range of coverage makes it immune to a large extent against signal interference from radio signals and other sources [9]. Furthermore, it is an ultra-reliable medium particularly in adverse weather conditions, during which having a properly functioning safety system is all-important. [9].
- On-board Units (OBU) designate the equipment that would be installed or retrofitted inside vehicles. OBUs enable the CV-equipped vehicles to communicate with other nearby vehicles, in addition to the dedicated RSUs [9]. CV-equipped drivers can benefit from a CV environment by receiving road and weather advisories, informational alerts, amongst others [9].

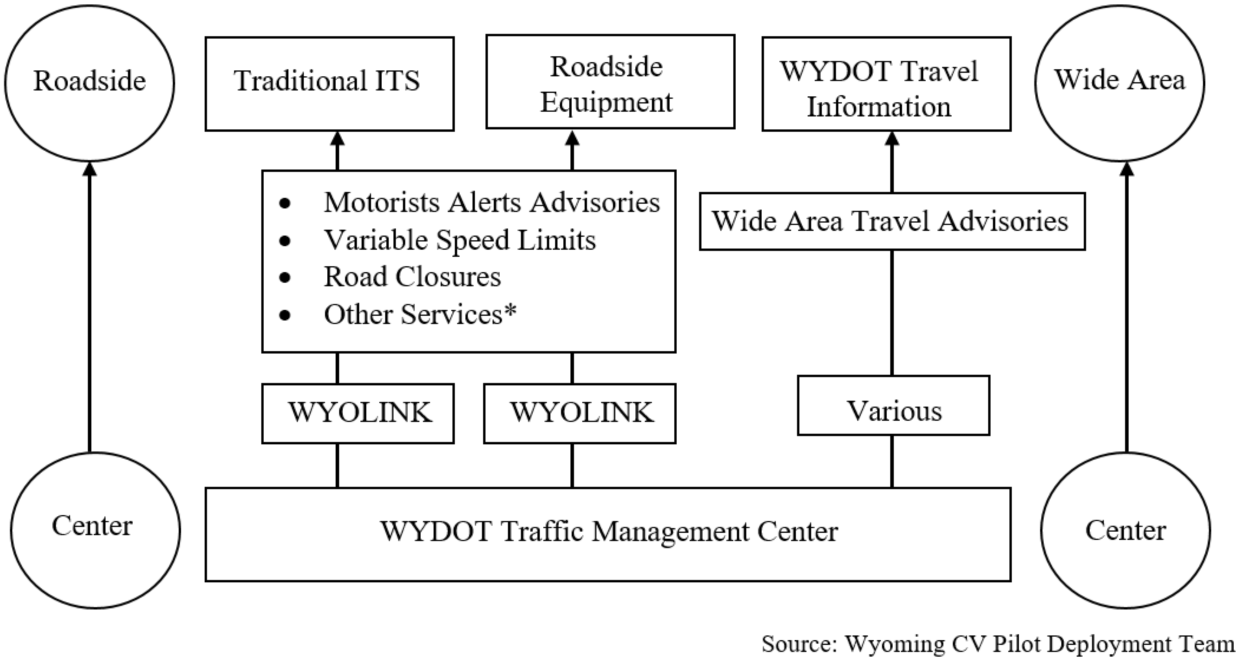
- RSUs presents the infrastructure part of the CV environment that support the V2I communications. RSUs receive geo-specific data from the CV-equipped vehicles and can communicate in turn a variety of information with the equipped vehicles that are beneficial to the drivers, such as signal phase and timing, road and weather advisories, amongst other types of warnings [17]. Figure 3 illustrates the RSU being deployed by the Wyoming DOT CV Pilot.

Figure 3 RSU used by the Wyoming DOT CV Pilot

- Backhaul communications enable the RSUs to communicate with the back offices or Traffic Management Centers (TMC) [17]. An effective network of backhaul communications requires a high-bandwidth and low latency to ensure timely exchange of information from the RSUs to the TMC and vice versa [17]. Backhaul communications are heterogeneous in the sense that several communication mediums can be applied, such as fiber optics, wireless communications, and leased communications [17].

3.2 Data Management Systems: Traffic Management Centers (TMCs), and the Cloud

The core of enabling a connected vehicle environment is effective management of data, proper administrative planning, and seamless dissemination of information [9]. A CV environment is expected to generate colossal amounts of data that need to be timely processed, analyzed, and reduced into meaningful and actionable insights, and then, in turn, feed back into the management of the transportation networks, and to guide the individual motorists on the road [17]. This will likely be the mission of the state department of transportations and local agencies [17]. Figure 4 provides an illustration on the role played by WYDOT as the back end of the CV operations. A momentous concern in this regard is the availability of the human and capital resources for the TMCs, and transportation agencies to handle vast and unprecedented amounts of information [17]. With this in view, cloud services offer a viable solution for the deployment of CV projects. As an illustration, a single connected vehicle is expected to generate gigantic volumes of data amounting up to 4 TB of data per day [18]. Handling large information banks will require the utilization of state-of-the-art Big Data Analytics hosted in the cloud in order to convert the huge sums of raw data into real-time useful and actionable information [19]. At the current state of practice, TMCs, for the most part, still rely on physical hardware systems for processing data. Nonetheless, a shift toward virtualized databases and decreased use of in-house physical equipment is occurring at a fast rate. This shift is enabled by the integration of databases, software, and hardware systems into Information Technology (IT) systems, namely cloud storage and cloud computing systems that are hosted over remote servers and managed by separate IT personnel [19].



Source: Wyoming CV Pilot Deployment Team

Figure 4 WYDOT Traffic Management Center Role in the CV Operations. Source: [21]

3.3 Safety Evaluation Studies for Work Zones

Improving highway WZsafety for trucks remains a challenging mission for the transportation sector, in the United States, particularly with a rapidly aging infrastructure and an increasing need for roadway maintenance. According to the Federal Highway Administration (FHWA), in 2015 alone, there was 96,626 WZcrashes in the United States, an alarming increase of 7.8 percent in frequency compared to 2014 [20]. Large trucks are overrepresented in WZcrashes, representing approximately 25 percent of motor vehicle fatalities, in comparison with 12 percent of highway fatalities being large truck-involved crashes [20]. Besides the over-involvement in WZcrashes, large truck-involved crashes often result in high severity and heavy fatality tolls particularly on the side of passenger vehicle occupants [21] [22]. A significant portion of WZfatal crashes involving large trucks occur in rural areas and interstates. In 2016, 27 percent of WZcrashes occurred on interstate roads in the United States. [23]. Work zones usually consist of four areas, namely: the advance warning area, the transition area or the taper area, the activity area, and the termination area. The advance warning area, a primary focus of this study, is designed to inform drivers of upcoming road activities and to provide navigation guidance [24]. WZcrashes predominantly occur in the activity area and to a lesser degree in the advance warning area, however, the latter is associated with the highest crash severity [22].

Abundant studies examined the contributing factors to WZcrashes. The Federal Motor Carrier Safety Administration (FMCSA) reports that more than 31 percent of fatal crashes involving large trucks are attributed at least, in part, to human factors [23]. “Speeding of any kind” and “driver distraction/inattention” are the most prominent driver-related factors contributing to 6.9 percent and 6.1 percent, respectively, out of all WZlarge-truck-involved crashes, in 2016 [23]. Speed variability between vehicles is another common factor for WZcrashes, due to vehicles slowing down or stopping when approaching WZactivities [25]. Unsurprisingly, more than one-fifth of fatal crashes involving large trucks are rear-end crashes [23]. Furthermore, vision obstruction due to weather conditions (fog, smog, smoke, etc.), roadway design, and large vehicles obstructing the view of other drivers contributed to more than 5 percent of the fatal crashes involving large trucks, in 2015 [23]. Adverse weather conditions, aggravated by other contributing factors, increase the severity of WZcrashes [26]. Similarly, crashes during darkness, with no-lighting, are often more severe in comparison with daylight time or darkness with roadway lighting. This is because reduced visibility often leaves drivers with limited time to discern obstacles and to elicit proper responses [27]. Failure to keep in the proper lane and failure to obey traffic laws, signs, control devices, and traffic officers contributed to an additional 5 percent out of all fatal crashes involving large trucks, in 2016 [23]. Moreover, forced and late merging behaviors near the taper area in work zones, with lane closures, can pose safety risks, especially when involving large trucks. Such behavior often compels drivers in the open lanes to engage in sudden and hard braking, in addition to other evasive maneuvers to accommodate the merging vehicle, thus increasing the risk of crashes [28]. All of the aforementioned contributing factors to WZcrashes share the commonality of being driven, at least in part, by human factors or driver behavior. Thus, implementing safety countermeasures that promote increased motorist' awareness of their driving environment and spur compliance could to the very least minimize the impacts of human factors on WZsafety.

WZsafety mitigation strategies have long been studied and implemented in the real-world. Use of changeable message signs and speed monitoring displays were found effective in controlling and harmonizing the speeds of vehicles [28] [29]. Flaggers, flashers, and pavement center/edge lines also have the potential to reduce WZfatalities [30]. Use of early merge strategies, including the static and dynamic early merge control systems in high volume rural freeways, is an effective strategy to reduce aggressive lane merging behavior and to calm traffic near the taper zone. Nonetheless, the use of early lane merge systems necessitates the presence of law enforcement to promote driver compliance [31].

While the use of conventional countermeasures and practices can have notable safety benefits, their effectiveness remains disproportionate against the sheer magnitude of the WZsafety challenges in the United States. In this regard, the development of CV technology is ushering in a new era for roadway safety. One advantage that could be leveraged by the connectivity of vehicles is the communication of early warnings. For example, accommodating the needs of large truck drivers, concerning performing early merges into the open lanes in work zones with lane closure, can be made possible by providing early in-vehicle lane closure warnings. Markedly, a survey found that almost half of the surveyed truck drivers prefer having WZW signs be placed as far as 3 to 5 miles ahead of the WZ[32].

Operating a vehicle is a complex task involving physical, cognitive, and visual interactions from the driver. Truck drivers encounter far more challenging environments than passenger vehicle' drivers do [33]. Navigating a WZcan introduce additional visual and physical workload for the truck drivers. A survey study revealed that 90 percent of truck drivers find WZnavigation riskier than driving under normal conditions [32]. Consequently, designing the HMI for CV applications, in consideration of the human factors and the complexity of the driving environment in a truck cab, is imperative, particularly when difficult driving conditions exist, such as a work zone. For instance, a well-designed HMI should strike a balance between effectively communicating information to drivers and minimizing driver distraction and nuisance [34] [35].

Li et al. (2013) studied the effectiveness of CV technology on worker's safety through person-to-vehicle communications, in work zones, in a simulator environment. WZwarning signs were communicated to drivers in the form of in-vehicle audio instruction/warning messages. Overall, the system was found to improve driver behavior and workers' safety. This was demonstrated through increased awareness of the traffic environment and better driver responses against potential hazards [34]. A simulator study, by Qiao et al. (2014), investigated the optimal modalities to warn drivers about potential forward collisions, in the WZadvance warning area, using smartphone generated warnings. The study concluded that sound and voice (male and female) warnings produced significant benefits in terms of decreasing drivers' speed, and increasing headway time and distance. Conversely, visual warnings worsened drivers' performance due to the additional visual workload imposed by the HMI [36]. Another study, by You et al. (2016), evaluated the effectiveness of using smartphone audio collision warnings for drivers attempting to turn left in a WZtermination area immediately followed by a T-intersection. The study indicated that warning had a positive impact on drivers' behavior demonstrated through a reduction in speed and brake-reaction distance [37]. In this respect, the pilot's WZW application aims to inform drivers of upcoming work zones, speed reductions, lane closures, and other obstacles and conditions [3]. Chapter 4 investigates the effects of truck drivers' exposure to the WZW application. Since the scenario involves driving under reduced visibility, assessment of the effects of exposure to adverse weather warnings is integral to the study.

3.4 Human Factors and HMI/UX Design

Human drivers predominantly rely on the visual sense to extract information from the driving environment. Research unequivocally demonstrates that driving is primarily a visual task; at least 90 percent of the information consumed, as part of the driving task, is the product of the streaming of visual information, such as the speed, road geometry, position relative to lane markings, brake lights of nearby vehicles, headway distance, traffic signs, amongst others [38] [39] [40]. At the same time, it is crucial not to undermine other human senses' contribution to the driving task, particularly the tactile and auditory senses [38].

The traffic environment, by its very nature, is a dynamic and continually evolving construct. As a result, the safe navigation of the traffic environment necessitates continual driver attention and monitoring of the roadway environment [41]. Relevant to this context, the safe driving involves two key mechanisms:

- Acquiring information about the traffic environment via an uninterrupted flow of information, particularly through the visual sense, and
- The effective cognitive processing of the acquired information or "raw data" in the way that serves the driver's ultimate needs and objectives [42] [33] [38].

Dysfunction can occur at the level of any of the aforementioned mechanisms, i.e., at the level of acquiring information or at the cognitive processing level [38] [42] [33] [43]. In our context, this sort of dysfunction is often referred to as distraction. As commonly cited in the literature, distraction, when conjoined with sudden changes in the driving environment or "pop-up events", often create a recipe for crashes/near crashes [42] [44].

Human drivers are prone to distracted driving and this often generates serious repercussions on public safety. In 2016 alone, distraction claimed the lives of 3,450 people in the US. Truck drivers are a prime category of drivers non-exempt from distraction [41]. A truck cabin, by its very nature, is a complex and workload-sensitive environment [33]. Vehicle characteristics such as size, braking distance, limitations to visibility and maneuverability, coupled with the need to perform work-related tasks while driving make the driving environment visually, physically, and cognitively demanding for heavy truck drivers [33]. Unsurprisingly, human factors lead the contributing factors for crashes involving large trucks. According to the FMCSA, 87 percent of the motor vehicle crashes involving large trucks are coded with human error as the critical reason (23 percent "travelling too fast for conditions", 22 percent "unfamiliar with roadway", 13 percent "fatigue", 10 percent "felt under work pressure carrier", 14 percent "inadequate surveillance", 9 percent "inattention", and 8 percent "external distraction") [45].

With increased vehicular connectivity with the outside world and a widening array of in-cabin systems, truck drivers are put under increased strain to multitask on the go. A study published by NHTSA revealed that approximately 65 percent of commercial truck drivers and safety/regulatory personnel (police, fleet managers) recognize distraction brought about by in-cabin devices, such as fleet management devices, dispatch communication systems, and cell phones, as being problematic for truck drivers [46]. Additionally, almost half of the interviewed truck drivers reported experiencing near-misses while using in-vehicle devices where momentary impairment is likely the culprit [46]. It is noteworthy that truck drivers generally perceive themselves as judicious as to when to safely use in-vehicle devices [46]. Nonetheless, being self-cautious of distraction or having this perception does not seem to be sufficient in preventing distracted driving for truck drivers.

In general, a well-designed HMI display provides proactive decision-making supports, and the driver can effectively perceive, interpret, and act upon this in a way that improves driver performance and increases safety [47]. Thus, HMI quality is determined by the drivers' ability to safely operate the vehicle while effectively using the in-vehicle systems [48]. Inappropriate integration may confuse, distract, or even annoy drivers, and could result in users refraining from using the system altogether [49] [33]. Consequences of HMI design, if not attended to, are likely to impact driver performance, particularly under heavy workload environments. This is because human capacity to interpret and handle information is limited [33]. Subjecting drivers to visual and cognitive workloads, beyond their available capacity to safely handle information, may put them at risk of failing to attend to the driving environment, thus increasing the potential of crashes [33]. Consequently, designing the HMI in such a way that is fully attuned to the various complexities drivers encounter is crucial. As an illustration, a real-life study, by Tijerina et al. (1995), found that communicating messages to truck drivers of two lines or more, via an in-cabin text messaging system, shortened the amount of time the truck drivers allocated to scanning the roadway for potential hazards [44]. All in all, the nexus of the CV HMI design practice should revolve around designing a user interface capable of communicating the adequate amount of information in such a way that triggers the desired response from the driver while not introducing visual distraction, nuisance, or high cognitive workload demands [33] [48] [49].

In this regard, CV safety applications primarily aim to improve users' situational awareness of impending hazards. Approaching the distraction and workload introduced by CV technology with the same manner non-safety in-vehicle devices are evaluated may misrepresent or distort the overall safety benefits of the technology. Nonetheless, understanding the impacts of the introduced technology within a comprehensive research framework that lays the ground for future design enhancements is all-important. As far as HMI design and ergonomics are concerned, the evaluation process should not just seek to draw conclusions on whether a particular design is distracting or not but also to quantify the extent of the introduced distraction and workload, in addition to identifying the underlying contributing factors and how the potential limitations could be addressed.

Factoring out the potential benefits of communicating safety information to drivers, off-road glances irrelevant to scanning the surrounding environment do compromise the safety of drivers at varying degrees [44]. A large-scale naturalistic driving study by the NHTSA established a direct link between drivers' visual distraction during/before "pop-up events" and crash/near-crash involvement. The study revealed that longer off-road glances are generally associated with higher crash risk and deterioration of driving performance. Off-road glances exceeding a total of 2 s, regardless of their purpose, substantially increase the crash/near crash risk by twice as much in comparison with normal driving conditions [44]. The study concluded that secondary tasks that are simple in nature, brief in duration, and generally carry little to no risks to the drivers [44]. It is noteworthy that drivers are generally spontaneously reluctant to look away from the driving scene for durations exceeding two seconds at a time [50].

There are many challenges that must be overcome prior to the implementation of HMI. NHTSA suggests that the main requirement of any in-vehicle human machine interface is to communicate messages timely while minimizing distraction [51][52]. According to Peter et al.[53], HMI devices are developed such that they can improve the driving task, and a safe and efficient HMI should be easily readable, clear, and interpretable that should be easy to manage. All these requirements are aimed to reduce the driver's cognitive workload and to reduce any kind of distraction. Similarly, a study by Sentouh et al. [54] pointed out that implementation of an HMI must address problems, such as the format/layout in which information is communicated, the circumstances for communicating information, as well as the order in which information is presented.

In order to evaluate the HMIs, current studies found in literature were based on a one or combination of the following methodologies: questionnaire survey, experiment in the field itself, or a driving simulator experiment. Cummings et al. [55] performed a driving simulator experiment to study the impacts of single and multiple in-vehicle notifications on driving performance. It was observed that a single alarm did not affect driver performance significantly. However, alarm reliability and collision types significantly affected driver performance. Similarly, Fitch et al. [56] observed that secondary alerts might result in confusion while performing an emergency maneuver. They compared the effectiveness of displaying multiple crash alerts simultaneously with presenting single alert at a time. The results showed that the participants who received multiple alerts (a FCW and a LCM warning) performed better than the participants who received only the collision warning. Several studies have also studied the effectiveness of different modalities of communicating the information to drivers.

Jakus et al. [57] found that communicating information based on visual only and audio-visual did not show significant difference. However, most of the drivers preferred the audio-visual modality. Similarly, Naujoks et al. [58] found that drivers preferred visual-audio modality since the audio warnings would alert the drivers without distracting them. Winkler et al. performed a driving simulator experiment to study the drivers' reaction to different types and modalities of in-vehicle warnings. It was observed that generic warnings were more effective, and the modalities should be chosen according to the requirement of the situation and driving behavior.

There are several studies using drivers' eye-movement measures for assessing the distraction of HMIs, traffic signs, or secondary tasks. Konstantopoulos et al. [59] studied the eye movements of experienced and novice drivers in different time of day using a driving simulator. It was observed that experiment drivers had better processing time and broader scanning of the road, in addition, it was concluded that low visibility conditions decreased the effectiveness of drivers' visual search.

Another research conducted by Konstantopoulos et al. [60] indicated that using in-vehicle information systems (IVIS) leads to reduced steering performance. The research also used a driving simulator to study the distraction effects of traffic signs installed on roadsides and the signs displayed on IVIS. The results showed that although the level of cognitive load did not change the degree of steering bias, the IVIS-type displays led to decreased lane variability, indicating that IVIS-type displays might make drivers more susceptible to cognitive interference.

Topolsek et al. used eye-tracking technology to study the visual distractions caused by roadside elements such as traffic signs and advertisements. They suggested that to reduce the impact of advertisements on safety, the advertisements should be placed on a raised level whereas the traffic signs should be placed on the street level. Similarly, Louw and Merat [61] performed a driving simulator experiment to assess the visual distributions of conventional and SAE level 2 automated vehicles. The participants' gaze dispersions in both horizontal and vertical directions were measured in different weather and workload scenarios. The results showed that on a Society of Automotive Engineers (SAE) level 2 automated vehicle, the participant had more disperse horizontal gaze compared to a conventional vehicle. Additionally, while performing a visual secondary task, the horizontal gaze of participants was more concentrated.

A report by the FHWA (2015) highly recommends that in-vehicle devices should use standard message formats, and easily recognizable signs and messages particularly those that are provided in the Manual on Uniform Traffic Control Devices (MUTCD). This is because unfamiliar drivers are susceptible to misinterpreting the meaning of non-standard messages and signs [49]. As illustrated in the FHWA's report, it is vitally important that CV warnings communicate all the message aspects a driver would need to execute a response to a problem, including the description of the problem, the expected action, the level of action (i.e., advisory, informative, warning, or prohibiting), distance/location to problem/action and the affected audience [49].

With the possibility of warnings going unnoticed by truck drivers, due to the visual demands of the driving task, coupled with typically noisy and high-vibration truck cabin environments, it is essential to leverage multimodal displays to capture truck drivers' attention to the presence of the CV warnings. A report by the NHTSA (2016) strongly recommends using auditory warnings combined with visual displays for all status information, cautionary warnings, and imminent warnings for heavy trucks [33]. Evidently, multimodal warning displays is a common practice for in-vehicle safety systems in the truck manufacturing industry, such as Volvo [62], Daimler [63], Kenworth [64].

According to the NHTSA's report (2016) on HMI design guidelines, audible warnings should project the urgency of the event or the situation. Fast or high-frequency audible signals or tones should be reserved for critical situations where immediate attention from the driver is required, whereas, slower signals, or chimes with few tones (e.g., 1 unit) should be used to convey lower priority information [33]. A good example from the state of the practice is the FCW system implemented in the Kenworth T680 and T880 heavy truck models. The system uses a three-stage warning to warn drivers about potential forward collisions. At the first cautionary level, the system issues single beeps at a frequency of 42 tones/minutes. As the following distance decrease (i.e. second cautionary level) tones are issued at a frequency of 80 tones/minutes (40 double beeps/minute). As the vehicle reaches an extremely critically short following distance, the system issues a continuous beep (frequency 188 beeps/minute) [64].

Richard, Campbell, and Brown (2008) best described general design guidelines for presenting concurrent warnings to drivers as follows:

> *"1) multiple crash avoidance warnings occurring simultaneously automatically be prioritized in terms of their severity and urgency, 2) only the highest priority crash warning*

> *should be presented in the auditory or haptic modality, 3) all crash avoidance warnings should be presented simultaneously in the visual modality, 4) imminent crash warning messages have priority over cautionary crash warning messages, and 5) target-specific warnings (e.g., a car in the vehicle path has been sensed) have priority over non-target-specific warnings (e.g., road friction is low), and 6) crash avoidance warnings should take precedence over all other in-vehicle warnings."* [65]

Single stage warnings should be reserved for imminent warnings (no cautionary warnings communicated) [66]. For FCW applications, one-stage alerts are most useful when the objective is to capture distracted drivers' attention and are easier for drivers to understand. At the same time, single-stage warnings may not leave drivers with a sufficient time window to both capture the communicated information and properly react to the imminent threat [66]. On the other hand, cautionary warnings, as part of a multiple-stage warning system, can provide drivers with increase time to react to potential hazards, however, they can be associated with increased interpretation as a nuisance or false alarms [66]. At the end of the day, two-stage warnings are useful when the desired outcome of the system is to support a safe headway distance (especially for heavy vehicles) [66].

Lead time/time-to-collision has a significant role in determining the effectiveness of a driver's response to a warning. While early alerts can provide drivers with enough time to react safely, they may be considered as false alarms, and thus, result in low driver trust. In contrast, imminent alarms are unlikely to be disregarded, however, they may not allow a sufficient time window for the drivers to interpret the warnings and engage in the proper response [67]. As an example, a study, by Wan, Wu, and Zhang (2016), examined 16 collision scenarios in which the lead time varied between 0-seconds and 60-seconds using a single-stage collision warning system. A lead time of five to eight seconds resulted in the optimal safety for the drivers demonstrated though the most gradual braking and shorter reaction times [67].

There is a lack in the literature on whether in-vehicle safety systems should provide drivers with a single alert about the first event or all alerts during a multiple conflict scenario. An experiment conducted on the Virginia Polytechnic Institute and State University smart road, by Fitch, Bowman, and Laneras (2014), investigated drivers' behavior in response to a single warning versus multiple warnings in a multiple-conflict scenario [56]. The study was conducted with the premise that different alerts within a multiple-conflict situation would distract drivers since they would be in the midst of responding to the first warning [56]. Drivers were presented with a FCW due to the appearance of a sudden object on the driving lane, as they tried to swerve to the adjacent lane to avoid the frontal collision, drivers received a Lane Change Merge (LCM) warning triggered by a vehicle present in the subject's blind spot. Results show that drivers who were provided with both the FCW and the LCM warnings were quicker to return to the original lane to avoid a potential collision with the vehicle in the adjacent lance, as compared to the subjects who only received the FCW [56]. Overall, the study concluded that multiple alerts in multiple-conflict situations are effective given that drivers are properly trained to use the system [56].

3.5 Law Enforcement Officer/ Highway Patrol

Highway Patrol Troopers/State Troopers are the state law-enforcement officers who are responsible for supervising and enforcing traffic safety compliance on roads and highways [68]. Highway Patrol troopers spend significant amount of time patrolling hundreds of miles each day looking for traffic violations, assisting motorists in need of help, and attending accident and other emergency scenes [69]. In a survey conducted in 476 officers from New South Wales Police, 75 percent of the officers indicated spending at least half of their shift in a police car. Seventy percent of these officers reported that they spend more than three quarters in a police vehicle [70]. Thus, safety while driving is of utmost importance for these officers.

The in-vehicle technologies provide drivers with a vast array of information and entertainment. For the highway patrol and general law enforcement officers, however, these in-vehicle devices serve as a mobile workstation rather than for entertainment. They have several devices installed in their cab, such as the Mobile Data Terminal (MDT), a radio, a siren box, a radar system, video cameras and others such devices. All these devices have made the work of police officers easier since now they can directly work from their cab rather than calling the dispatch for information. However, the interaction with these devices demand a great deal of visual, mental, and cognitive load.

Secondary tasks, such as turning on a radio, changing stations, using the dashboard and performing other secondary tasks while driving, have been proven to increase the subjective workload on the driver, thereby causing cognitive as well as visual distractions [71] [72] . In 2017, 3,166 fatalities occurred on US roadways, all of which involved distracted driving [73]. Out of 6.29 million crashes in 2015, 14 percent were a result of distracted driving [74].

Police officers, including Highway Patrol, are frequently required to carry out emergency response tasks and may need to access important information while driving. The complex and visually demanding situation and requirement to perform multitasks divert the officer's attention, significantly increasing the dangers of a crash. LEOs are found to be distracted greatly due to the requirement to perform secondary tasks, such as using MDTs and talking on the radio simultaneously while driving [7]. From 2010 to 2014, 1,021 crashes involving emergency vehicles, in the State of Texas, were attributed to officer distraction and inattention [7]. Emergency vehicle accident reports in Minnesota, from 2006 to 2010, show 14 percent of crashes involving driver distraction, out of which 12 percent were the distractions caused by in-vehicle technologies and the use of MDTs, resulted in 7 percent of these crashes [7].

Statistical data show that 14 percent of the crashes involving police officers are caused by distraction [75]. One half of all these crashes, which involved distraction due to in-vehicle technologies, were due to the police officer interacting with the MDT [75]. Callander, 2007 conducted a research project where he tried to quantify the workload due to intensive secondary tasks in police vehicles, such as performing a license plate query and changing the radio channel. In both cases it was found that the workload increased by over 700 percent [76].

Anderson et.al, 2005 studied the multi-tasking behaviors of the general duty police officers. The study included full-shift ride-a-longs with 121 police officers. From the analysis of the data recorded in ride-a-longs, it was found that 77 percent were using the MDT while driving. Fifty five percent of officers were observed to be doing at least one other task apart from driving and using MDT, 11 percent were doing two other tasks, and 7 percent were observed to be doing 3 other tasks [77].

Noh (2011) conducted extensive research to analyze the Fatality Analysis Reporting System (FARS) data for LEO's motor vehicle crashes, from 1980 to 2008 [78]. The first harmful event data from 1980 to 2008 shows that "Collision with motor vehicle in-transport" accounted for 53 percent of crashes involving LEO fatalities, in a passenger vehicle. The manner of collision being angled (55.4 percent), head-on crashes (27 percent), rear-end crashes (13 percent), and sideswipe crashes (5 percent). For the "most harmful event", 47 percent of the time, the police's passenger vehicle crashes were collision with motor vehicle in-transport [79]. Forty three percent of the crashed vehicles had the initial impact point at the front, 24 percent at the left side, 13 percent at the right side, and 7 percent at the rear side of the vehicle [79].

Another study was conducted to study the characteristics of officer-involved vehicle collision, in California. A total of 35,840 vehicle collisions involving LEOs, in California, from 2000 to 2009, were studied. An average of 3,600 officer-involved collisions occur each year in California. The results showed that rear-end collision were the most common and involved 30.4 percent of the total crashes [80].

A similar study regarding the LEO vehicle crashes in Florida examined 31,438 crashes that involved 33,639 law enforcement vehicles. Rear-end collision were found to be the most common and represented 16.2 percent of cases; driver distraction was found to be a factor in 1.1 percent of these crashes; and following too closely was a contributing case in 1.8 percent of the crashes [81]. The manner of crashes and the impact points suggest that a number of these crashes might have been avoided with the use of CV technology.

The focus of this research is on Wyoming Highway Patrol. With the introduction of the Wyoming CV Pilot project, 35 Wyoming Highway Patrol Vehicles will be fitted with OBUs to access the CV technology [82]. According to the Wyoming Highway Patrol website, 210 Wyoming state troopers patrol along the 6,800-mile state highway system [69]. Combined, they drive over 5 million miles a year, writing over 89,000 citations, and investigating over 7,000 crashes. On average, a trooper is involved in some sort of activity once every 30 miles he/she patrols [69].

The WHP are frequently involved in chasing criminals or high-speed pursuits. The data from 1996 to 2015 show that over 23 fatalities occurred during high speed pursuits, which involved 1 occupant in the police vehicle, 18 occupants in the chased vehicles, 2 occupants in the other vehicles, and 2 non-occupants [83]. By number, this fatality rate is the sixth lowest for all the states in the US, but the pursuit related death, per 100,000 residents, is 4.5 percent for Wyoming, which is the third highest. This means the police pursuits, in Wyoming, are the third most dangerous in the US [83]. According to the statistics from Cheyenne Police Department, 33 pursuits occurred in 2016. The average maximum speed during the pursuits was 70.3 mph, with the maximum reaching 123 mph. Twenty seven pursuits occurred in 2017, and 43 pursuits occurred in 2018 [84].

During a ride along, conducted with the WHP, the troopers were observed to be driving much higher than 100 mph under emergency circumstances, all while performing secondary tasks of using MDT, talking on the radio, and using the Siren Box.

A few cases of pursuits by the WHP were studied. Table 1 shows the location, length of pursuit, highest speed reached during pursuit, the weather and time of pursuits, and the reason for pursuits.

Most of the pursuits reached speeds above 100 mph, with the maximum-recorded speed being 150 mph. A few of these pursuits were conducted during the night, and some were conducted during adverse weather conditions, with low visibility [85].

Table 1 WHP Pursuit Case Studies [85]

Location	**Miles/ Duration**	**Speed**	**Time**	**Date**	**Reason for Pursuit**
North of Casper, I-25	NA	NA	NA	03/13/2019	Fleeing a traffic stop
I-80	91miles	110 mph	9:00 am	08/08/2017	Presence of narcotics
US 20-26	NA	95 mph	10:15 pm	04/22/2018	Shots fired
I-70	NA	130 mph	2:00 pm	12/6/2016	Suspected to be a bank robber
Casper- Rawlins US 220	NA	130 mph	4:58 am	11/15/2016	Eluding, reckless driving, drugs
I-80	NA	110 mph	NA	11/13/2016	Stolen vehicle- Found after running vehicle’s license plate
I-25	NA	145 mph	12:55 am	09/26/2016	Stolen vehicle- Erratic driving
I-80 and US 30	2.5 hours	NA	10:30 am	08/17/2016	Speeding
I-90	70 mile	110 mph	5:30 pm	05/2/2016	Stolen vehicle/ No license plate/ checked VIN
I-80	NA	NA	9:55 pm	NA	Warrant for homicide
US 85	4 miles	105 mph	3:58 pm	04/11/2016	Speeding
South of Buffalo, I-25	NA	150 mph	2:40 pm	11/11/2015	Speeding
I-80 near Rock Springs	185 miles/ 1 hr 46 mins	130 mph	12:21 pm	11/9/2015	Stolen vehicle
I-80 east of Evanston	57 miles	110 mph	3:30 pm	10/31/2015	Stolen vehicle
US 287	NA	135 mph	8:27 am	10/16/2015	Stolen property, reckless driving and speeding
Eastbound of I-90	30 mile	120 mph	11:50 am	08/2/2015	Speeding
I-25	92 mile/ 1 hr 11 mins	102 mph	10:30 pm	03/18/2015	Speeding
I-80 Elk Mountain	163 miles	140 mph	NA	08/19/2014	Stolen vehicle
US 30	100 mile/ 1 hr	120 mph	11:00 pm	08/29/2012	Stolen vehicle

Apart from pursuits, there are several emergency cases that the officers need to attend to, which can include crime scenes, attending accident scenes, and act as the first responders. Their job requires them to travel at high speeds, often without considering adverse road and weather conditions.

3.6 Training Modalities

In the transportation industry, training of truck drivers has been considered as an essential element for the success of businesses. In the early 2000s, Kuncyte et al. outlined the requirements of dangerous-goods truck driver training in the North America and European countries [86]. The authors summarized how, in North America, it is the responsibility of the employer to provide adequate training to truck drivers. The employer needs to determine the duration and content of the training program, and assess the qualification of each truck driver. However, in European countries, such as the Netherlands and Sweden, driver training and testing must receive national level accreditation. The authors pointed out that, though all the training programs aimed at providing truck driver's appropriate training to prevent potential accidents during the transportation of dangerous goods, there is no global standard to assess the quality of training.

Similarly, Gargoum et al. investigated the acceptance of a potential standard driver training program, and indicated that it is necessary to establish standards for truck driver training [87]. Generally speaking, a well-designed training program should clearly outline an entire sequence of training required during a driver's career. Morgan et al. designed three training programs for entry-level Commercial Motor Vehicle (CMV) drivers [88]. The training types included 1) conventional training (certified training course plus behind-the-wheel driving), 2) simulator training (certified training course plus driving simulator training), and 3) Commercial Driver License (CDL) focused training. Overall, it was found that driving simulator training resulted in effects equivalent to conventional training, and, to some extent, the simulator training outperformed CDL-focused training. The authors pointed out that simulator-based training may not be adequate to transfer driving skills from simulator to an actual vehicle. To solve this issue, Hirsch et al. developed a simulator-based training to measure the transfer of driving skills learned in the truck simulator to the real truck [89]. The results demonstrated that a truck simulator with a well-designed instructional program tended to be an equivalent or more effective method for novice truck drivers. However, all the aforementioned research was focused on the pre-license training, which aimed at providing novice drivers with the basic truck driving skills. With the evolution of vehicle technology, Advanced Driver Assistance Systems (ADAS) have been introduced into the market to address safety issues. Nevertheless, the key to the effectiveness of ADASs is how drivers use them, particularly under high workload conditions. Several studies have shown that an advanced post-license driver-training program improved drivers' situation awareness.

Chapman et al. evaluated the effects of driver training on novice drivers' visual search pattern through a field test using an instrumented vehicle [90]. It was found that the driver training produced significant changes in the drivers' search patterns, and some of these changes remained detectable 3 to 6 months later. Pradhan et al. evaluated the effects of a personal computer (PC) based risk awareness and perception training program through a driving simulator experiment [91]. Simulation results revealed that trained drivers were almost twice as likely as untrained drivers to scan and recognize the risky regions. Similarly, Fisher et al designed a PC-based training program to train drivers to recognize risks both on the driving simulator and on roads [92]. Results showed that the PC-based training program had substantial effects on novice drivers' awareness of where they should scan the roadway for information, which was assumed as a surrogate of reducing their likelihood of a crash.

Fisher et al. developed a PC-based risk awareness training program, and evaluated its effectiveness using a driving simulator [93]. The results suggested that PC-based risk awareness training programs have the potential to reduce the high crash rate among inexperienced drivers.

Rosenbloom et al. employed a questionnaire-based method to investigate the effects of advanced driving training on participants' risk perception of driving situations [94]. It was found that in general, higher levels of perceived risk were reported after training as compared with before training. The effects of training were more significant for females and older adult drivers than for male and younger adult drivers. Walker et al. revealed that drivers who were subject to advanced driver training showed an increase in the number of new information elements that comprised their situation awareness, and an increase in favorable driving behaviors [95]. Beanland et al. summarized the efficacy of driver training and indicated that post-license training programs aimed to enhance driving skills that related to crash prevention, such as hazard perception and advanced vehicle control skills [96].

Begg and Brokland examined the association between participation in a defensive driving course and the effect of time-discount on traffic offenses [97]. Based on the interview of 1,763 fully licensed drivers, it was found that drivers who took the defensive driving course were relatively more compliant with the traffic conditions and less likely to crash or receive traffic offense notices. In view of the potential safety benefits from driver training programs, an increasing number of studies have been performed to develop post-license driver training programs.

Petersen et al. assessed the effects of a 2-day post-license driver training program on brake performance in cars with antilock braking systems (ABS) [98]. Results indicated that the driver who took the post-training used a smoother braking profile that enhanced postural stability and reduced the activation of ABS. Stanton et al. developed an advanced driver coaching system and concluded that drivers in the coaching condition improved their situation awareness and driving skills, and reduced attributions of external locus of control [99]. Isler et al. employed video-based road commentary training to improve drivers' hazard perception skills [100][101]. Through a focus group study, it was found that the road commentary training improved young drivers' hazard identification skills to the level of the experienced drivers, through a with–without comparison. This research concluded that drivers who took the training performed significantly better in hazard perception, speed choice, overtaking, and so forth than the matched untrained group. Crundall et al. investigated the effects of verbal commentary training on drivers' hazard perception skills [102]. The results showed that the trained group tended to be more confident and reduced speed in better time when approaching hazards. Wang et al. developed and tested a driving simulator–based training intervention to help novice drivers acquire higher-order perceptual and cognitive skills for safe driving [103].

Evaluation results demonstrated that the training intervention had positive effects on improving novice drivers' abilities to anticipate, recognize, and deal with hazards during the simulated driving. Goode et al. presented an overview of using driving simulators to train driving- related procedural and higher-order cognitive skills, as well as teamwork skills for vehicle crews [104]. The article summarized that simulation training effectively supported drivers' higher-order cognitive skills, such as hazard perception. Petzoldt et al. pointed out that the conventional forms of driver training usually only provided descriptive knowledge of how to drive [105]. However, the computer- based training has the potential to provide new ways to deliver advanced driving skills, such as hazard cognitive skills to the driver. After investigating the benefits of longitudinal training style in the public transit industry, Bart and Reep suggested that with the rapid upgrading of technologies, it is crucial to involve new educational technologies and updated training theories to facilitate employees' transfer of new knowledge [106].

In summary, previous research demonstrated that a well-developed driver-training program has significant positive benefits to transportation society. In current practice, the most used driver training methods were computer-based training and driving simulator training. Nevertheless, most of the existing driver training programs were designed for non–truck drivers, particularly novice drivers. There is still a lack of a unified education and training program for commercial truck drivers. In addition, among the limited truck driver training practices, there is no dedicated post-license training program on CV technology. Because of the high workload of commercial truck drivers, such as long hours of driving, difficulties in controlling the vehicle, use of ancillary in-cab devices, and so forth, and considering the challenging driving conditions in Wyoming during winter, it is necessary to develop an effective training program to deliver the CV technology to commercial truck drivers.

The Human Factors Design Guidelines for Driver Vehicle Interfaces suggests that any training on driver support system should train the drivers to read and interpret the warning signs, provide instructions on appropriate response, and inform drivers about any limitations in the system [52]. The guideline also suggests that the effectiveness of training can be increased using a part-task approach or variable priority approach where different components of the system are focused at different times [107].

William et al. assessed the impact of an elaborated training on manual control recovery in an automated car. The results showed that training decreased response time, decreased the number of interactions with pedals, increased trust in automated driving and also improved human-automation performance [108].

The Law Enforcement Driver Training Reference Guide suggests several instructional methodologies for training the drivers on different aspects of law enforcement driving. The methodology includes class lectures, slides, relevant videos, case studies, facts, and statistics, etc. For hands on training on emergency driving tasks, driving simulators are suggested since they provide realistic examples for training purpose [109]. Many police driving agencies require the officers to take a classroom course and a hands-on driving course. The classroom course is designed to give them knowledge and ideas about different aspects of law enforcement driving, whereas the hands-on driving is focused to implement the knowledge in the field [110], [111].

CHAPTER 4. HMI DRIVING SIMULATOR SCENARIOS DEVELOPMENT AND CV TRAINING FRAMEWORK

This chapter deals with the design of the experimental framework for the Wyoming CV Pilot Project. Two different E-training modules and hands on driving simulator experiments were developed which was specific to the truck drivers and the Wyoming Highway Patrol (WHP). The purpose of the e-learning module is to interpret to the users the function of each CV application; then, the driving simulator training module aims to provide the users a hands-on training on how to properly react to the received CV warnings. In addition, a standalone online e-learning module has been developed to train drivers from fleet partners who may not be able to take the hands-on training.

4.1 Training Methodology

Based on the review of the state-of-the-practice post license driver training programs, the proposed CV training program contains two major components: an e-learning module and a hands-on driving simulator training module. In line with the USDOT guidance for developing driver-training materials [31], this study employed a five-step iterative procedure for the development and evaluation of the training materials, as illustrated in Figure 5.

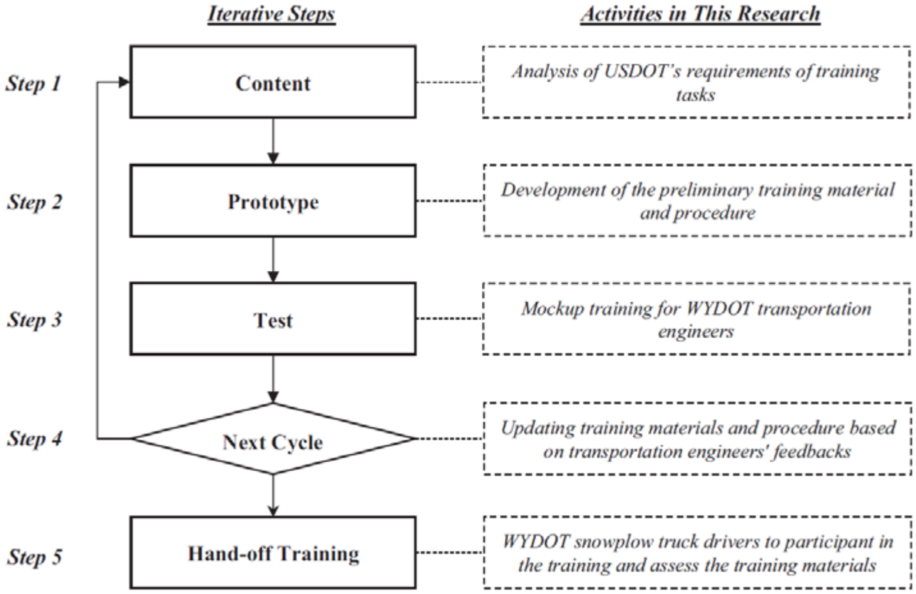


Figure 5 Simple 5-Stage Iterative Training Design Model (Source: [31])

Before the training, a proposal that explained potential risks to participants, and procedures for protecting the privacy and confidentiality of the participants was submitted to the University of Wyoming Institutional Review Board (IRB) to get approval to use human subjects in the CV training. The approval procedure conformed to the US Department of Health and Human Service regulations and policies for the protection of human subjects' rights and welfare. The training started with an introduction of the background of this training program; then, participants were asked to read and sign the consent form, which detailed the general purpose of the study, training procedure, potential risks, during driving simulator training, confidentiality of personal and training data, and so forth. In the next step, a prE-training questionnaire was conducted to collect the demographic profile, driving experience, crash history, and experience with existing ADASs of each participant. Subsequently, the e-learning module illustrated to participants the basic components of the Wyoming CV system, the concept and function of each CV warnings, and the proper response they should implement. Several quizzes were included in the E-training module to evaluate participants' understanding of the training material. It was assumed that a participant needs to correctly answer a minimum of 75 percent of the questions before he or she can move to the hands-on driving simulator training.

The driving simulator training aimed to provide participants with a simulated environment where they could practice the CV warnings that were introduced in the e-learning module. After the driving simulator training, a post-training questionnaire was employed to collect the participant's assessment of the CV applications, such as his or her acceptance of the CV applications, how useful he or she feels the CV applications would be in the real world, desirability and efficiency of each CV application, and so forth. Additional discussions about the participant's understanding of the CV warnings displayed on the HMI and recommendations to the training approach and materials were performed through face-to-face conversations with the participants. Figure 6 and Figure 7 show the training flowcharts for the two driving simulation experiments.

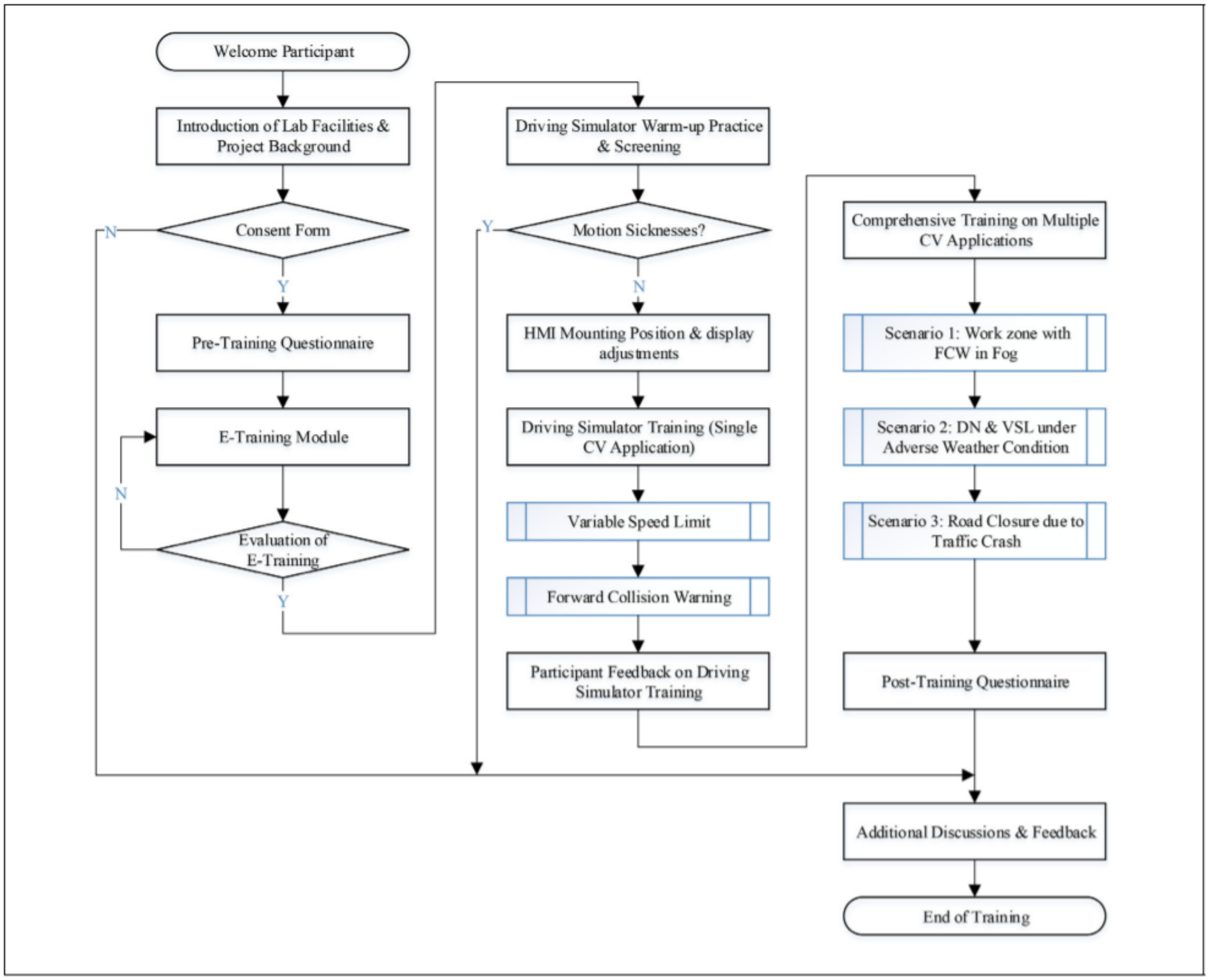


Figure 6 Flowchart of the Training Framework for Commercial Truck Drivers.

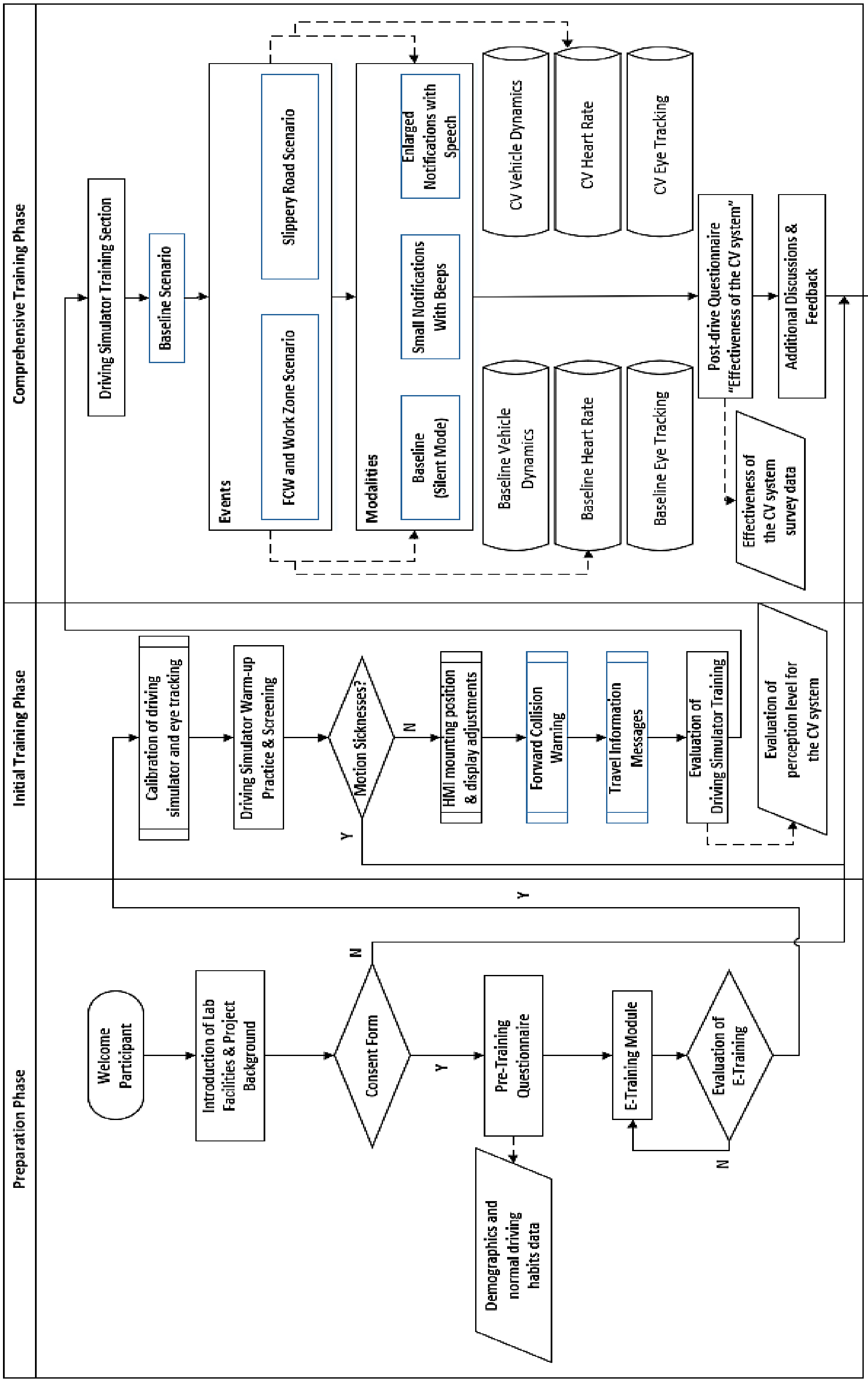


Figure 7 Flowchart of the Training Framework for Wyoming Police Patrol Troopers.

The two driving simulator experiments had the same idea of basic experimental framework. However, each experiment was developed based on the regular driving tasks and the expected driving workload. Additionally, vehicle dynamics are distinctively different between the two driver populations (i.e. police patrol and truck drivers), as well as their driving capabilities. Adverse weather conditions, slippery road surfaces, and presence of work zones were the three main schemes that were tested in both experiments. Environment complexity, dynamic events, and driving tasks were altered based on the extensive review and focus groups conducted to develop both experiments.

Focus groups were conducted by inviting professionals from WYDOT to review and approve the simulated scenarios. Comments and modifications were made to finalize the driving scenarios that were later tested with the commercial and snowplow truck drivers. Developing the driving scenarios for highway patrol was more complicated and advanced due to their driving behavior, complexity of driving, and the nature of their job. They often drive at high speeds through difficult road/weather conditions, and under enormous secondary workloads leading to an increased risk of crash. Also, the highway patrol are highly trained so they require additional complexity.

To develop a realistic driving simulator experiment for highway patrol, the complex driving environment, and driving behavior for troopers should be investigated. In this regard, two ride-along shifts were performed with troopers of the WHP. Each ride-along lasted almost three hours. Although, previous studies have shown that the presence of a ride-along affects the normal driving of highway officers [112], these two ride-along were extremely helpful to get information about the driving behavior, driving requirements, and risks involved that helped to develop a realistic framework of the training program. Prior to the ride along, the researchers signed a release and waiver of claims forms that contained a detailed information about the anticipated risk that might result from the ride along.

Before starting the ride along, the officers provided information about the different devices equipped inside the patrol car. Once the ride-along started, the trooper scanned through hundreds of events that were displayed on his MDT screen. During the three-hour interval of the first ride along, the trooper attended three events; two pullovers and one accident. In both pullovers, the officer drove at speeds much higher than posted speed to stop the violating vehicle. In one of the pullovers, the speed of the patrol car reached over 130 mph. In the accident event, the trooper was assigned to two incidents at the same time, and had to make several calls, via both radio and cell phone, to figure out which incident the dispatch required him to respond to. He had to drive more than 38 miles to reach the incident scene, which was completed in 18 minutes. The majority of the time, the speed of the patrol car was well over 120 mph. Similarly, in the second ride along, the trooper attended two events; a traffic-stop and possible suicide attempt scene. Since this was an emergency case, he was speeding throughout the route to reach the scene on time.

Table 2 summarizes all the activities the trooper performed in the 18-minute ride to the accident scene in first ride-along. The most indulging and frequently performed events were observed to be radio/cell phone conversations, interaction with siren box, and glancing at the MDT. Even at such high speed, the trooper was observed to be driving one-handed most of the time (56.76 percent).

Table 2 Summary of Activities Performed During 18-minutes of Ride-Along Event

Activities	**Time (Sec)**	**Percentage of Total Time**
MDT Glance	25	2.25
Radio - Listening	40	3.60
Radio - Talking	22	1.98
MDT Interaction (Button Press)	2	0.18
Cell Phone Interaction	10	0.90
Cell Phone hands free talk	33	2.97
Interacting with Siren Box	335	30.18
One hand driving (Including all activities that require a hand)	630	56.76

To ensure a realistic and approved driving scenario, the WHP officers from the Safety Education and Training divisions were invited to test the entire experimental setup. Some important feedbacks were obtained during the focus group review. Some feedbacks obtained from the focus group review were:

- Since the highway patrol cab is already crowded with many in-vehicle devices, a small 5.5-inch screen shall be used as the HMI and it shall be mounted on the center console just beside the dashboard. The WYDOT CV Pilot Program is utilizing a 10-inch tablet for other vehicle types.

- The scenarios shall be made more difficult with higher visual/cognitive workloads. The scenarios shall include realistic events, such as accidents or high-speed pursuits.
- All scenarios shall be designed to accommodate high-speed driving.
- The patrol cab shall be made more realistic and shall include the most frequently used in-vehicle devices, such as MDT, radio and siren, etc. Tasks related to these devices shall be include in the scenarios.

All the analysis and observations were accounted for while developing the scenarios. Afterwards, a final scenario acceptance was in initiated by a focus group study, inviting two highway troopers to test the final developed driving scenarios.

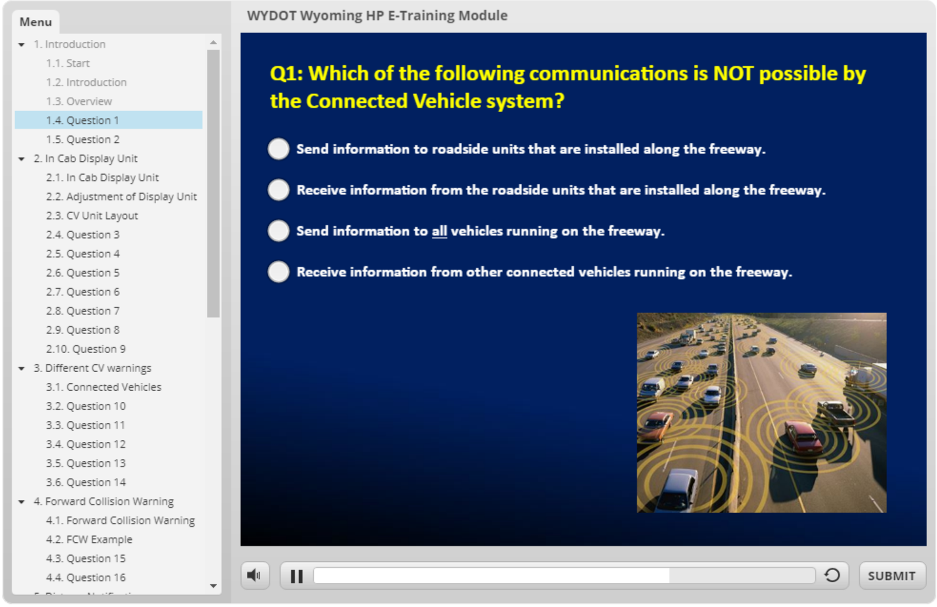
4.2 E-learning Module

The contents of the e-learning module and simulation scenarios of the driving simulator training module were determined based on the requirements of USDOT's training tasks. After the development of the preliminary training material and procedure, five professional transportation engineers from WYDOT and the partner transportation consulting company were invited to participate in a mockup training. Additionally, two officers from WHP were invited to test the E-module for highway patrol. This was considered a necessary step before providing training as they helped the research team to identify potential issues of the developed CV training materials and procedure, in which their feedbacks were accounted for and addressed.

The e-learning started with a 2-min video that introduced the background of the CV pilot deployment program, in Wyoming. This video, as posted on the WYDOT CV pilot's official website, described the significance of I-80 as a key freight corridor in Wyoming, and safety challenges that have been faced by both the WYDOT and commercial truck drivers. This video further introduced the purpose of the WYDOT CV pilot deployment program, the operating principle and technologies involved, and the information that would be provided to the commercial truck drivers. Then, the e-learning module described the basic components of the WYDOT CV system, including the physical equipment (e.g., HMI and the windshield mounting system), the visual elements of the system interfaces, locations of different setting buttons and their functions, the various ranges of the corresponding HMI and alerts they could receive or send, and the proper response they should implement. Moreover, the e-learning module illustrated the description and function of each CV warning. To facilitate participants' understanding of different CV warnings, the developed CV warnings were classified into three categories: 1) FCW, 2) distress notification (DN), and 3) traveler information messages (TIM). On average, it took 30 to 40 min for a participant to complete the e-learning module.

4.3 Online Training Module

Online training is considered an effective education method these days. With growing use of information technologies, online training provides education as well as training opportunities to trainees in many ways. Online training offers a convenient way of undertaking the customized online training module at any place and any time. Since most of the participants have little to no idea about the CV technology, it is important that each person driving a CV be trained on the features and the safe use of the technology. It is expected that over 210 highway patrol cars will be fitted with the CV technology, as well as 400 trucks. However, all of these participants will not be able to make it to the lab to participant in the hand-on driving simulator training and the E-training provided at WyoSafeSim. Thus, an online training module was developed. The training module was developed using Articulate 360 software. To make the training more interactive and interesting, pictures, videos, and voiceovers were added. The online training module followed an information-followed by questions format. A total of 20 questions were asked to the participants. The participants need to correctly answer at least 16 questions to pass the exam. At the end of the training, the participants can go back and see all the questions they answered incorrectly. Figure 8 shows screenshots of the developed online training modules using Articulate 360.



Q1: Which of the following communications is NOT possible by the Connected Vehicle system?

- ○ Send information to roadside units that are installed along the freeway.
- ○ Receive information from the roadside units that are installed along the freeway.
- ○ Send information to all vehicles running on the freeway.
- ○ Receive information from other connected vehicles running on the freeway.

Figure 8 Screenshot of the Developed Online Training Module

4.4 Human Machine Interface Display Layout

One of the key components of the CV system is the onboard HMI that delivers the received CV warnings to drivers, as illustrated in Figure 9. The participants were educated from the e-learning module that the main function of the CV system is to only provide timely warnings to inform the driver with real-time information about upcoming hazardous roadway and weather conditions, and the CV system will not control his or her vehicle or affect his or her driving. In addition, the HMI has customization capabilities for participants to adjust the volume, brightness, contrast, text size, mounting eye position, and so forth, based on their preferences. Participants were also educated about the priority level of CV warnings and how to recognize the most urgent alert in case of multiple alerts appearing simultaneously on the HMI. In general, four priority levels were defined in the order of 1) FCW, 2) speed limit (including Variable Speed Limits (VSL); 3) critical warnings, and 4) advisory warnings. Within the critical and the advisory warnings, warnings that were more urgent were displayed closer to the driver, that is, on the left side of the HMI, as illustrated in Figure 9. As previously mentioned, a 10-inch tables screen was tested and equipped with commercial truck drivers, while a regular cell phone was tested and used with highway troopers.

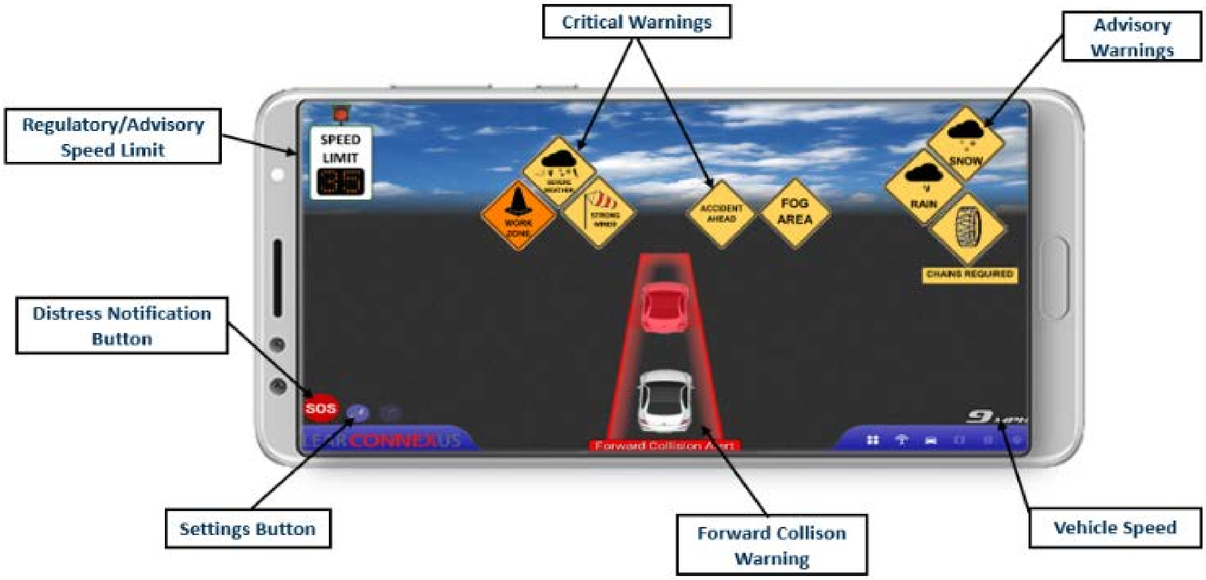


Figure 9 HMI Display Layout

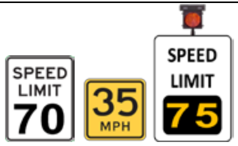
4.5 Description of CV Warnings

As mentioned before, in this study the developed CV warnings were classified into three categories: FCW, DN, and TIM, respectively. FCW is used when a forward collision might be encountered on the roadway while driving. The developed FCW has two warning levels: the cautionary level (HMI displays a yellow warning when the time to collision is greater than 5 sec. and less than 10 sec.), and the imminent alert level (HMI displays a red warning when encountering a high possibility of forward collision; the alert FCW will be triggered when the time to collision is less than 5 s). When being triggered, the FCW appears on the HMI with a series of loud beep sounds to alert drivers to the forthcoming collision situation. In addition to the interpretation notes that have been listed in the e-learning module, a short animation was developed by the research team to provide participants a more intuitive illustration of under what conditions the FCW alerts will be activated, and how the visual and auditory warnings look or sound when they are activated.

DN aims to present to the participants how to transmit an emergency message in the CV environment. A CV driver should press the DN button displayed on the HMI when the vehicle has been involved in a crash or in other distress situations. The CV system generates and broadcasts a distress message to the nearest RSU; the RSU will forward it to the WYDOT CV system. When an RSU is not within the communication range, the message will be received by other CVs that are in the vicinity and forwarded to the nearest RSU. The DN will include the location, time of message, distress message explanation (e.g., airbag deployed, vehicle disabled, operator initiated). The DN received by nearby CVs will also be broadcasted to notify oncoming CVs that a distressed vehicle is ahead.

The main functions of TIM are to 1) warn CV drivers of any high likelihood of dangerous driving conditions that will be encountered while driving on the freeway, and 2) provide advisory information to assist drivers to eliminate the potential safety hazards. A TIM will appear on the HMI with a single beep sound to alert drivers to the forthcoming driving condition. Specifically, the developed TIM includes: spot weather warnings (rain, snow, fog, strong wind, and severe weather); road surface condition warnings (icy road surface and slick spot road surface); WZW (including distance to the WZand lane-drops); variable speed limits (VSL) (usually displayed with other conditional warnings to provide adequate operating speeds for existing road and weather conditions); road closure and restrictions (including road closure because of road work, road damage, or existing severe weather conditions, requirement for snow chains, restriction on road usage for specific vehicle types, such as light trailer or light high profile vehicle); parking availability; and other advisories (such as an accident ahead). Detailed descriptions of each CV warning, including its sign that will be displayed on the HMI, messages delivered, and appropriate responses to the warnings, are summarized in Table 3.

Table 3 Summary of the Developed CV Warnings and Appropriate Responses

CV Warning	Sign of Warning	Messages Delivered	Appropriate Response
Forward Collision Warning (FCW)		An impending front-end collision with a connected vehicle ahead in the same traffic lane and direction of travel.	An immediate breaking is required to avoid rear ending the vehicle in front.
Distress Notification		A distress notification will be sent to other equipped vehicles as well as emergency services or local traffic management center to seek emergency help.	Distressed vehicle driver: Press SOS button on the left bottom corner of the display. CV drivers: Be aware of the distressed vehicles and drive with extreme caution.
Spot weather		A spot weather condition such as rain, snow, fog, strong wind, or severe weather ahead.	Driver should be alerted to the forthcoming weather condition, keep the vehicle on the right lane without overtaking any leading vehicle, and drive with caution.
Road Surface Notifications		An icy or slick spot road surface will be encountered on the roadway while driving.	Driver should be alerted to the forthcoming slippery road surface condition and drive with extreme caution.
Road Closures and Restrictions		A road closure to all types of vehicles, or road closed to certain vehicle types such as light trailers or light high profile vehicles.	Drivers need to exit the road, park in the nearest parking area, or cancel the trip.
Work Zones		Work zone ahead, lane closure, and speed limit.	Driver should keep the vehicle on the left lane without overtaking any leading vehicle.
Parking availability		When a parking or rest area will be encountered on the roadway while driving.	Driver should be informed about the forthcoming parking or rest area availability.
Other advisories		An accident will be encountered on the roadway while driving.	Driver should be alerted to the forthcoming accident situation and drive with extreme caution to avoid secondary crashes.
Speed Limits		Regulatory Speed Limits and Variable Speed Limit (VSL): Enforceable by law. Advisory Speed Limits: Non-regulatory but inform drivers of a safe driving speed.	Regulatory and VSLs should always be followed no matter what. Advisory speed limits should be followed as far as possible.

4.6 Driving Simulator Training

4.6.1 Apparatus

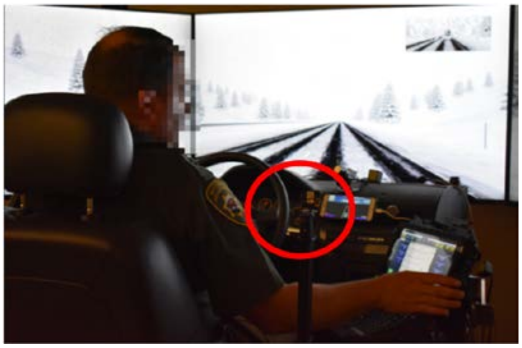
Two driving simulator housed at the University of Wyoming were used to conduct this research. The two driving simulators were built to resemble a semi-truck and a passenger car. The high-fidelity semi-truck cab simulator is modeled after a 2000 Sterling AT9500 18-wheeler semi-trailer and the open cockpit cab passenger car is modeled after a Ford Fusion 2004. The two simulator provided motion feedback using two rotational and one translational degree of freedom (roll, pitch, and heave) utilizing four D-box actuators. Along with the motion feedback, kinematic changes in velocity and acceleration approximated the conditions of driving in a real-life setting. A 3000W 5.1 multi-speaker sound system was used to replicate the background noise in a truck cab. Furthermore, a low-frequency vibration transducer mounted on the vehicle floor produced engine and road-like vibrations. The high-definition SimObserver software was used to collect vehicle dynamics from the driving simulator. Three 55-inch screens were used to disseminate the driving environment providing a 140 degrees field of view. Vehicle kinematics and measurements were programmed in each simulator to mimic real life vehicle kinematics and driving performance for the two vehicles.

In addition, the driving simulator was equipped with a high-definition SmartEye® Tracking system to track the subjects’ head position and gaze direction in three dimensions (3D). The system’s hardware uses a three-camera configuration mounted in different angles on the simulator. The accompanying software provides eye-tracking measurements in the form of raw data collected at a rate of 60 Hz or the equivalent of a reading every 16.67 ms. A 3D world model of the driving simulator objects was mapped into the eye tracking software. The world model enables the software to identify the objects at which a subject’s gaze intersect (e.g., CV HMI, center console, forward view, instrument cluster, etc.), as illustrated in Figure 10. The 3D models for the truck and the passenger car were developed in the lab to capture the actual layout settings.

Figure 10 Eye Tracking System and the World View

The first comprehensive upgrade provided to the two simulators integrated and simulated the HMI to communicate warnings visual and auditory forms. Figure 11-A shows the integrated HMI and its location within the truck-driving simulator, and Figure 11-B shows the integrated HMI and its location within the highway patrol driving simulator.

A- Subfigure A - HMI Mounting Location on the Driving Simulator for Truck Driver



B- Subfigure B -HMI Mounting Location on the Driving Simulator for Highway Patrol

Figure 11 Integrated Human Machine Interface (HMI) in the Two Driving Simulators

The integration included hardware and software upgrades, as well as programming for the added screen to display notifications based on time sensors, proximity sensors, and dynamic sensors. A new visual component with in and out channels was added to the driving simulator operating model to receive signals from the developed scenarios and send other signals to display notifications based on the programmed sensors in the scenario development. Additionally, all the images used for the notifications and the HMI design were developed in the lab using photo edit software.

Further integration was performed for the passenger car to mimic the equipment in a highway patrol car. The most frequently used in-vehicle devices was the MDT and the radio scanner. Both pieces of equipment were added to the cab, in which the MDT was integrated into the driving simulator system. The MDT software was developed to mimic the software used by the WHP simulating the same visual display and functions. The added radio scanner was mounted on the center console to be used within the scenario as a main communication tool between the highway patrol and the dispatch unit.

Since the LEOs have their own lingo, jargons, and ten-codes, the transcript had to be developed by listening to several real-life conversations between a dispatcher and on-duty WHP officers; the voice-over of dispatch recordings were performed by a professional radio presenter. Furthermore, a siren on/off system was embedded into one of the buttons on steering wheel similar of a trooper's car, in which a siren is triggered once the button is pressed and the driver behavior for the surrounding vehicles are modified to simulate actual driving behavior around a dispatched highway patrol car.

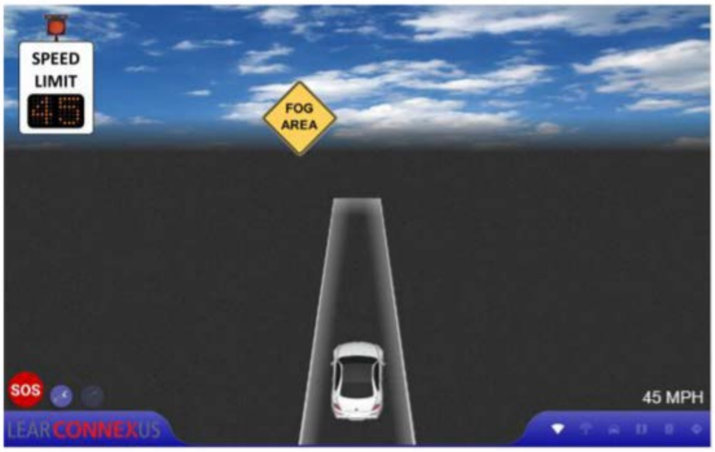
4.6.2 Warm-Up Driving Practice

The purpose of the warm-up driving practice was to let the participants get familiar with the functions of the driving simulator environment. The participants also need time to adjust themselves to the brake and acceleration pedals. The participants were informed on the consent form that the only potential risk to them during driving simulator testing could be a slight motion sickness (slight car sickness, fatigue, dizziness, eye strain, the potential of feeling anxious or stressed, or slight light-headedness) because of the conflicting body cues of visual movements without actual body movements. The warm-up driving practice in the simulator were used to help reduce the chance of motion sickness as participants become acclimated to the simulator. Participants could quit the test anytime, if they start to get motion sickness, feel uncomfortable, or simply do not wish to continue. The CV training team were present to observe all activities during the training, and to take action if it was deemed unsafe for any reason or if a participant appeared to experience abnormal behavior. The driving simulator-training platform was designed as a two-way four-lane freeway segment with 75 mph speed limit to represent the basic operating conditions of freeway I-80, in Wyoming. During the warm-up driving practice, each participant drove 5 to 10 minutes; additional practice time was provided to participants who needed more time to get familiar with the driving simulator environment.

4.6.3 Training on a Single CV Application

The driving simulator training module started with two single-CV application scenarios to practice the typical CV applications that participants had been educated on during the e-learning. The FCW driving simulator-training scenario aimed to provide participants training on how to take advantage of CV system's FCW to avoid potential collisions, particularly under low visibility conditions. Participants first accelerated to the normal freeway driving speed; fog gradually appeared on the road until the visibility limit was within 260 ft. A slow-moving truck was designed to change lane ahead of the participant's vehicle; the slow-moving truck would randomly make sudden stops while driving. With V2V communication technology, an advisory and an FCW alert was displayed in the HMI with beep sounds to notify the driver with the possibility of having a forward collision. A dynamic sensor, which is a combination of a time sensor, proximity sensor, and time to collision (TTC) sensor, was employed to trigger the truck so that FCWs were activated at the designated time to collision (10-seconds for an advisory warning and five-seconds for an imminent warning, in front of the simulator vehicle). This indicated that participants could practice more than one time by reducing or increasing the simulator vehicle speed to change the time headway to the front truck. The VSL driving simulator training scenario aims to provide participants training on how to take advantage of CV system's advisory speeds when driving under adverse weather conditions. Figure 12-A shows received FCW, while Figure 12-B shows the VSL warnings during the driving simulator training.

A- Subfigure A - FCW Notification Displayed on the HMI



B- Subfigure B - VSL Notification Displayed on the HMI

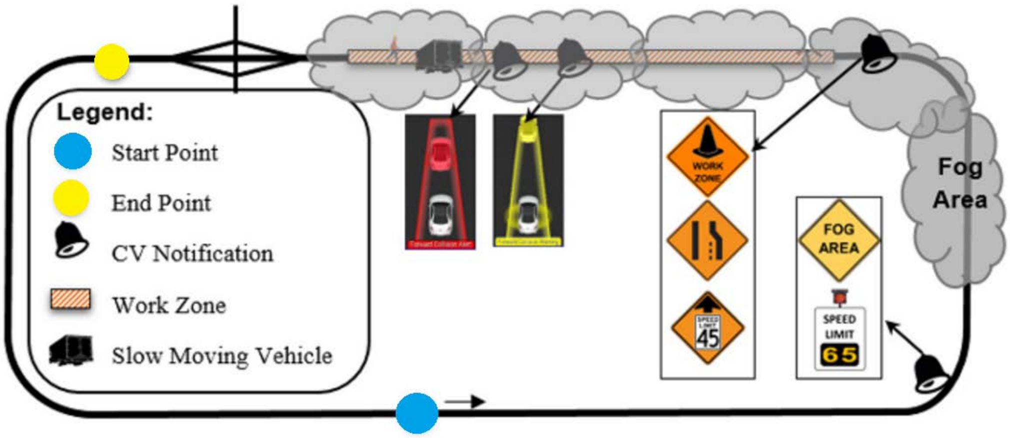
Figure 12 HMI Display for Different Driving Simulator Training Scenarios

4.6.4 Comprehensive Training on Multiple CV Applications

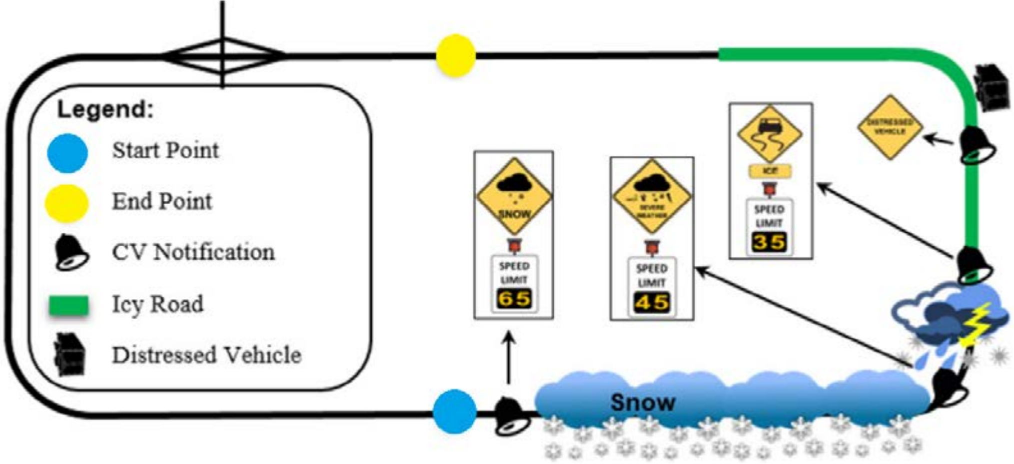
Each participant drove each developed scenario twice, during which minor changes that would not affect the driving performance was provided to eliminate any learning effect. The first driving simulation had the HMI deactivated (baseline scenario) and no CV warnings were communicated, during the second simulation the HMI was activated to communicate the CV warnings (CV scenario). A total of six driving scenarios were tested, where the driving order of the scenarios was randomly assigned to minimize potential learning and adaptation effects.

For the truck experiment, all notifications were communicated in the form of audible signals (double beeps) and visual displays on the HMI. Vocal instructions were not tested, as vocal notifications could be easily masked out with the truck cab loud environment. However, the vocal modality, as well as other modalities, were tested with the highway patrol experiment. The design of the HMI visual and auditory displays conformed with the NHTSA human factors design guidelines for heavy-vehicle user interface [33]. In addition, all visual displays were standard warning signs obtained from the MUTCD, as per the FHWA's guidelines recommending the use of familiar messages and standard MUTCD signs for in-vehicle safety systems [49].

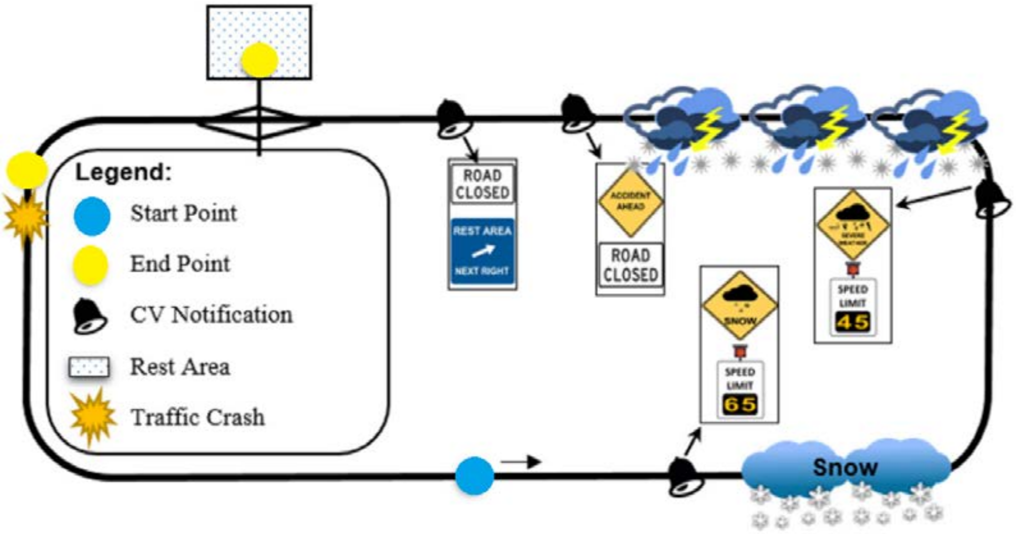
The experiment involved the testing of two distinct applications; the SWIW and the WZW, in addition to the rerouting application that was only tested with the truck driving experiment. Figure 13 shows the layout of the three developed testing scenarios with commercial truck drivers, where part (A) represents the WZscenario, part (B) shows the SWIW scenario, and part (C) is the layout of the rerouting scenario. WZW and SWIW scenarios were the only two scenarios provided to the highway patrol, as the rerouting application does not apply for them. Additional dispatch messages and increased work load was provided, in which subjects were requested to engage a dispatched event. Figure 14-A is the layout for the SWIW scenario and Figure 14-B shows the layout for the WZW scenario.



A- Subfigure A -Truck Driving Simulator layout for the Work Zone Scenario

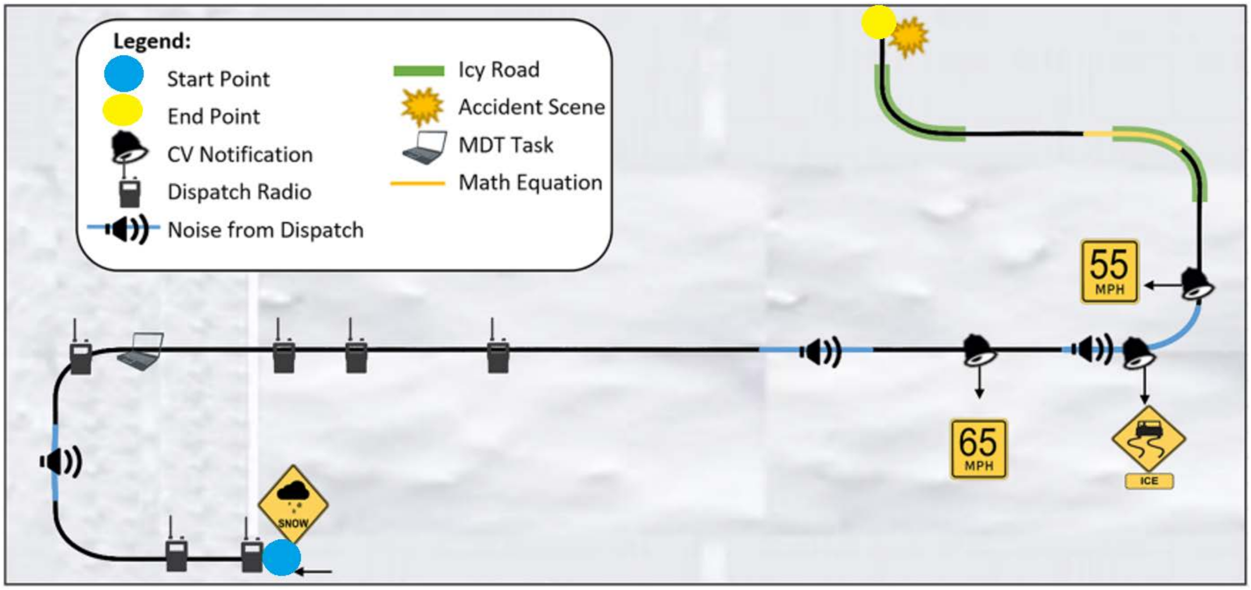


B- Subfigure B - Truck Driving Simulator layout for the Slippery Road Scenario

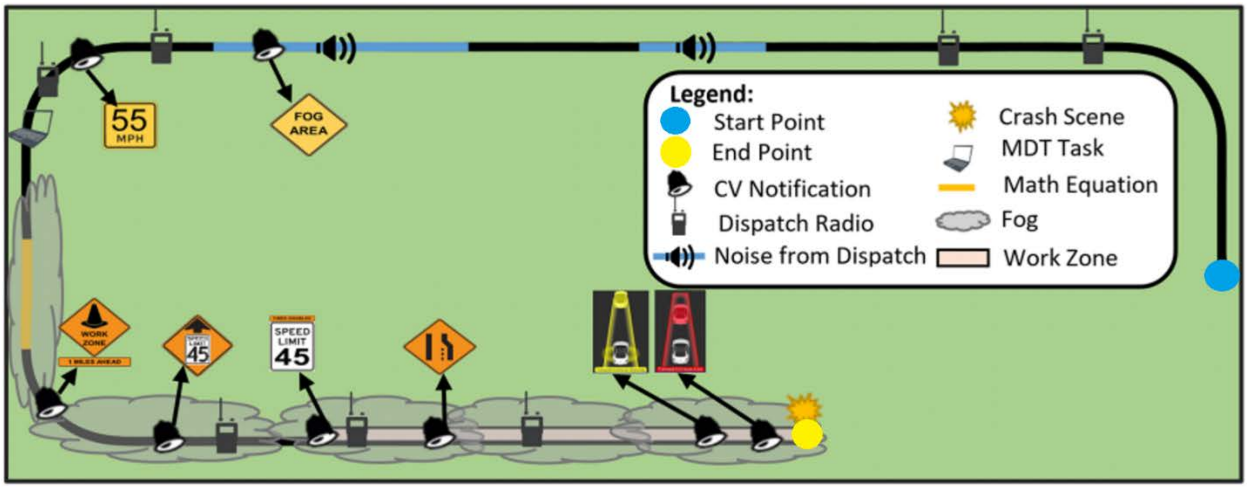


C- Subfigure C - Truck Driving Simulator layout for the Rerouting Scenario

Figure 13 CV Scenario Layouts for the Truck Experiment



A- Subfigure A - Slippery Roadway Scenario



B- Subfigure B - Work Zone Scenario

Figure 14 CV Scenario Layout for the Highway Patrol Experiment

CHAPTER 5. EVALUATION OF THE HMI DRIVING SIMULATOR EXPERIMENT

The experiment was designed to include two surveys serving as an evaluation tool for the different experimental section within the training framework. The first survey was mainly constructed to collect demographics and basic information about the participants regarding their driving behaviors and experience. This per-survey was provided after the consent form to start the experiment. Within the E-training several questions were examined to assure the gained knowledge and comprehension of the CV technology. Finally, the second survey, post-training survey, was given at the end of the experiment to evaluate the effectiveness of the training framework and the effectiveness of the CV technology.

5.1 Participants Demographics

Two distinct and professional populations/groups participated in this study. The first tested group were professional snowplow and commercial truck drivers from WYDOT; a total number of 18 truck drivers were recruited to participate in the CV training program. All the participants were males; their ages ranged from 21 to 61 years. Among the 18 participants, 13 graduated from high school, 4 have a college degree, and 1 has a postgraduate degree. All participants had a valid CDL and had been driving for an average of 12.5 years (0.5 to 35 years). The participants reported having driven an average of 20,000 miles in the preceding year (minimum 5,000 and maximum 30,000). All the participants reported that they had encountered reduction in visibility because of snow, blizzards, fog, smoke, or heavy rain while driving on the I-80, in Wyoming, from November 2016 to May 2017.

The second group participating in the CV pilot were highway patrol trooper from WHP. A total of 10 WHP troopers took the training. The participating troopers were all males, between the ages of 26 to 60 years. The troopers had been working for an average of 7.8 years for WHP (minimum 1 year and maximum 23 years). They reported their average annual mileage over the past 5 years to be over 30,000 mi. All the participating troopers said they performed secondary tasks of talking on radio, scanning road traffic condition, and using MDT while driving. All of them reported to be using I-80 corridor more than 4 times a week, with each trip being an average of 200 mi. All the participants reported that they had encountered reduction in visibility because of snow, blizzards, fog, smoke, or heavy rain while driving on the I-80 corridor. Two of the troopers reported that they had been involved in a crash on I-80 while on duty. One of the crashes was during inclement weather condition and resulted in personal injury.

5.2 Evaluation of E-Learning

Several quizzes were provided during or at the end of the e-learning, which aimed to evaluate participants' understanding of the CV system and assess the effectiveness of the training program. The E-training module was developed in an "information-followed by-quiz" format. The e-learning quizzes contained a total of 26 single-choice questions for truck drivers' module and 25 questions for highway patrol. The questions were mainly about the CV system, HMI display, response to CV warning, and so forth. Statistical results showed that the participants had an average score of 85 and 85.6 for truck drivers and highway patrol, respectively (score range from 72 to 96). Table 4 and Table 5 summarize the description, the solution, and the accuracy rate of each question for truck drivers and highway patrol, respectively. Questions that had a low accuracy rate (e.g., lower than 50 percent) were identified; these questions were further interpreted to the participants during the face-to-face conversation session.

Table 4 Summary of CV E-Learning Questions for Truck Drivers

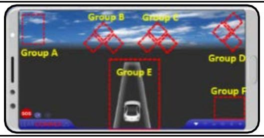
Q#	Description of Question	Correct	Mean Score	Note
1	Which of the following communication technology is NOT used by connected vehicle system?	Send information to all the vehicles running on the freeway.	66.7 percent	CV system sends and receives information to RSUs and other CVs only.
2	The FHWA/Wyoming DOT connected vehicle pilot project will be deployed on …………..	I-80 Corridor in Wyoming with a total of 402 miles.	88.9 percent	N/A
3	Which of the following statements regarding the connected vehicle system is correct?	Connected vehicle system aims to provide timely warnings and notifications about upcoming hazards and road conditions to drivers	94.4 percent	N/A
4	What should the driver do prior to driving the truck?	Check for firmware updates; adjust the position of the display unit; customize the display unit screen.	88.9 percent	N/A
5	For semi-trailer trucks, driver can set the trailer settings prior to the driving. Which of the following parameters CANNOT be set for each trailer?	Trailer weight	83.3 percent	Driver can set trailer height, width, and length.
6	Which of the following statements is NOT correct?	All the trucks on I-80 will have the connected vehicle technology	94.4 percent	N/A

Q#	Description of Question	Correct	Mean Score	Note
7	How long will the warning be displayed on the in-cab display?	The warning will be displayed on the in-cab display until the event is over.	94.4 percent	N/A
8	How frequently should drivers look at the in-cab display while driving?	Drivers can only look at screen when it is safe to do so.	94.4 percent	N/A
9	Click to select the appropriate group on the in-cab display where each of the following warnings are located.	Answers were based on the CV warning locations illustrated in Figure.	94.4 percent	Participants need to click the locations of speed limit, critical and advisory warnings on the HMI
10	Which of the following warnings have the highest priority when it appears on the in-cab display simultaneously?	Forward Collision Warning	88.9 percent	N/A
11	Which of the following statements regarding the Forward Collision Warning notification is NOT correct?	FCW notification will be displayed on the screen with a single beep sound to alert drivers of the forthcoming collision situation.	50 percent	Continuous loud beeps will be played until the risk of having a crash is over.
12	When Forward Collision Warning appears on screen, what is the correct response that drivers should make?	Drivers need to brake immediately to avoid rear ending the leading vehicle.	88.9 percent	N/A
13	If your vehicle is connected and you are involved in a crash or distress situation, which of the following responses should you make to avoid secondary crashes?	Press the distress notification button displayed on the in-cab display to send an emergency message.	83.3 percent	If possible, move the vehicle out of the driving lane.
14	Which of the following statements regarding distress notification is correct	Because not all vehicles are connected or equipped with distress notification, drivers need to keep watching out for distressed or slow-moving vehicles.	99.4 percent	N/A
15	The connected vehicle system will provide the following advisory weather condition warning when?	A combination of several adverse weathers	94.4 percent	N/A
16	When you get a ‘‘fog area’’ warning, you should	Keep the vehicle on the right lane without overtaking any leading vehicle; reduce speed and drive with extreme caution; turn on the hazards light	94.4 percent	N/A
17	If you are driving on a highway in heavy rain, you must slow down your vehicle to avoid	Hydroplaning	100 percent	N/A
18	When an ‘‘icy road’’ warning appears on the in-cab display, you should:	Reduce speed and keep the vehicle on the right lane without overtaking any leading vehicle.	88.9 percent	N/A
19	When a ‘‘chains required’’ warning appears on the in-cab display, you should:	Stop the vehicle at the nearest chain installation area and install chains to avoid skidding.	100 percent	N/A

Q#	Description of Question	Correct	Mean Score	Note
20	When a ‘‘road closed’’ warning appears on the in-cab display, you should:	Exit the road to a rest area or cancel the current trip.	100 percent	N/A
21	What should you do when the following warning appears on the in-cab display?	Reduce speed and drive with extreme caution to avoid secondary crash.	100 percent	Accident ahead warning sign
22	When a ‘‘no light trailers’’ warning appears on the in-cab display, which of the following statements is correct?	Vehicles with light trailers should exit the road, park in the nearest parking area, or cancel the trip.	88.9 percent	Other vehicle drivers do not need to exit the road.
23	When the ‘‘truck parking’’ notification appears on the in cab display, which of the following statements is NOT correct?	Truck drivers must exit the freeway to the truck parking area.	50 percent	This is an advisory notification. Must exit only when ‘‘truck parking’’ is combined with ‘‘road closed’’
24	When the following work zone warnings appear on the in-cab display, you should:	Be aware of the work zone warning and drive with extreme caution; change to (or keep driving on) the right lane when it is safe to do so; gradually reduce speed to 45 mph before entering the work zone.	66.7 percent	N/A
25	What information should be placed under the work zone warning?	Distance till the work zone starts	66.7 percent	N/A
26	Which one of the following statements regarding the advisory/regulatory variable speed limit warning is correct?	Variable speed limit warning aims to provide drivers advisory operating speed for the current road and weather conditions.	44.4 percent	N/A

Table 5 Summary of CV E-Learning Module Questions for Highway Patrol

Q#	Description of Question	Correct	Average Score	Notes
1	Which of the following communication technology is NOT used by connected vehicle system?	Send information to all the vehicles running on the freeway.	100 percent	CV system sends and receives information to RSUs and other CVs only.
2	The FHWA/WYDOT connected vehicle pilot project will be deployed on:	I-80 Corridor in Wyoming with a total of 402 miles.	90 percent	N/A
3	What is the purpose of Connected Vehicle Technology in Wyoming Highway Patrol vehicles?	To increase safety and mobility by informing highway patrol about impending collision, weather conditions, and active work zones.	90 percent	N/A
4	Which of the following statements regarding the connected vehicle system is correct?	Connected vehicle system aims to provide timely warnings and notifications about upcoming hazards and road conditions to drivers.	100 percent	N/A
5	Which of the following statements is NOT correct?	All the Wyoming Highway Patrol vehicles on I-80 will have the connected vehicle technology.	80 percent	N/A
6	How long will the warning be displayed on the screen?	The warning will be displayed on the screen until the event is over.	100 percent	N/A

Q#	Description of Question	Correct	Average Score	Notes
7	The volume of notifications on your CV app should be adjusted prior to driving so that.	It is not masked by in-cab and siren noises; the beeps will not startle you while driving; you don’t have to interact with the HMI while driving.	60 percent	N/A
8	How frequent should drivers look at the screen while driving?	Drivers can only look at screen when it is safe to do so.	100 percent	N/A
9	Click to select the following groups on the screen.	Answers were based on the CV warning locations illustrated in Figure.	87.5 percent	
10	Which of the following notifications has the highest priority when it appears on the screen simultaneously? Select its location in the display unit: (Figure same as above)	Forward Collision Warning	95 percent	N/A
11	Which of the following statements regarding the Forward Collision Warning (FCW) notification is NOT correct?	FCW notification will be displayed on the screen with a single beep sound to alert drivers of the forthcoming collision situation.	80 percent	Continuous loud beeps will be played until the risk of having a crash is over.
12	When Forward Collision Warning appears on screen, what is the correct response that drivers should make?	Drivers need to brake immediately to avoid rear ending the leading vehicle.	100 percent	N/A
13	When you get a “Fog Area” notification, you should:	Keep the vehicle on the right lane without overtaking any leading vehicle; Reduce speed and drive with extreme caution; Turn on hazard’s lights.	90 percent	N/A
14	If you are driving on a highway in heavy rain, you must slow down your vehicle to avoid	Hydroplaning	100 percent	N/A
15	When “Icy Road” notification appears on the screen, you should:	Reduce speed and keep the vehicle on the right lane without overtaking the leading vehicle.	90 percent	N/A
16	You are driving to attend an accident scene. On the way you hear beeps coming from the screen. What should be your reaction?	Drive with extreme caution as the road surface might have slippery spots and follow the recommended speed for your safety.	87.5 percent	
17	When Road Closed notification appears on the screen	Drivers should exit the road to a rest area or cancel the current trip.	100 percent	N/A
18	What should you do when the following notification appears on the screen?	Drivers should reduce speed and drive with extreme caution to avoid secondary crash.	100 percent	
19	When the following notifications appear on the screen, you should:	Be aware of the work zone warning and drive with extreme caution; change to (or keep driving on) the right lane when it is safe to do so; gradually reduce speed to 45 mph before entering the work zone.	100 percent	
20	What information should be placed under the work zone notification?	Distance till the work zone starts.	80 percent	N/A
21	Which one of the following statements regarding the advisory/regulatory Variable Speed Limit notification is correct?	Advisory/Regulatory Variable Speed Limit notification aims to provide drivers advisory operating speed for the current road and weather conditions.	70 percent	N/A

Q#	Description of Question	Correct	Average Score	Notes
22	While on a high-speed pursuit, the following notifications appear on the CV app. What should be your reaction to these notifications?	Reduce speed to match the advisory speed limit and drive with caution through the foggy area.	44.4 percent	
23	If it becomes necessary to perform a secondary task such as interacting with the MDT/Radio you should:	Not lose focus on primary driving task; Give high importance to CV warnings, especially FCW; Never take glances greater than two seconds off the road.	89 percent	N/A
24	If you hear loud continuous beeps while looking away from the road, what should you do first?	Quickly look ahead at the road and react appropriately.	100 percent	N/A
25	What is the correct sequence of actions to be taken when the HMI beeps? Choose one from each of the pairs.	A. Look at the screen when it is safe to do so. B. Scan through all the notifications on the screen. C. Follow every mandatory as well as advisory warnings that are on the screen. D. Take short intermittent glances rather than a long one if there are many warning messages.	91.7 percent	N/A

5.3 Evaluation of Driving Simulator Training

A post-training questionnaire was employed to collect participants' opinions of the CV applications after the driving simulator training. Participants were asked for their opinions on the CV applications, such as how useful they feel the CV system would be in the real world, desirability and efficiency of the CV applications, and so forth. Responses were measured on a 7-point Likert scale (example: Strongly Disagree to Strongly Agree). Accordingly, the evaluation results were converted to a 1 to 7 score, where 1 corresponds to very low evaluation and 7 to very high evaluation. It was found that, in general, participants provided positive responses to the developed CV training materials and procedure.

For the truck driving experiment, 15 out of the 18 participants stated that the driving simulator training provided them with a better understanding of various CV applications in comparison with e-learning (average score 5.5); all the 18 participants stated that the e-learning plus driving simulator training approach is an effective training method for delivering the basic knowledge needed of the WYDOT CV system. All of them reported that it was easy to understand the CV warnings displayed on the HMI during the driving simulator training (average score 6.1). Generally speaking, 17 out of the 18 participants stated that the CV system provided them with improved road condition information (average score 5.7); 17 out of the 18 participants stated that CV system increased their safety while driving (average score 5.7).

It was found that the troopers were positive about the developed training program. Nine out of 10 participants stated that the most effective training would be the combination of E-training and driving simulator training. They reported that in comparison to the E-training, the driving simulator training provided them with a more comprehensive knowledge about various CV applications (average score 5.7). Generally speaking, the troopers reported that the CV warnings displayed on the HMI were easy to understand (average score 6.2). Likewise, the troopers also evaluated specific CV notifications in terms of effectiveness, usefulness in real world, and ease to understand. They average scores ware 5.3 for adverse weather notifications, 5.7 for FCW, 5.1 for road surface condition notifications, and 5.3 for WZnotifications.

In general, in-person discussions conducted after the simulator experiment showed a very positive feedback regarding the design of the driving scenarios. Participants stated that the simulated environment reflected the actual driving conditions, in Wyoming. Additionally, they mentioned that the vehicle dynamics for the driving simulator is very similar to the actual vehicles they drive. Furthermore, they mentioned that the training was comprehensive and succeeded to explain the CV technology using the E-training and the hands-on training using the driving simulator.

CHAPTER 6. EVALUATION OF THE HMI PERFORMANCE FOR TRUCK DRIVERS

This chapter provides comprehensive analyses conducted on the data obtained from the vehicle dynamics of the driving simulator. The raw data obtained from the driving simulator is a 60 HZ big data set, including vehicle location, surrounding vehicles locations, longitudinal and lateral speed, longitudinal and lateral acceleration, lateral positons from lane center and roadway center, gear level, steering angle, pitch, heave, and yaw rates. Sixty readings per seconds are provided for the aforementioned variables. Data are synchronized and collected using the SimObserver system, in which vehicle dynamics are combined in spreadsheets and matched with the collected video footage of the study. Extensive data processing were conducted to develop vehicle trajectories to conduct speed and acceleration analysis to investigate the effectiveness of the presence of the HMI that communicated CV notifications. The scenario results and analysis for truck drivers are detailed in the following sections.

6.1 Analyses on Spot Weather Impact Warnings (SWIW) and Work Zone Warnings (WZW) Scenario Using Vehicle Dynamics

The data analyses was developed to serve two main objectives: 1) assess the successive impact of exposure to the notifications within the CV scenario, and 2) compare the driver behavior and performance change, between the CV scenario and the baseline scenario where the CV notifications are muted. To assess the behavioral effects of the CV warnings on longitudinal control of the vehicle, several behavioral measures were used for both applications comprised of mean speeds, speed standard deviations, mean accelerations, maximum decelerations, and percent of participants activating brakes.

The WZW application is comprised of multiple notifications communicated within a short time interval. Assessing the impacts of these notifications on lateral control, markedly from a distraction standpoint, was crucial. Using the lateral lane offset, the number of lane exceedances and percent time off-lane were determined for both the CV and baseline scenarios, in the WZadvance warning area. Lane exceedance is a performance measure brought forth by the Alliance of Automobile Manufacturers (AAM) to evaluate the effect of secondary tasks from in-vehicle devices on driving performance. A lane exceedance occurs when one of the vehicle's tires departs the outer edge of the 4-inch standard width lane marker by WYDOT [113]. Acceptance criteria by the AAM stipulate that the number of lane exceedances under a secondary task should not be higher than the baseline conditions [114]. The end of a lane exceedance event was marked when the vehicle tires no longer crossed the lane marker. It is noteworthy that lane changes were not counted as lane exceedances. Subsequently, percent time off-lane was calculated, as adopted in the literature [115]. In order to compare driver behavior between the baseline and the CV scenario, spatial coordinates of the location of the CV notifications were superimposed on the baseline scenario drive coordinates. Descriptive statistics consisting of summary statistics and box plots are used to describe driver behavior. Paired and one sample t-statistics value (t) tests using IBM SPSS software were performed to assess the differences for the behavioral measures at the five percent significance level. Additionally, Levene' test was used to assess the equality of variances for the mean speeds between the two scenarios.

The consecutive effects of the two weather notifications (fog warning followed by a 55 mph advisory speed warning) on driver behavior were assessed and compared with the baseline scenario. The effects of each notification on driver behavior were examined for an interval of 5 seconds. The fiveseconds analysis window reflects the prompted driver behavior following each warning in the short term [116]. Analyses were initiated following the activation of the auditory warnings given two additional seconds to accommodate the average driver perception-reaction time [34].

6.1.1 Effects on Longitudinal Control

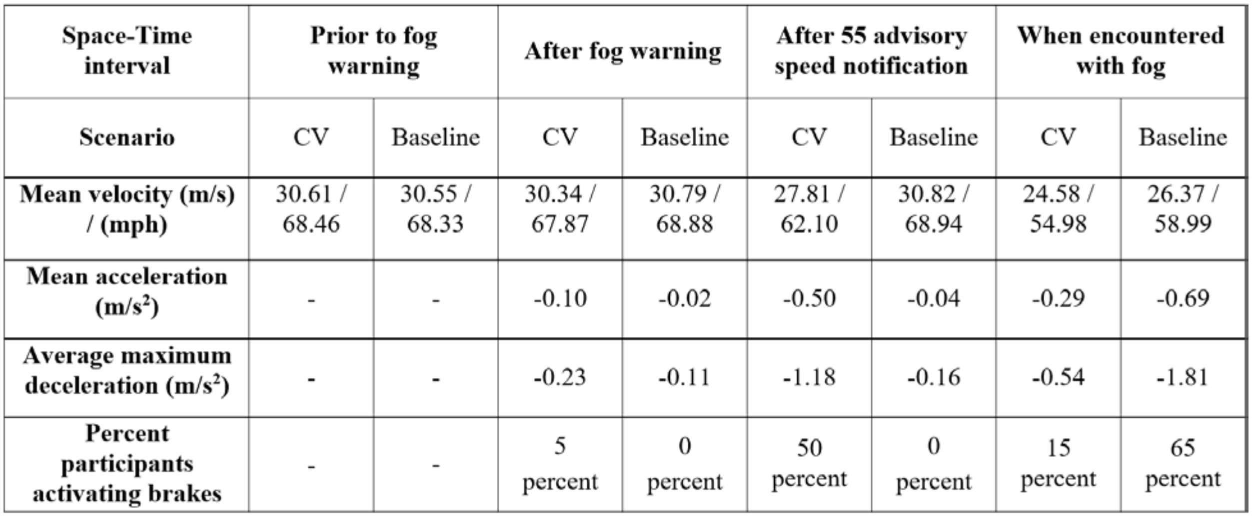
In both the baseline and CV scenarios, participants maintained very similar speeds prior to the location, at which the first CV notification was activated with an average speed of 68.5 mph for both scenarios in the 75 mph corridor, during the clear weather conditions. No statistically significant difference in mean speed was detected ($t(19) = -0.198$, $p = 0.845$). Unaware of the upcoming fog, drivers, in the baseline scenario, maintained a constant speed throughout the clear weather conditions. In the CV scenario, the activation of the first notification informing drivers about the upcoming fog triggered minor reductions in speed. However, no statistical significance in difference for the mean speeds in comparison with the baseline scenario was established ($t(19) = -1.558$, $p = 0.136$).

Following the exposure to the 55 mph advisory speed in the second notification, significant reductions in speeds were observed. Mean driver speed following the second notification was found significantly lower in comparison with the baseline scenario ($t(19) = -5.120$, $p < 0.0001$), and in comparison with the mean driver speed measured following the the first notification (t(19)

= -5.273 , p < 0.0001). These results suggest that informing drivers about the upcoming weather event or condition did not prompt changes in driver speed selection. However, the activation of the second notification, suggesting an advisory speed, triggered a more noticeable driver response against the invisible hazard

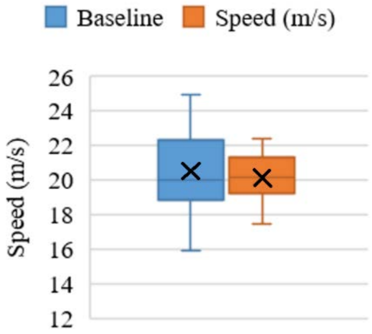
As expected, drivers in the baseline scenario, when encountered with the heavy fog, greatly reduced their speeds, with an average reduction of about 10 mph for the baseline scenario, in comparison with a further reduction of 7 mph reduction in the CV scenario. Mean driver speeds once in the fog were still significantly higher in the baseline scenario comparative to the CV scenario (t(19) = -2.448, p = 0.024). The severe reduction in speed, as drivers transitioned from the clear to the foggy weather conditions, brought forth aggressive braking and deceleration responses among several of the baseline scenario drivers. This was substantiated through the statistically significantly higher maximum decelerations (t(19) = 4.043, p = 0.0007) and mean accelerations in the baseline scenario (t(19) = 2.714, p = 0.014). Markedly, 65 percent of the participants resorted to braking in the baseline scenario, while only 15 percent of the participants applied the brakes in the CV scenario when encoutered with fog. Table 6 provides the summary statistics for the effects of the CV weather notifications on longitudinal control.

Table 6 Summary statistics of the longitudinal control analysis

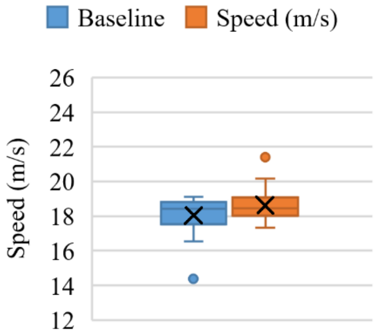


Space-Time interval	**Prior to fog warning**		**After fog warning**		**After 55 advisory speed notification**		**When encountered with fog**	
Scenario	CV	Baseline	CV	Baseline	CV	Baseline	CV	Baseline
Mean velocity (m/s) / (mph)	30.61 / 68.46	30.55 / 68.33	30.34 / 67.87	30.79 / 68.88	27.81 / 62.10	30.82 / 68.94	24.58 / 54.98	26.37 / 58.99
Mean acceleration (m/s^2)	-	-	-0.10	-0.02	-0.50	-0.04	-0.29	-0.69
Average maximum deceleration (m/s^2)	-	-	-0.23	-0.11	-1.18	-0.16	-0.54	-1.81
Percent participants activating brakes	-	-	5 percent	0 percent	50 percent	0 percent	15 percent	65 percent

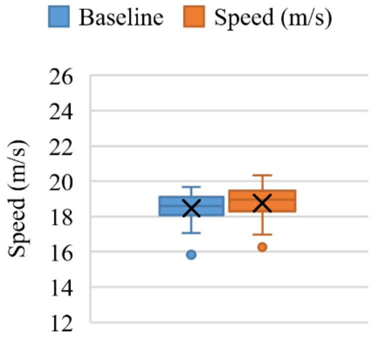
While driving under the foggy weather conditions, drivers encountered the WZadvance warning area triggering the activation of four distinct WZnotifications communicated in the CV scenario. Due to the potential overlapp of the effects of multiple CV notifications communicated within a short time interval, the analysis of the effects of CV notifications was aggregated over space: prior and after the 45 speed limit warning in the advance warning area, followed by the activity area. The analysis of mean driver speed along the two sections of the advance warning area (prior to and after the 45 mph speed limit), and the activity area revealed very similar mean speeds in comparison with the baseline scenario. Mean driver velocities are indicated using “X” signs in the box plots as shown in Figure 15.



A- Subfigure A - Velocity in Advance Warning Area – Prior to the 45mph Speed Limit



B- Subfigure B - Warning Area – After the 45mph Speed Limit



C- Subfigure C -Velocity in Activity Area

Figure 15 Box Plots for Driver Speeds in each of the Work Zone Sections

In addition, no statistical significance could be established for the difference in mean speed along the three WZ areas on the 5 percent significance level. It is noteworthy that nearly all participants were compliant with the speed limit, once driving in the 45 mph speed limit zone, regardless of the scenario. Against this background, a study by Li, Yu, and Qiao (2013) revealed that exposing drivers to advance audio warnings about upcoming WZ traffic signs prompted drivers to reduce their speeds early on when entering the WZ[34]. It is noteworthy this was not the case in this study, which could be attributed, in part, to the presence of the reduced visibility conditions prompting the participants to maitain lower speeds regardless of the scenario.

Remarkably, the evaluation of mean speeds revealed higher speed variance among the participants in the baseline scenario, in the WZadvance warning area, prior to the 45 mph speed limit warning. This is manifested in the larger span between the 25th and 75th percentile (lower and upper sides of the rectangles) distributions in the baseline scenario.

This is also observed in the greater variability of the participants's speeds along the same area in the baseline conditions compared to the CV conditions, as Figure 16 illustrates. Using Levene's test, a statistically significant larger variance for mean speeds in the baseline scenario was established at the five percent singnificance level (F(1,38) = 7.111, p = 0.011). No statistical significance for the difference in speed variability was detected for the two following sections at the same significance level. Additionally, the effects of exposure to the CV warnings on the individual variability of the drivers' speeds, along the two section of the advance warning area, was assessed. One sample paired t-tests using the relative change in the participants standard deviation of speeds along the two sections of the advance warning area were conducted.

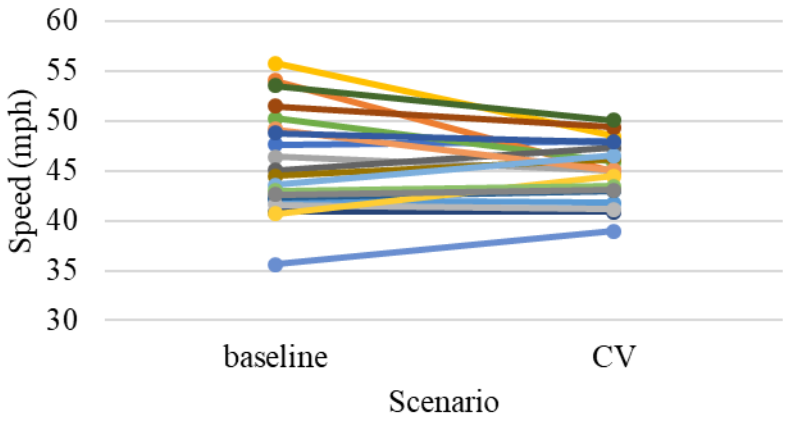


Figure 16 Scatter Plot for the Participants' Speeds Prior to 45 mph Speed Limit

Results show that in the WZadvance warning area prior to the 45 mph speed limit area, the standard deviation of the participants in the CV scenario is statically significantly lower compared to the baseline conditions, as shown in Table 7. In other words, the individual drivers drove with more harmonious speeds along this section of the work zone. This result was not found statistically significant in the advance warnings area following the 45 speed limit.

Table 7 T-Statistics for Longitudinal Speed

Test	t-Value	P (Probability)	Mean difference	95 percent Confidence Interval
Relative change in standard deviation of speed - Prior to 45 mph speed limit	-3.18	0.005	-1.10	[-1.83, -0.38]
Relative change in standard deviation of speed - After 45 mph speed limit	0.11	0.915	0.02	[-0.33, 0.36]

The reduced variability prior to the 45 mph speed limit resembles the findings reported in a study by Li, Yu, and Qiao (2013). The latter suggested that the communication of the early WZW reduced the speed variability from the posted speed limit [34]. The statistcally unchanged variability in mean driver speed once driving in the WZ45 mph area could be explained by the fact that the participants in the baseline scenario prior to entering 45 mph speed limit zone were not capped by any speed limit tailored to the reduced visibility conditions.

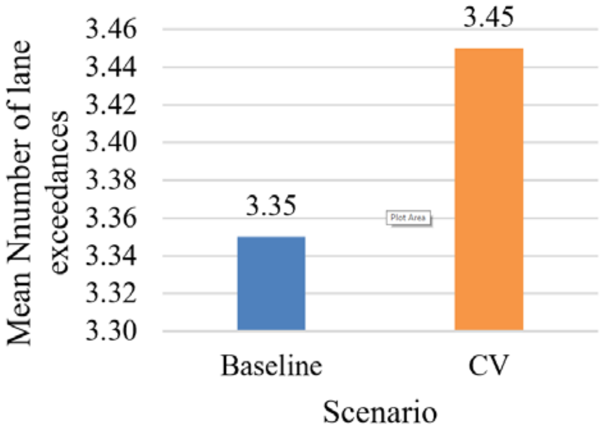
Alerting drivers to the upcoming fog did not prompt significant reductions in speed. However, the second notification carrying actionable message content (55 mph advisory speed), triggered a noticeable reduction in driver speed. These findings corroborate the NHTSA design guidelines for

CV safety messages, underlining that warnings should not only identify the problem but also provide an action element, in addition to the level of instruction (permissive, advisory, prohibited, etc.) [33]. Overall, the exposure to the two CV weather notifications prompted drivers to gradually reduce their speed and prompted smoother braking responses, when encountered with fog. Hence, the exposure to the weather notifications has high potential to prepare and guide motorists to safely navigate reduced visibility conditions in rural freeway settings.

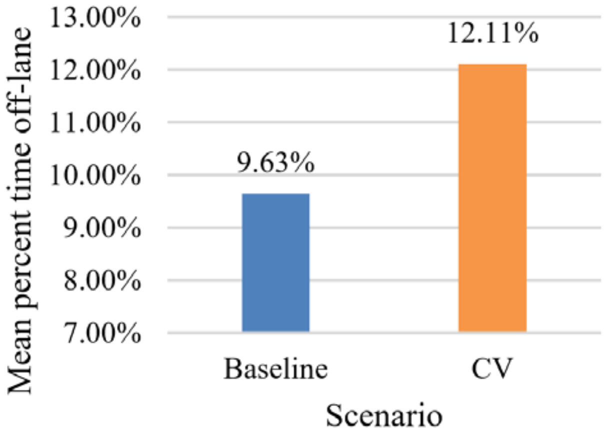
The comparison of mean driver speeds along the different WZ areas, between the CV and baseline scenarios, did not present any noticeable difference. The appropriate speed selection and compliance with the WZ speed limit, regardless of the scenario, reinforces the expected driving performance from professional truck drivers accustomed to poor visibilty conditions, in Wyoming. More importantly, the CV weather and WZ notifications were found to reduce the speed variance for the individual participants, in addition to between the participants in the advance warning area, a leading contributing factor for WZ crashes. This finding suggests that CV notifications induced a more harmonious traffic flow in the WZ advance warning area, suggesting an auspicious future for WZ safety, under the age of CV technology.

6.1.2 Effects on Lateral Control

The exposure to the CV advance warning area notifications was found to slightly increase the number of lane exceedances experienced in the WZ advance warning area. However, no statistical significance was detected in comparison with the baseline conditions (t(19) = -0.180, p = 0.859). The analysis of the percent time off-lane revealed a pronounced (25 percent) increase in the percent time off-lane comparative to the baseline scenario. Following a review of the recorded video logs of the experiments, it was found that 60 percent of the participants performed an early lane merge into the continued lane, in response to the advance CV lane closure notification, prior to the location of the road static right-lane closure sign. Thirty-five percent of the participants in the CV scenario merged into the open lanes following the road static lane closure sign. Distinctively, one participant performed a late merge at the taper area in the CV scenario against an earlier merge in the baseline scenario. Figure 17-A shows the lane exceedance behavior and Figure 17-B shows the percent of time off-lane obtained from the driving simulator dynamics.



A- Subfigure A - Lane exceedances



B- Subfigure B - Percent time off-lane

Figure 17 Lane Exceedance Behavior for Truck Drivers Experiment

The analysis of the effects of CV WZ notifications on lateral control reveals that the frequency of lane exceedances slightly increased, however, with no statistcial significance. The notable increase in the percent time off-lane implies that the participants took longer time to correct the vehicle's lateral position when out of the lane. This finding could be predictable given that multiple warnings, in the form of visual and audible warnings, were communicated to the participants within a short period of time. As a result, participants may have been compelled to frequently divert their attention away from the road to the HMI. It is noteworthy to emphasize here that the WZ application was not tested under normal driving conditions but rather under complex conditions in the form of poor visibility. All in all, the design of the notifications appears to satisfy the distraction acceptance criteria by the AAM [114]. Nonetheles, it is important that the HMI design upgrades be directed toward reducing the distraction introduced from the display of the HMI notifications.

The early lane merge behaviors observed in the CV scenario reveal that the majority of participants were aware and effectively processed the information communicated over the HMI. More importantly, the drivers benefited from the early lane closure warning by merging into the open lane well ahead of the taper zone, a behavior the FHWA highly recommends for truck drivers [21]. Hence, early lane closure warning has a strong potential to reduce late and aggressive lane merges performed by truck drivers in real-life settings. At the same time, findings indicate that a smaller group may have still relied on the road static signs for guidance, despite the presence of the CV notifications. Moreover, distraction is also suspected of deteriorating the performance for one driver manifested in the late merge performed at the taper zone, in the CV scenario, compared with the baseline scenario. Overall, potential areas of improvement include improving drivers' perception of the HMI warnings, while minimizing potential distraction effects. To this end, future work will leverage eye-tracking data to develop a clearer understanding of the truck drivers' behavior.

6.2 The Effectiveness of the HMI in Miltigating the Effect of Secondary Crashes

The designed driving simulator scenario to test the impact of the HMI on secondary crashes was a divided two-way four-lane freeway to simulate the driving environment of I-80 during the winter season. All the surrounding roadside features were covered in snow. The pavement surface was built to simulate a lightly snow-covered surface, which was close to dry road surface condition, and the visibility was clear. The posted speed was 75mph, with low traffic volumes to represent the rural driving conditions, in Wyoming. The scenario started with very light snow weather, where the first TIM#1 was displayed on the HMI, showing a 75 mph regular speed limit and a snow notification. Driving conditions remained clear until the subject vehicle passed the first curve, in which the participant received TIM#2, showing 65 mph VSL, as the snow intensity will be increasing. Visibility and weather conditions started to deteriorate before reaching the second curve. The participants received a notification, TIM#3, showing a severe weather condition and 50 mph VSL. Severe weather conditions and low visibility were simulated after passing the second curve. Subsequently, the participants received a distress notification stating that there was a road closure due to an accident, which is shown in TIM#4. A rerouting TIM#5 notification was displayed, showing that there was a nearby truck parking area at the upcoming exit. About 0.75 miles (1.2 km) ahead, a crash scene was simulated behind a third curve. It is worth mentioning that the content of the TIMs was generally adopted from the MUTCD standard signs. The signs in the MUTCD are standard signs that are commonly used, easy to understand and convey the required message. A schematic layout of the designed driving scenario is shown in Figure 18.

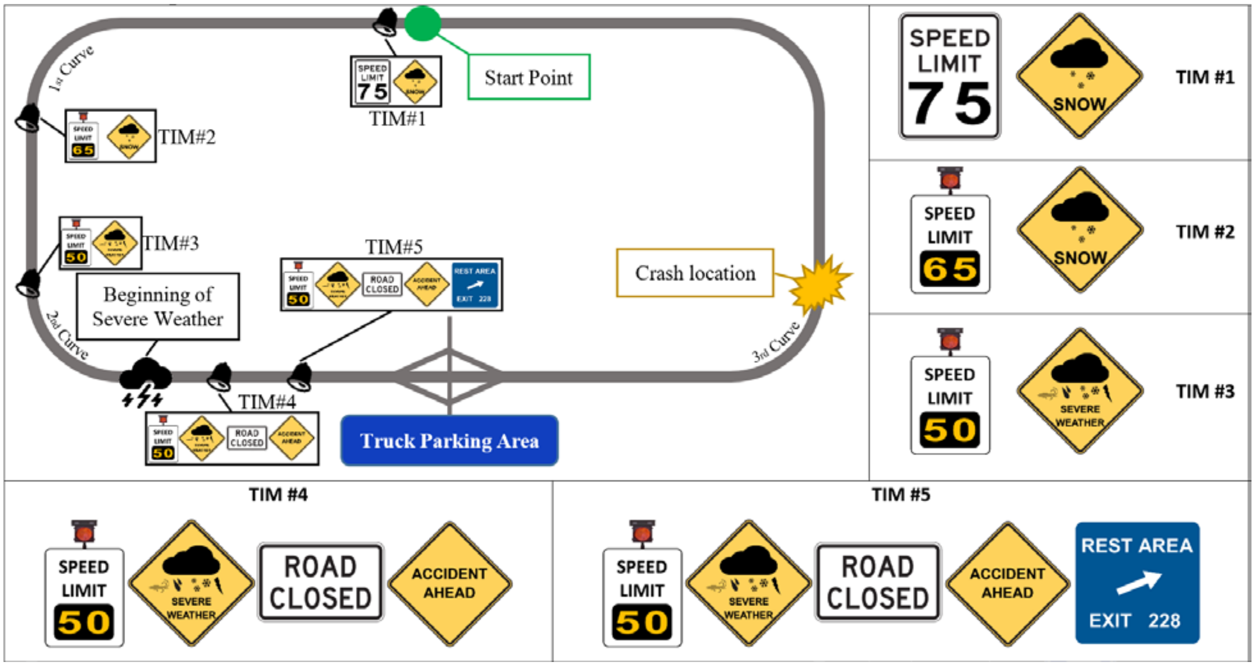


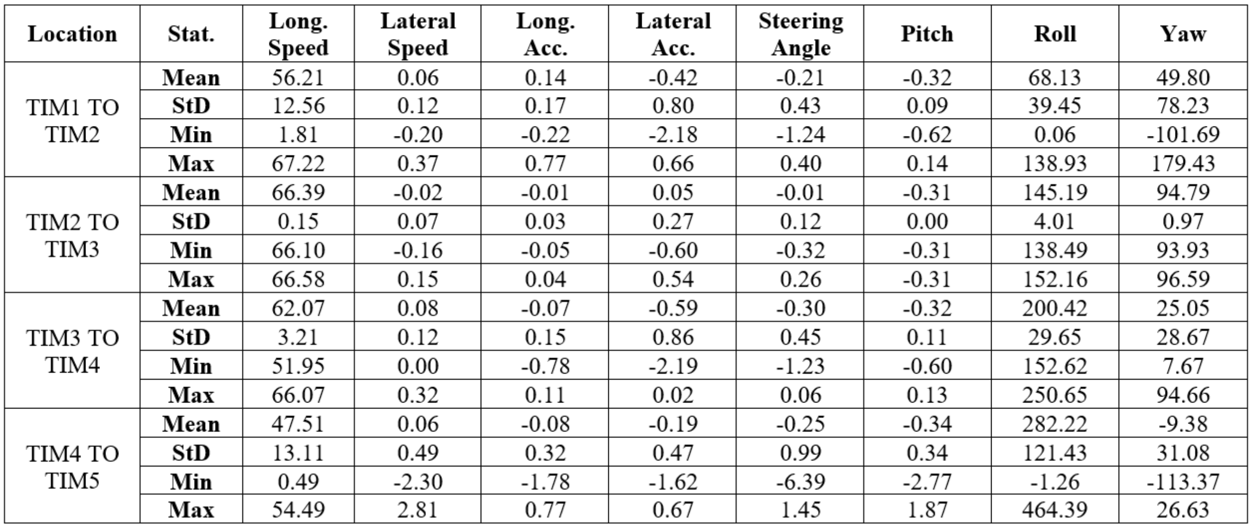
Figure 18 Driving Simulator Scenario Layout

All the communicated TIMs were associated with a beep sound to notify the participant that a new warning was displayed on the HMI. It is worth mentioning that TIMs with high importance were displayed on the far left side of the HMI (i.e., regulatory and advisory speed limits), which is the closest side to the drivers' eyesight. Less important notifications were displayed on the middle part of the HMI (i.e., snow, severe weather, road closed, accident ahead). At the far right side of the HMI screen, TIMs with the lowest importance were displayed (i.e., rest area exit).

This study is part of the CV pilot deployment project, in Wyoming, where several notifications were tested in the UW driving simulator. Each participant drove a total of six main scenarios, in addition to two mini-training scenarios, and a warmup scenario. To eliminate the learning effect for participants, scenarios were randomly assigned to each participant. Additionally, changes to the surrounding static environment (e.g., side slopes, horizontal curve direction, etc.) were simulated while maintaining the main dynamic events geographically at the same locations. The experimental design and the random order were adopted to facilitate the scenario comparison between CV and non-CV.

The total length of the driving scenario was about 5.9 miles (9.5 km). The data observations were averaged every 32.8ft (10m), where the subject vehicle can pass this distance in less than a second for all the designed operating speeds. Vehicle trajectories for the 23 participants were extracted and averaged for the CV and the non-CV scenarios on the 10m aggregation level. The scenario was divided into multiple sections based on the expected change in driving behavior of participants while encountering the different designed events. Mainly, the sections were located between the communicated TIMs. Table 8 and Table 9 show the descriptive analysis of the extracted driving simulator parameters for the CV and the baseline scenarios.

Table 8 Descriptive Analysis of the Driving Simulator Vehicle Kinematics for the Non-Connected Vehicle Scenario (baseline Scenario)



Location	Stat.	Long. Speed	Lateral Speed	Long. Acc.	Lateral Acc.	Steering Angle	Pitch	Roll	Yaw
TIM1 TO TIM2	**Mean**	56.21	0.06	0.14	-0.42	-0.21	-0.32	68.13	49.80
	StD	12.56	0.12	0.17	0.80	0.43	0.09	39.45	78.23
	Min	1.81	-0.20	-0.22	-2.18	-1.24	-0.62	0.06	-101.69
	Max	67.22	0.37	0.77	0.66	0.40	0.14	138.93	179.43
TIM2 TO TIM3	**Mean**	66.39	-0.02	-0.01	0.05	-0.01	-0.31	145.19	94.79
	StD	0.15	0.07	0.03	0.27	0.12	0.00	4.01	0.97
	Min	66.10	-0.16	-0.05	-0.60	-0.32	-0.31	138.49	93.93
	Max	66.58	0.15	0.04	0.54	0.26	-0.31	152.16	96.59
TIM3 TO TIM4	**Mean**	62.07	0.08	-0.07	-0.59	-0.30	-0.32	200.42	25.05
	StD	3.21	0.12	0.15	0.86	0.45	0.11	29.65	28.67
	Min	51.95	0.00	-0.78	-2.19	-1.23	-0.60	152.62	7.67
	Max	66.07	0.32	0.11	0.02	0.06	0.13	250.65	94.66
TIM4 TO TIM5	**Mean**	47.51	0.06	-0.08	-0.19	-0.25	-0.34	282.22	-9.38
	StD	13.11	0.49	0.32	0.47	0.99	0.34	121.43	31.08
	Min	0.49	-2.30	-1.78	-1.62	-6.39	-2.77	-1.26	-113.37
	Max	54.49	2.81	0.77	0.67	1.45	1.87	464.39	26.63

Table 9 Descriptive Analysis of the Driving Simulator Vehicle Kinematics for the Connected Vehicle Scenario

Location	Stat.	Long. Speed	Lateral Speed	Long. Acc.	Lateral Acc.	Steering Angle	Pitch	Roll	Yaw
TIM1 TO TIM2	**Mean**	55.40	0.04	0.13	-0.39	-0.18	-0.28	-0.83	41.38
	StD	11.85	0.09	0.16	0.73	0.37	0.10	1.59	82.31
	Min	1.88	-0.18	-0.25	-2.06	-1.14	-0.58	-4.23	-164.26
	Max	64.22	0.26	0.68	0.65	0.35	0.20	0.23	179.05
TIM2 TO TIM3	**Mean**	60.63	-0.01	-0.20	0.04	-0.02	-0.29	-0.02	90.94
	StD	1.90	0.05	0.15	0.26	0.12	0.00	0.09	1.05
	Min	58.34	-0.12	-0.55	-0.59	-0.32	-0.29	-0.20	90.07
	Max	63.52	0.13	0.07	0.52	0.25	-0.28	0.22	92.96
TIM3 TO TIM4	**Mean**	47.21	-0.01	-0.06	-0.34	-0.08	-0.28	-1.25	18.21
	StD	4.99	0.03	0.15	0.49	0.14	0.10	1.90	30.14
	Min	43.56	-0.07	-1.00	-1.33	-0.49	-0.60	-4.48	-0.25
	Max	58.29	0.14	0.08	0.02	0.13	0.14	0.23	90.58
TIM4 TO TIM5	**Mean**	31.49	-0.01	-0.09	-0.05	0.01	-0.29	-0.28	28.04
	StD	9.28	0.11	0.44	0.35	1.30	0.49	0.72	49.06
	Min	2.13	-0.26	-2.47	-1.36	-2.56	-1.75	-2.45	-132.33
	Max	44.31	0.84	0.58	1.72	9.85	0.83	0.53	158.91

Comparing the mean speed for the first section (between TIM#1 and TIM#2), almost 2 mph difference was found, with nearly the same standard deviation value for CV and non-CV scenarios. This shows that the performance of the drivers in the first section was not different for CV and non-CV scenarios.

To decide on the suitable statistical test that should be applied to compare the two means of speed for CV and non-CV scenarios, the speed distribution should be initially investigated. Using the Kolmogorov Smirnov test, it was found that the two distributions were not normally distributed with a P-value of 0.034 and 0.047 for CV and non-CV scenarios, respectively. Accordingly, the nonparametric Mann-Whitney U test was employed to compare the two scenarios.

The core analysis performed on the driving simulator parameters focused on the speed as the main safety performance measure, and Surrogate Measure of Safety (SMoS) was considered to evaluate the CV pilot performance [117]. Figure 19 shows the speed profile of the subject vehicle operation under the CV and non-CV conditions averaged over the 23 participants. It was expected to have an insignificant difference in operating speed for the CV and the non-CV at the first section of the developed scenarios, which is located between TIM#1 and TIM#2. Figure 19 showed that the two trajectories in this section almost have the same average speed.

Mann-Whitney U test was conducted to statistically assess whether the two-speed trajectories are different or not. The nonparametric test was selected because the two-speed profiles were not normally distributed. The results showed that the means of the speed profiles were not significantly different at the first section located between TIM#1 and TIM#2 (U=10368, P = 0.174). This result depicted that the behavior of the drivers for the two scenarios were similar before receiving the reduced speed limit, in which the average speed for the non-CV and the CV scenarios were 56.21 and 55.40 mph, respectively.

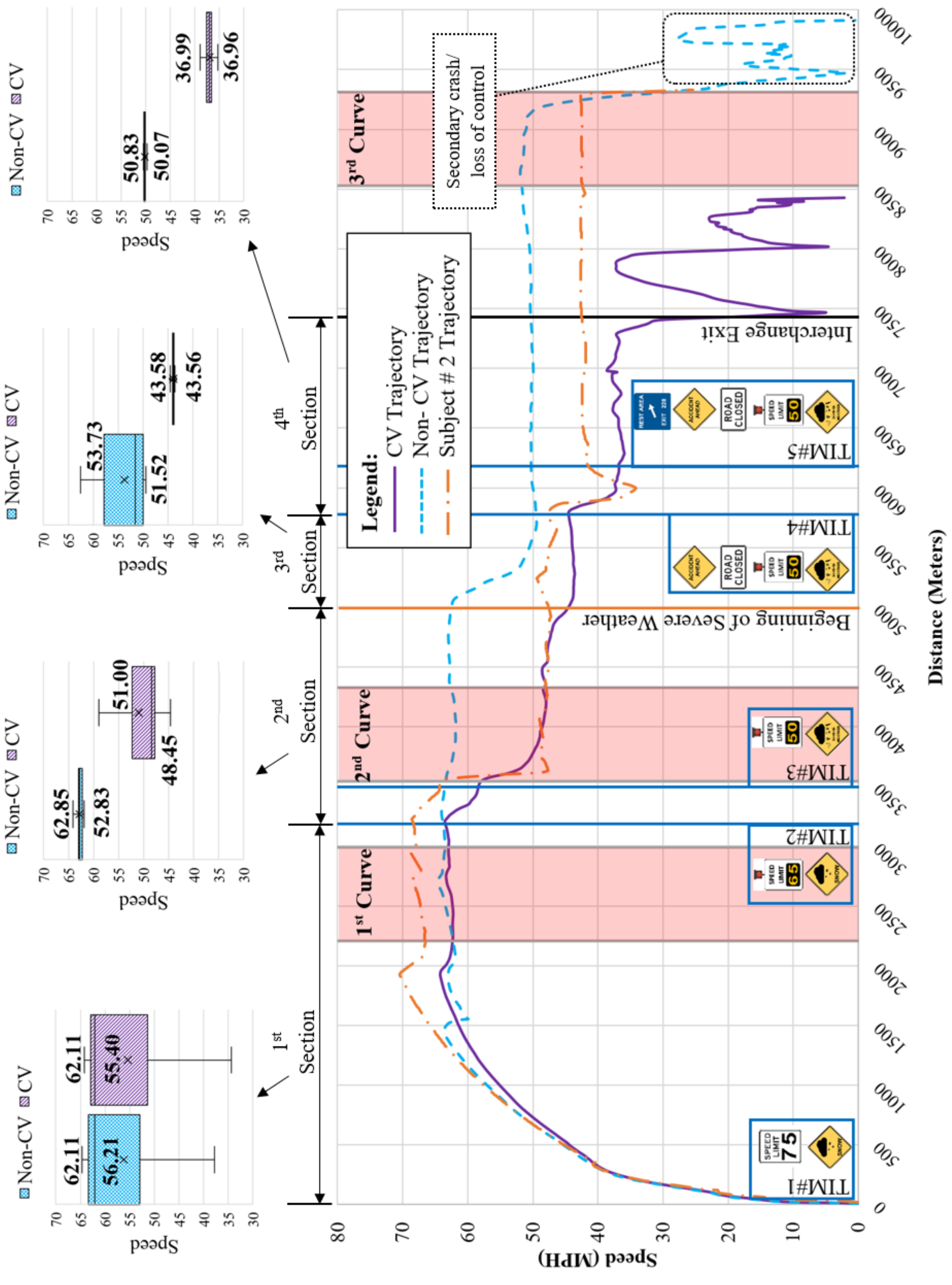


Figure 19 Subject Vehicle Trajectories for CV and non-CV Scenarios

A variation in speed selection between the CV and non-CV scenarios after disseminating TIM#2 was observed. This change in speed selection in the CV scenario was a result of the provided operating speed of 65 mph, which acted as the actionable element for the communicated message. Providing a warning notification, accompanied with an appropriate executable action, would increase the driver's compliance to the communicated message (2, 3). The Mann-Whitney test Value showed that there was a statistical difference between the average selected speed in the second section, located between TIM#2 and the beginning of the weather event (U=17637, P<0.0001). The box plot for the second section, in Figure 19, shows that the average speed for the CV scenario (48.54mph) was less than the average speed of the non-CV scenario (62.83mph). This reduction in speed highlights the benefits obtained from the CV notifications communicated in TIM#2 and TIM#3 on speed selection, as it reflects the optimum speed appropriate for the condition. It is worth mentioning that TIM#3 included a regulatory speed of 50 mph and a severe weather notification that alerted the drivers of the upcoming weather event, which would be encountered one mile ahead of the location where the notification was received.

A gradual reduction in the speed until the participants entered the severe weather section could be observed in the CV speed profile. The speed profile for the non-CV scenarios showed a sudden drop in the speed at a distance of 500 meters from the start point of the adverse weather (5000 m), as they encountered a suddenly reduced visibility. The average speed for the non-CV profile from the weather event till TIM#4 was 53.73 mph, with a higher speed variation compared to the CV scenario. The difference in average speeds between the two driving scenarios was significantly different (U=3160, P=0.0001). This result showed that the CV notification had a dual impact on drivers; 1) reduced their operating speed, and 2) reduced the speed variation among drivers. This is in line with a wide body of literature that reduction in speed variability would help in enhancing the overall safety, especially when encountering a severe weather event with reduced visibility [118]–[121].

At the location where TIM#4 was initiated, a further reduction in speed was observed for the CV scenarios. TIM#4 delivered a message that there was a crash ahead of their current location, and they expected to see a road closure due to this crash. This information increased the situational awareness for the CV scenario drivers. They adopted a more cautious, focused, and alerted driving behavior as they expected an upcoming hazardous situation, which explains the observed consistent less variable reduction in speed. The statistical test showed a significant difference between the average speed of the CV and the non-CV scenario (U=13861, P<0.0001) for the speed profiles in the forth section.

Information on the upcoming truck rest area was communicated before an exit located on the interstate. The results showed that 22 out of 23 drivers (95.7 percent) exited the roadway. Only one participant decided to continue driving using the designed scenario to reach the crash location without exiting the roadway. It could be observed from the speed profile of the non-CV drivers that they continued driving at a speed of 50 mph until they reached the crash scene location. A sudden variation in speed and several spikes could be observed right after the third curve, where the crash scene was simulated. This speed behavior shows that the drivers were involved in a secondary crash and/or lost control of the subject vehicle because of encountering stalled traffic due to a crash. The video recordings showed that 100 percent of the non-CV drivers were involved in a secondary crash. The speed profile showed a significant speed variation at the end of the graph, which represented their unsuccessful attempt to maintain control on the vehicle and avoid the secondary crash. It is worth mentioning that simulating crashes in the 3 Degrees of Freedom (DOF) WyoSafe driving simulator lab was not favored by the IRB, due to the potential adverse impact on the participants. Accordingly, when the participants passed through a simulated plane sensor, a secondary crash was recorded. This observation signifies the importance of the CV notifications, where it showed its benefit in reducing secondary crashes. Communicating timely information about upcoming hazardous situations would help in saving lives, reducing road injuries, and enhancing traffic safety on our roadways.

Figure 19 also included the speed profile of the only CV driver that decided not to exit the roadway at the rest area exit. The participant speed profile showed that the driver adopted a higher speed than the mean speed, although he did not exceed the provided regulatory speed. After receiving the road closure notification, he adopted a speed limit of nearly 43 mph, which was lower than the displayed speed by about 7 mph. The participant kept maintaining a stable speed until he reached the crash scene. The driving simulator recordings showed that the participant was able to avoid a secondary crash and stopped safely before colliding with the simulated crashed vehicles.

6.3 Driver Ratings for the CV Applications Communicated Using the HMI

Drivers' ease of understanding and perception of the effectiveness of the CV notifications were assessed using a seven-point Likert Scale. Ease of understanding ranking range from 1 to 7 where a ranking of 1 denotes “not easy to understand”. Similar scale progression is used for assessing the effectiveness of the CV notifications. Furthermore, drivers’ subjective assessment of the distraction introduced from the CV notifications was also collected (1: extremely distracting, 4: moderately distracting, 7: not distracting at all). Driver ratings are illustrated in the box plots in Figure 20. The majority of participants found both the adverse weather and WZ notifications effective for the real-world and easy to understand. In terms of the distraction brought about by the display of notifications on the HMI, the majority of participants ranked CV applications between being not distracting at all and moderately distracting. Remarkably, 15 percent of participants ranked CV notifications for being more than moderately distracting. Moreover, 65 percent of the participants reported that CV technology would provide the highest benefit under poor visibility conditions compared to lower rankings for other conditions (daytime, nighttime, slippery road, and vision blocked).

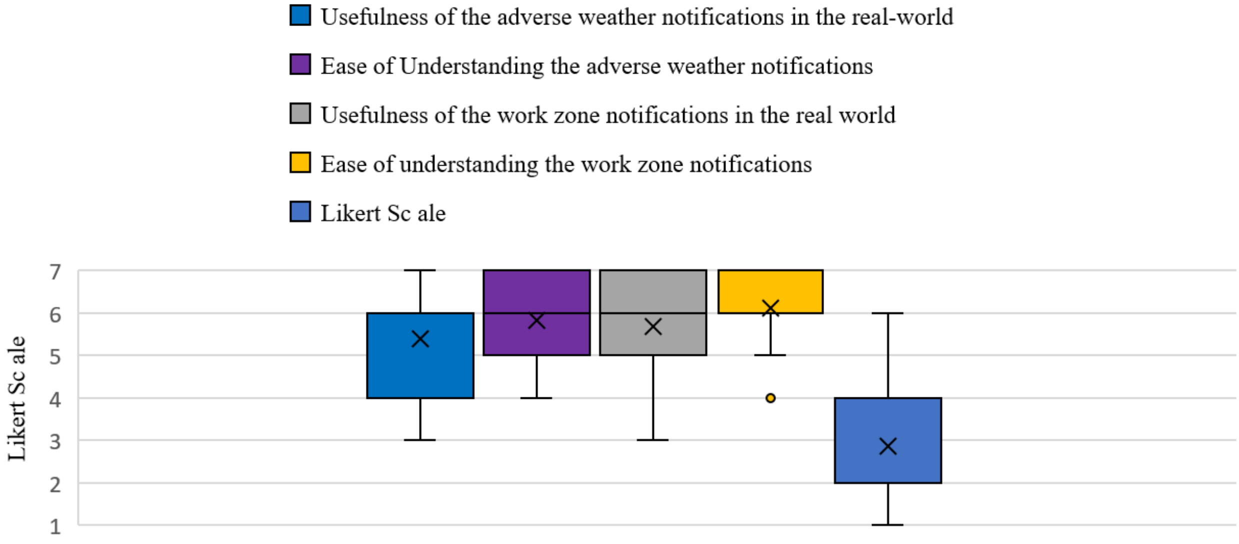


Figure 20 Driver Ratings on a Seven-Point Likert Scale

The analysis of driver ratings demonstrates that both the weather and WZ CV notifications were effective in conveying information to the drivers. Furthermore, both applications gained high driver approval as being effective for the real world [122]. In addition, participants perceived CV notifications to be the most effective during poor visibility conditions [122]. These results suggest that CV applications have high potential to garner widespread public approval and adoption among the community of truck drivers. While most participants’ rankings indicate experiencing a slight to moderate distraction from the CV notifications, few participants’ rankings suggest that they experienced more than moderate levels of distraction. Thus, reducing the distraction emanating from the WZ HMI notifications proved again to be of importance[123] [122].

CHAPTER 7. EVALUATION OF THE HMI PERFORMANCE FOR HIGHWAY PATROL

This chapter provides the analyses and results obtained from the highway patrol experiment to evaluate the HMI for the CV pilot. Two scenarios were developed and tested for highway patrol experiment, in which each scenario was driven under CV technology, as well as disabling the CV notifications. Additionally, several communication modalities were investigated. The driver behaviors and vehicle dynamics were evaluated to assess the performance of the HMI. Furthermore, the distraction and workload added by the presence of the HMI was assessed using performance measures from the vehicle dynamics as well utilizing the eye tracking data.

7.1 Data Analysis and Dependent Variables

Several CV notifications were provided to the participants throughout the driving experiment. However, these notifications can be clustered together as SWIW and WZW. The performance was evaluated separately for these two CV applications. The first included the performance and driving behavior of subjects' in an adverse weather with slippery roads. Several CV warnings were provided to the subjects as they approached the slippery road. These included advisory speed limits and ice patches ahead notifications. Similarly, for the work zone scenario, different WZ notifications were provided, which included the WZ ahead, speed limits, and lane closure warnings. Several vehicle dynamic measures, such as speeds, brake activation, lane offsets, slip, and standard deviations were obtained for the different modalities and compared. Since the work zones passed through a foggy area, it is noteworthy to mention that the effects of WZW on driving performance may have included the effects of exposure to the fog. For the slippery road scenario, the most critical section was the slippery road surface. Thus, the effects of different notifications on this slippery curve was focused more in the study. Longitudinal control, lateral control, and brake activations in the slippery curve were compared between the modalities to see if the CV modalities performance was any better than the non-CV baseline scenario. For the work zone scenario, the speed profiles inside the activity and advance warnings areas were evaluated and the brake activation following a FCW notification was compared between the modalities.

To investigate and compare the driver behavior before and after the CV notifications, data was reduced and extracted for five seconds before the notification, five seconds during the notification and five seconds after the notification. The five second analysis interval gives an indication of immediate/short term driver behavior before, during, and after a notification location [116]. Similarly, the data was examined for time intervals of 20 seconds before and after a notification. The 20 second analysis window reflects how a driver responds to notifications over a longer time [116]. For the five second analysis, a during time window was taken into consideration as the message would take about five seconds to be delivered completely and to be perceived by the driver.

Since different participants travelled at different speeds, the spatial coordinates of the locations of CV notifications were considered for comparison. Although no CV warnings were presented in the baseline scenario, the comparison was performed based on the performance of the participants at these locations. Descriptive statistics and inferential statistics were performed using R-Studio and IBM SPSS software. Paired and one sample t tests, one-way Analysis of Variance (ANOVA) were used to assess the differences between the performance at a five percent significance level. All post-hoc tests were done using Bonferroni correction. The different modalities tested could be concluded as follows:

- baseline with no CV notifications.
- Enlarged Icons with Beeps (EBeeps)
- Enlarged Icons with Voice (EVoice)
- Small Icons with Beeps (SBeeps)

7.2 Effects of Weather Notifications on Driver Behavior

In the Slipper Road Scenario, three different SWIW notifications were presented, ice patches ahead", speed limit 65 mph, and speed limit 55 mph. The aim of all these notifications was to prepare the participants for the icy and slippery curve that could be presented on the road. Thus, the performance of the participants in these slippery curves would show whether the CV warnings were effective or not. To assess the impact of the ice patches notifications, the first slippery curve, shown in Figure 21, was taken into consideration because it was the first curve with slippery road and showed the real effect of CV notifications. For the second curve, the results were biased as the participants who drove through the first curve would follow the CV warnings and adjust their speeds accordingly, thus leading to better results.

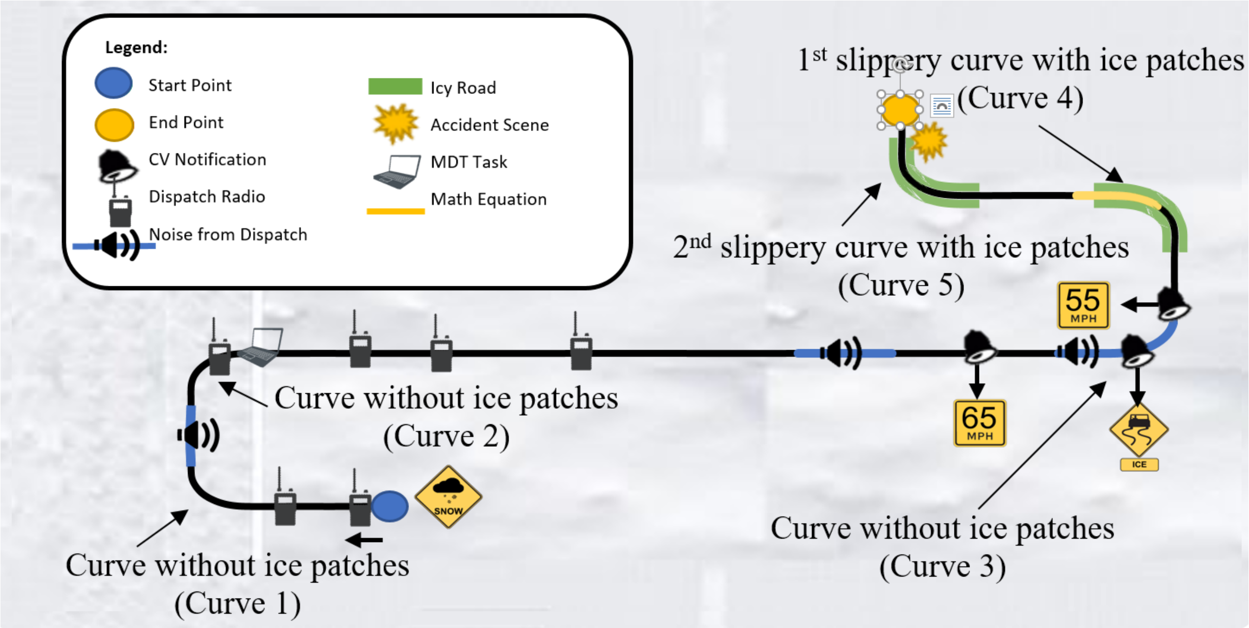


Figure 21 Slippery Road Scenario for the Highway Patrol Driving Simulator Experiment

7.2.1 Effects on Longitudinal Control

Figure 22 shows the average speeds of all the participants in different modalities for curve 4. At the start of the curve, the average speed of participants was about 87 mph for baseline. Once they got into the curve, the participants started decreasing their speeds, but six of the nine participants could not retain control in the slippery curve and slipped off the road. However, for the CV modalities, the participants received CV notifications beforehand, alerting them about the icy road conditions ahead, and they also received a notification about the safe advisory speed limit on the curve. The speed at the start of the curve was about 69 mph, 65 mph, and 63 mph for EBeeps, EVoice and SBeeps designs, respectively. Even though these speeds were higher than the advisory speed of 55 mph, the participants were careful and passed safely through the icy curve. Only one participant crashed in the EBeeps modality, and there were no crashes in EVoice and SBeeps modalities. The speed of the participants entering the curve (average speed for the first 10 meters of Curve 4) was found to be significantly different for the baseline and the CV modalities ($F_{(3,31)} = 14.836$; $p<0.001$). A Bonferroni post-hoc test revealed that the speed in the baseline scenario was significantly higher than each of the CV modalities. There was no significant difference in the entering speeds between any of the CV modalities.

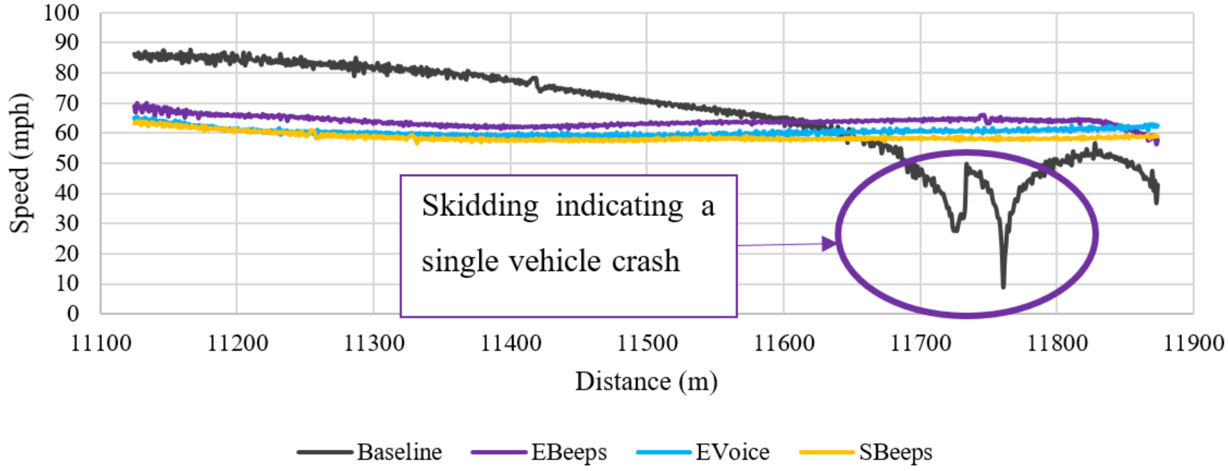


Figure 22 The Average Speeds of Participants in Different Modalities on Curve 4

Just before the accident by about an average distance of 33 feet (10 meters) before accident, the mean speed of the participants was still significantly higher in the baseline scenario compared to the CV modalities ($F_{(3,31)}$=22.221, $p<0.001$). There was no significant difference in average speeds between the CV modalities.

7.2.2 Effects on Lateral Control

Similarly, Figure 23 shows the average lane offset of all the participants for Curve 4. For the baseline scenario, after about 655 feet (200 meters) into the curve, the participants could not keep a lane at all with the cars slipping continuously from one lane to the other. The smoothest and the least fluctuations among all the CV modalities was found to be in EVoice and EBeeps modalities. This means that the participants drove much carefully and followed the safe advisory speed limit provided prior to the start of Curve 4 when provided with CV notifications.

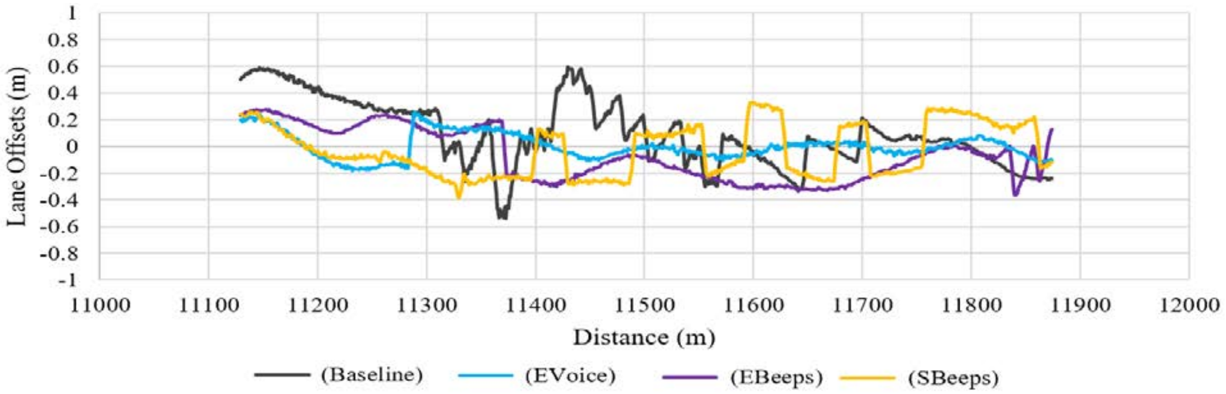


Figure 23 The Average Lane Offset of Participants in Different Modalities in Curve 4

7.2.3 Effects on Brake Activation

Figure 24 shows the average brake activation within Curve 4 for all the participants in different modalities. It can be seen that for all the CV modalities (EBeeps, EVoice, and SBeeps), the participants seem to be applying brakes well before the start of the curve until about 7 miles (11,300 m) into the experimental track where they reach a speed of about 62 mph. The braking behavior is a result of the safe advisory speed (55 mph) provided to the participants to navigate through the slippery curve. On the other hand, for the baseline scenario there was no brakes applied at the start of the curve. Once the cars started slipping away from the road, the participants seemed to be applying brakes abruptly. Also, the participants applied the brakes firmly as opposed to the CV scenarios where the braking was slow and smooth. Using a one-way ANOVA, the brake activation of the participants entering the curve (average brake activation for the first 33 feet (10 meters) of Curve 4) was found to be significantly different for the baseline and the CV modalities ($F_{(3,31)}$=2.953; p=0.048). A Bonferroni post-hoc test revealed that the brake activation was significant higher in Enlarged Beeps modality compared to the baseline scenario. No significant difference in brake activation was found between the other modalities. Similarly, just before the accident the brake activation was significantly higher for the baseline modality compared to each of the CV modalities ($F_{(3,31)}$=3.706,p=0.022).

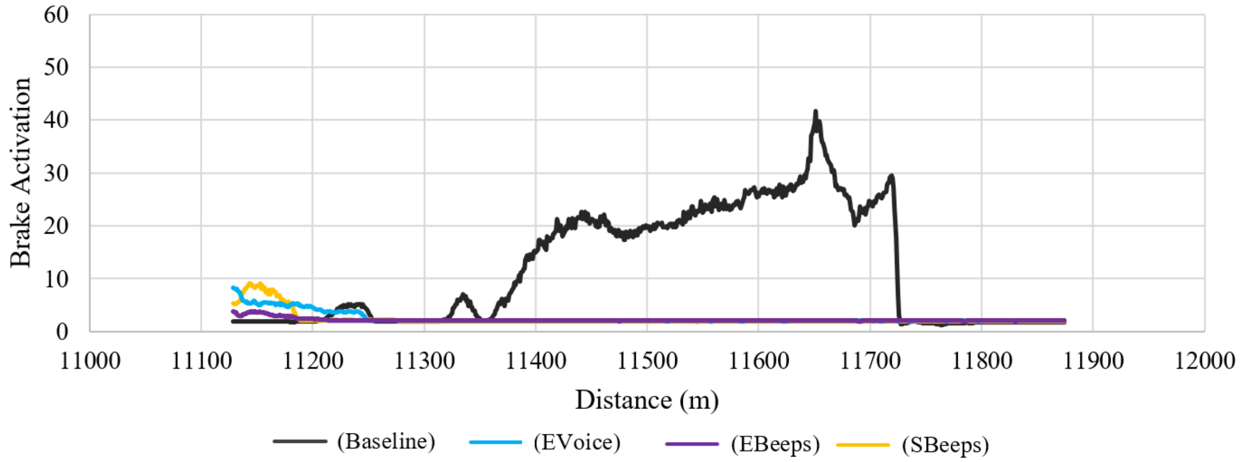


Figure 24 The Average Brake Activation in Different Modalities for Curve 4.

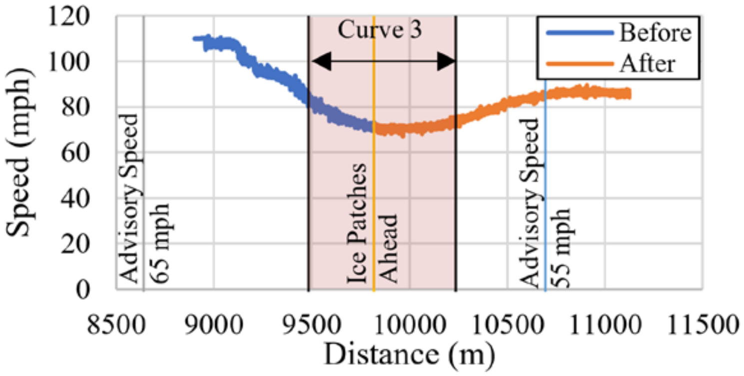
Comparisons of speeds, lane offsets, and brake activation were done for five seconds before the notification, five seconds during the notification, and five seconds after the notification for each of the notifications in each of the non-CV, as well as the CV modalities. A one-way ANOVA was used to compare the performance measures in different time frames for different modalities.

For the slippery road scenarios, based on a one-way ANOVA, there was a significant difference between the mean speeds for the different modalities in the five seconds before period ($F_{(3,31)}$=4.563; p=0.009), five seconds during period ($F_{(3,31)}$ =5.278; p=0.005), as well as the five seconds after period ($F_{(3,31)}$ =8.106; p<0.001) of the Advisory 55 mph notification. For the five second before period and five second during period, the baseline scenario had significantly higher mean speeds compared to the EVoice modality and the SBeeps modality. Similarly, for the five second after period, the mean speed was significantly higher in the baseline scenario compared to each of the CV modalities. There was found to be no significant difference between the mean speeds, mean lane offsets or mean brake for the other two CV notifications.

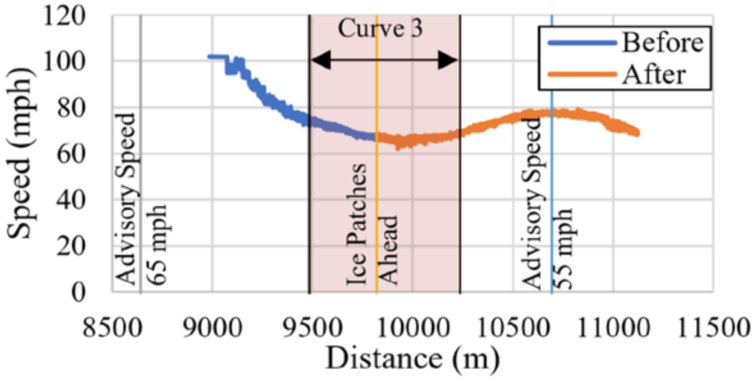
Like the five-seconds analysis, the speeds, lane offsets and brake activation were analyzed for 20 seconds before a notification is played to 20 seconds after the notification. A comparison was done between the different modalities for these 20 second intervals using a one-way ANOVA.

For the slippery road scenarios, a significant difference was found in the mean speeds between the modalities in the 20 seconds before period, as well as the 20 seconds after period for ice patches ahead notification and advisory 55 mph speed limit ahead notification. Twenty seconds before the ice patches ahead notification was played, the participants seemed to have a significantly higher mean speed values for the baseline scenario compared to the SBeeps modality ($F_{(3,31)}$=3.679;p=0.023). Also, they had a higher standard deviation value compared to the CV modalities. Twenty seconds after the ice patches ahead notification was played, the participants seemed to decrease their speeds for the CV modalities, whereas, there was no decrease in speed for the baseline scenario. The baseline scenario had a significantly higher speed 20 seconds after the notification compared to the SBeeps and EVoice modalities ($F_{(3,31)}$= 4.186; p=0.014). Similarly, before the advisory 55 mph notification was played, the participants had significantly lower mean speeds in the EVoice modality compared to the baseline scenario ($F_{(3,31)}$=3.326; p=0.032). More interestingly, 20 seconds after the notification was played, all the CV modalities seemed to have a significantly lower speeds than the baseline scenario ($F_{(3,31)}$=13.642; p <0.001). The participants seemed to brake harder in the baseline scenario compared to each of the CV modalities.

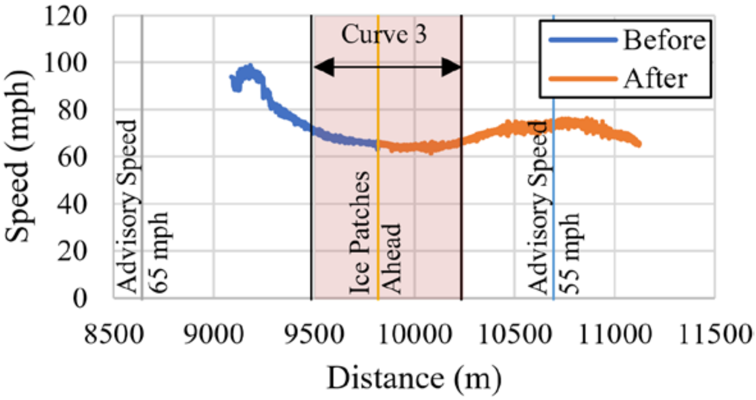
The ice patches ahead notification is the most critical, as it informs the drivers about the possibility of slick spots or black ice area ahead, and chances of accident if driving at high speeds. Thus, to visualize the effects of this notification, graphs of speed versus distance were created for 20 seconds before and 20 seconds after the notification, as shown in Figure 25-A to Figure 25-D . During this analysis interval, three different CV notifications were provided. First, an advisory speed limit of 65 mph, second the ice patches ahead notification, and third an advisory speed of 55 mph. The analysis interval also included Curve 3. Prior to the advisory speed of 65 mph, the participants were found to be speeding in all modalities. For baseline, they were traveling at about 110 mph in average, whereas for all CV modalities the velocity was 100 mph in average at the start of analysis interval. The speed eventually dropped to an average of 70 mph for the baseline scenario, and 65 mph for all CV scenarios as they reached the center of Curve 3 where they were provided with the ice patches ahead notification. As the participants left Curve 3, they started speeding again in all four modalities. However, soon they encountered another advisory speed limit of 55 mph in the CV modalities, after which the participants were found to be slowing down unlike the baseline scenario. The entering speed in Curve 4 (curve with ice patches) for baseline was about 84 mph, whereas it was 68 mph, 64 mph, and 63 mph for enlarged icons with beeps, enlarged icons with voice, and small icons with beeps, respectively.



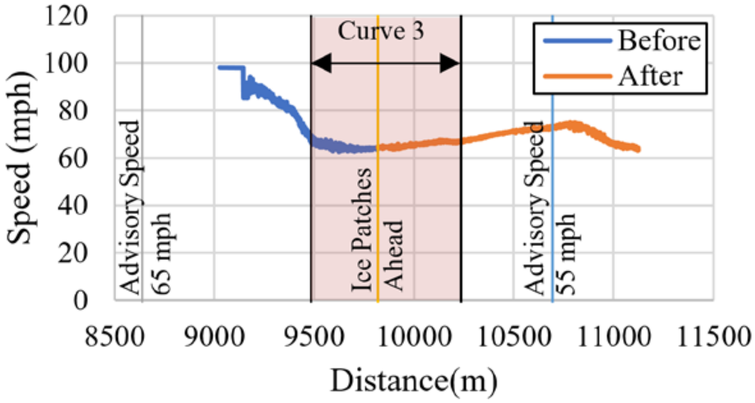
A- Subfigure A - baseline Scenario



B- Subfigure B - Enlarged Icons with Beeps



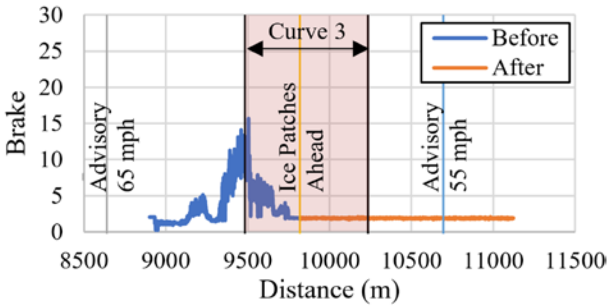
C- Subfigure C - Enlarged Icons with Voice



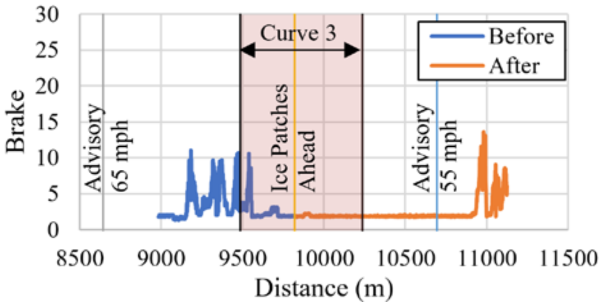
D- Subfigure D - Small Icons with Beeps

Figure 25 Average Velocity 20s Before and After "Ice Patches Ahead" Notifications

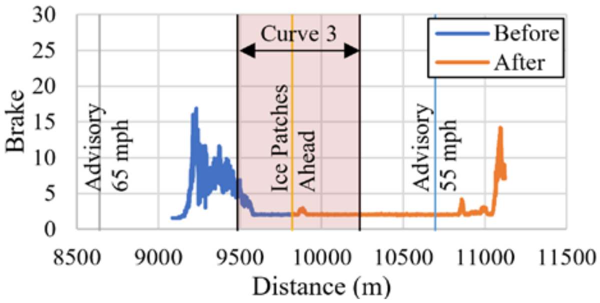
Similarly, graphs were plotted for brake activation versus distance to see how the participants braked in the different modalities when provided with the CV notifications. Figure 26-A to Figure 26-D show the graphs for average brake activation of all participants 20 seconds before the ice patch ahead notification and after the notification until the start of curve 4. In the baseline scenario, no brakes were applied at the location of ice patch ahead notification or advisory 55 mph notification. However, for all other CV modalities, slight braking was applied after the ice patch ahead notification and the participants braked harder when they got the 55 mph ahead notification.



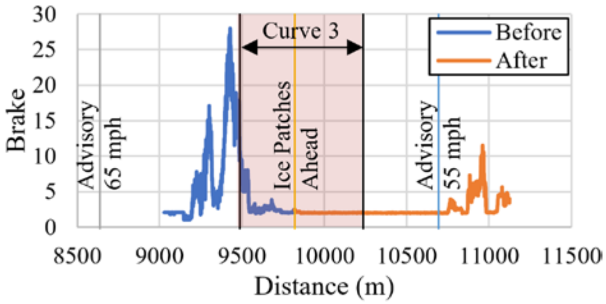
A- Subfigure A - baseline Scenario



B- Subfigure B - Enlarged Icons with Beeps



C- Subfigure C - Enlarged Icons with Voice



D- Subfigure D - Small Icons with Beeps

Figure 26 Brake Activation 20s Before and After the "Ice Patches Ahead" Notification

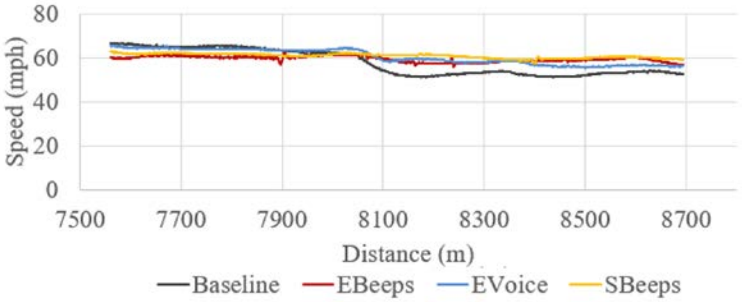
7.3 Effects of Work Zone notifications on Driver Behavior

As the participants approached the WZ area, they were provided with four different WZ notifications. Since these notifications are provided at short intervals, there is a possibility of the effects being overlapped. Thus, to look at the effects of the notifications, the notifications are aggregated over space:

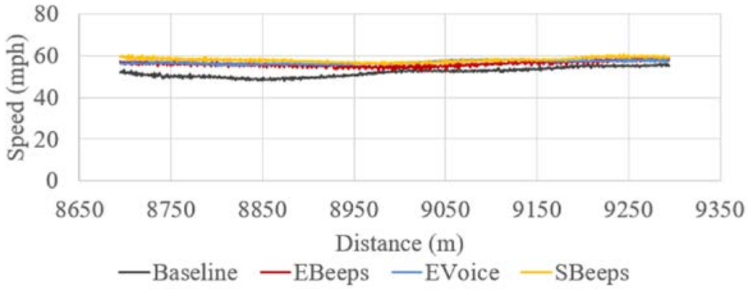
1. Advance Warning Zone
    a. "Work Zone 1 mile ahead" to "Speed Limit 45 mph" (Before 45 mph)
    b. "Speed Limit 45 mph" to "Right Lane Closed" (After 45 mph)
2. Activity Area

7.3.1 Effects on Longitudinal Control

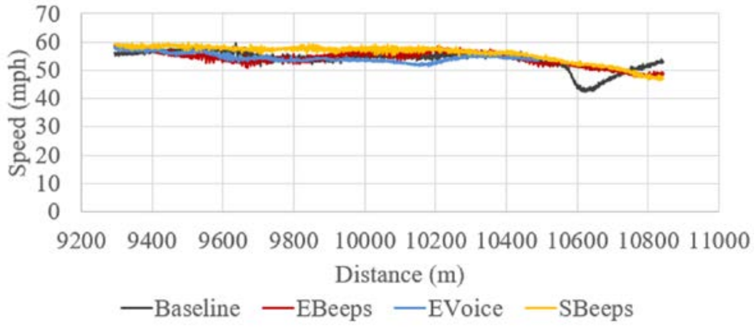
Speed profile plots were prepared for the different WZ areas as shown in Figure 27. In the Activity Area, the speed profiles for the four modalities seemed to be the same as given in Figure 27-C. However, in the both the advanced warning zones, the speeds in CV scenarios seemed to be higher than the speeds in the baseline scenario, as depicted in Figure 27-A and Figure 27-B. The CV notifications did not seem to make any significant impacts in the advance warning zones.



A- Subfigure A- Speed profile before the 45mph work zone speed limit



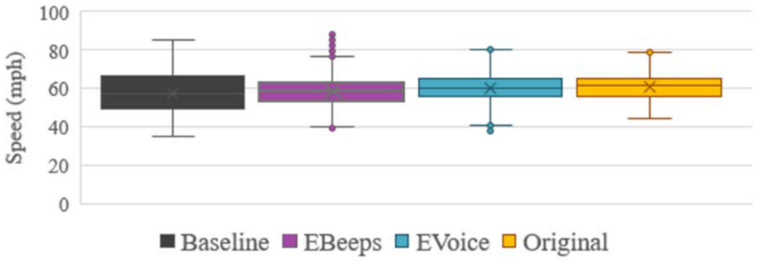
B- Subfigure B - Speed profile after the 45mph WZ speed limit



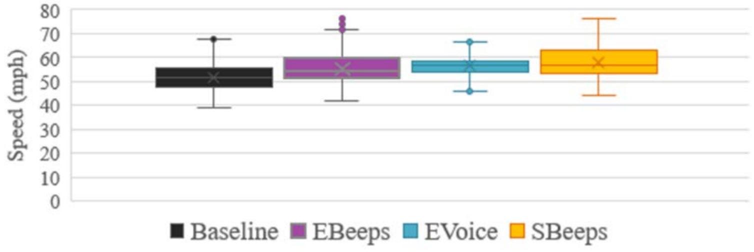
C- Subfigure C -Speed profile in activity area

Figure 27 Speed Profiles in Advance Warning Zones and Activity Area

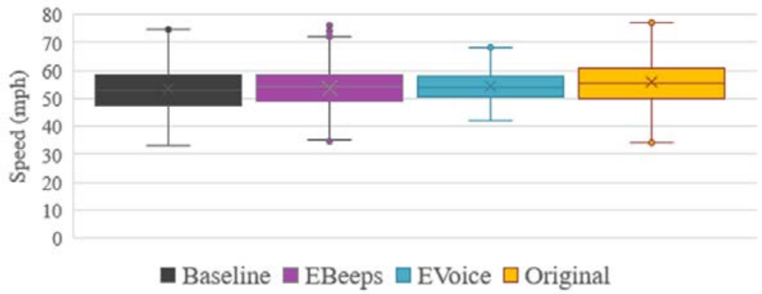
Figure 28 shows the boxplots created to assess the speeds varied between the scenarios in different WZ areas. The mean speeds in the advance warning zones before 45-mph was almost similar for all scenarios. However, the baseline scenario seemed to have a higher variability compared to the CV scenarios prior to the 45-mph speed limit area. For the advance warning zone after the 45-mph speed limit, the CV scenarios seemed to perform worse than baseline with the speeds being higher than the mean speeds in baseline scenario. EVoice had the least variability and SBeeps had the highest variation and the highest speeds. Finally, in the Activity Area, the participants had very similar speeds for all the scenarios (CV and non-CV). EVoice had the least variability in the speed. In addition, no statistical significance was found for the difference in mean speed between the three WZ areas at a five percent significance level.



A- Subfigure A - Speed profile before the 45mph WZ speed limit



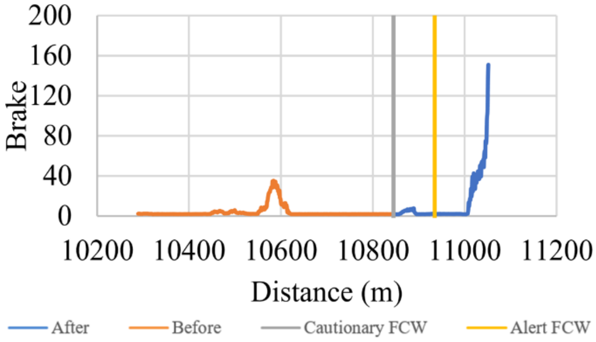
B- Subfigure B - Speed profile after the 45mph work zone speed limit



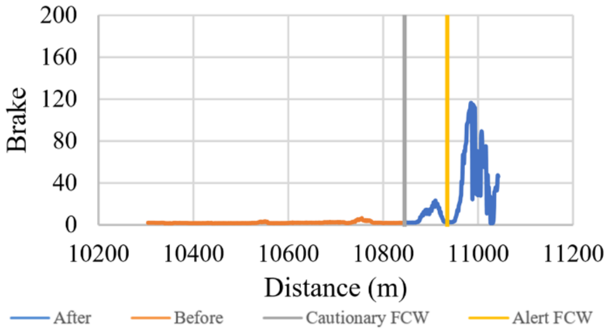
C- Subfigure C - Speed profile in activity area

Figure 28 Boxplots for the Variation in Speeds between different Modalities in Advance Warning Zones and Activity Area.

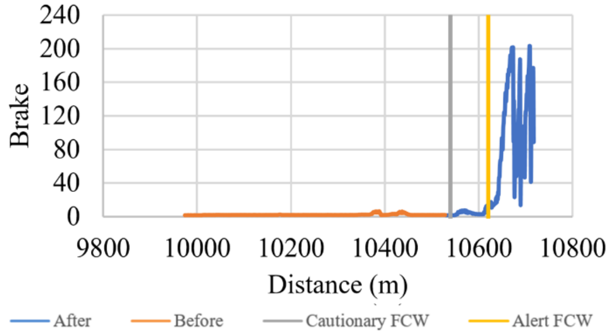
To investigate the participants' behavior receiving the FCW warnings, a graph of brake activation versus distance was plotted, as shown in Figure 29. The graph shows that the participants driving in CV scenarios seemed to apply brakes mildly after the cautionary yellow FCW sign was presented. However, the brake application at this location in the baseline scenario was very low compared to the other CV modalities. For the CV modalities, the participants seemed to apply brakes immediately after receiving the alert notification bringing the vehicles to stop. However, in the baseline scenario the participants were not able to anticipate the impending collision and applied brakes abruptly only after they came very close to the crash scene.



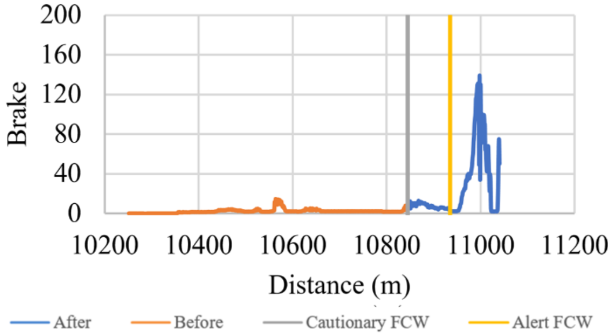
A- Subfigure A - baseline scenario



B- Subfigure B - Enlarged icons with beeps scenario



C- Subfigure C - Enlarged icons with voice scenario



D- Subfigure D - Small icons with beeps scenario

Figure 29 The Brake Activation 20secondsBefore and 20secondsAfter the FCW.

7.3.2 Five Second Analysis Interval

Comparisons of speeds, lane offsets, and brake activation were done for five seconds before the notification, five seconds during the notification, and five seconds after the notification, for each of the notifications in each of the non-CV, as well as the CV modalities. A one-way ANOVA was used to compare the performance measures in different time frames for different modalities.

For the WZ scenario, based on a one-way ANOVA, there was found to be no significant difference between any modalities for five seconds before, five seconds during, or five seconds after any of the notifications. The only significant difference found was between the mean braking on FCW notification. For FCW, a significant difference was found between the modalities in five seconds after the notification ($F_{(3,31)}$=5.465; p=0.004). The participants in baseline were found to be braking at a significantly higher rate than the participants in the EBeeps and the participants in SBeeps modality. Although not significantly different, the mean speeds in most of the baseline modalities was found to be higher than the mean speeds in CV modalities.

7.3.3 Twenty Seconds Analysis Interval:

Similar to the five-seconds analysis, the speeds, lane offsets, and brake activation were analyzed for 20 seconds before a notification is played to 20 seconds after the notification. A comparison was done between the different modalities for these 20 second intervals using a one-way ANOVA.

For the WZ scenario, based on a one-way ANOVA, there was no significant difference between any of the modalities 20 second before the notification or 20 second after the notification for any of the notifications apart from work zone (WZ) 1 mile ahead and FCW. For the WZ 1 mile ahead notification, a significant difference in mean brake activation was found between the modalities for 20 seconds after the notification was played. The baseline scenario had a higher brake activation compared to each of the CV modalities ($F_{(3,31)}$=4.187; ,0=0.013). For the FCW, the mean speeds were significantly different between baseline and EBeeps, baseline and EVoice, and baseline and SBeeps for the 20second time window after the notification was played ($F_{(3,31)}$=36.522;p<0.001). For all these cases, the baseline had a higher mean speed value. Also, the brake activation was found to be significantly higher for the EVoice modality compared to the baseline scenario ($F_{(3,31)}$=4.363; p=0.011).

7.4 General Insights of the Effectiveness of the HMI for Highway Patrol

Before discussing the results of the experiment, it is noteworthy to mention that the driving behavior of highway officers is completely different from the driving behavior of normal drivers. The nature of their job requires them to drive at high speeds regardless of the road and weather conditions. This makes it difficult to see if the CV warnings are helping the law enforcement drivers perform better. Furthermore, the distractions due to secondary tasks and cognitive workload makes it even more difficult to see if the introduction of CV system actually makes an impact. Moreover, due to the requirement to attend the emergency scene, as soon as possible, the troopers cannot be mandated to follow each and every advisory warning. The officers were nevertheless provided a training on the importance of the CV warnings. The E-training module provided the participants with a thorough knowledge about the different CV warnings. The trainees were advised to follow all the warnings as far as possible, if not drive carefully, and follow the most important CV warnings, such as the FCW without any delay.

7.4.1 Effects on Weather Notifications

A five second before/after analysis showed that the advisory 55 mph speed limit did produce significant change in the mean speeds of the drivers in the CV modalities. The drivers had significantly lower speed five seconds after the notification compared to five seconds before the notification. This shows that once the advisory 55 mph CV warning was provided, the drivers seemed to lower the speed in all the CV modalities. For the non-CV modality however, no change in speed was found five seconds before the notification location, and five seconds during or after the notification. The participants did not seem to react immediately following the 65-mph speed limit notification and ice patches ahead notification. However, a 20 second before/after analysis showed that the participants decreased their speeds following the ice patches ahead notification, as well. SBeeps and EVoice modality had the most significant reduction in speed following the ice patches ahead notification. The slow reaction to this notification might be because the participants had already lowered their speeds following the advisory 55 mph notification, so they did not feel the necessity to lower their speeds until they came close to the ice patches.

The CV warnings also brought out a significant decrease in lane offsets and improved the lateral control. EVoice and EBeeps modalities seemed to have the least lane offsets. Similarly, the brake activation analysis showed that the participants benefited more with the CV warnings as they braked well in advance to the icy curve, unlike the baseline scenariowhere the participants braked only after they started to slip.

Overall, the advisory weather warnings notifications seemed to produce significant improvement in the driving behavior of the officers. Hence, the exposure to the CV notifications has the potential to prepare the motorists beforehand about the dangers lying ahead, and to navigate them safely through hazardous road and weather conditions in rural freeway settings.

7.4.2 Effects of Work Zone Notifications

Both five-second and 20 second analysis showed no significant difference in mean speeds, lane offsets, or brake activation before and after each of the notifications in any of the modalities. The comparison of mean speeds between the baseline and the CV modalities for the different WZ zones did not present any significant difference. Interestingly, the drivers seemed to have slightly higher speeds for each of the CV modalities compared to the baseline in the AWZ. This might be because the participants relied on CV warnings to notify them of any critical situations ahead, and thus drove faster to reach the accident scene. Additionally, for the baseline, the WZ signs are placed only on the roadside so driving at high speed under heavy a foggy condition might cause missing out on these signs, however, in the CV scenarios, warnings were presented on the HMI screen so there was less chance of missing out on the WZ signs.

In overall, the WZ warnings did not produce a significant difference in the driver behavior. It, however, might have resulted in over reliability on the CV warnings leading to increased speed.

7.4.3 Effects of Forward Collision Warning Notification

A five-second and 20 second analysis showed that in each of the CV modalities, the participants braked smoothly following the cautionary and alert FCW. For the baseline, however, the participants braked at the very last moment and braked very hard trying to bring the vehicle to stop. For CV modalities, once the cautionary FCW yellow was provided, the participants slowed down, which made it easier for them to come to a complete halt when the alert FCW red went off. According to several studies, FCW system has the ability to reduce rear-end collision from as low as 7 percent to as high as 80 percent [124]. This study corroborates to the findings of several other papers which show that FCW is an effective way to decrease rear-end collisions.

CHAPTER 8. ASSESSMENT OF THE WORKLOAD AND DISTRACTION INTRODUCED BY THE HMI

Truck cab and highway partol vehicles are equipped with mutliple control systems and dashboards are continusly used as secondary tasks while driving based on the task and vehicle operation needs. This chapter deals with the distraction potential of the CV HMI display in highway. The focus of this chapter is to assess the CV warnings, and to see whether these notifications are easy to understand, and whether they cause any distractions or workloads on drivers. Most HMI's convey vital information via the display unit which require drivers to take glances off road. The WYDOT CV Pilot also includes an in-vehicle display unit mounted on the cab. To analyze the level of workload and distraction caused by the CV HMI, psycho-physiological measures (eye tracking data), performance measures (vehicle kinematics data), and subjective measures (questionnaire surveys) were employed.

Adding a display to the crowded interior of the cab might impose and increased workload or add a distraction to the driver. To ensure a safe operation for the drivers, an assessment of the introduced workload and distraction for adding the HMI was conducted. Vehicle dynamics and an advaced eye tracking system were used in the assessment process. The assessment was conducted to truck drivers as well highway patrol.

8.1 Eye Tracking Parameters and Data Collection

Eye tracking technologies produce a huge amount of data. To understand this data, it is important to first understand some basic eye movements' terminologies.

1. Fixations

   A fixation occurs when the eyes gaze are stationary i.e. when a person fixates his eyes to a particular target. The target area under fixation is generally considered to be visually attended to by the observer. According to International Organization for Standardization (ISO) 2014 standards, fixations generally vary between 100 to 2000 millisecond for in-vehicle devices. Fixations lower than 100ms are very rare. Thus, this study uses only the fixations which are greater than 100ms.

2. Saccades

   These are fast eye movements used to bring images of particular areas of the visual world to fall onto the fovea. Saccades occur between fixations points.

3. Glance Duration:

A glance duration is the total time that starts from the point in time at which a driver begins directing their gaze toward the area of interest or target until the point in time at which the driver moves away from the area of interest [33] [39].

4. Gaze Direction:

A gaze direction describes the direction of the gaze and is calculated as the average of the two gaze vectors originating at the physical eyes [125].

The eye tracking system consisted of three eye tracking cameras from Smart Eye Pro. Smart Eye Pro is a non-intrusive video based head and gaze tracking system which uses cameras at different locations to measure both the subjects head position and gaze directions [125]. The system installed at WyoSafeSim lab had three cameras. Two cameras were placed on the top of the dashboard and one camera was mounted to the right of the mid console, as shown in Figure 30. This allowed both the eyes to be tracked in almost all the directions.

Figure 30 Smart Eye Cameras Mounting Locations

To operate the smart eye tracking system, the following tasks had to be completed [125]:

1. Assembling the system: The system had to be assembled and mounted in such a way that the cameras are directed directly to the eyes and are not blocked by any objects. To make sure that the eye tracking system captures all eye movements in all directions, two cameras were mounted on the dashboard, one to the left of the driver and one to the right, and one

camera was mounted to the right of the driver on the side of the mid-console. This would allow accurate measures even when the driver moved his head to look at the HMI.

2. Calibration: Proper calibration of the cameras were performed for each participant at the start of the driving simulator experiment, once the warmup drive was completed. To calibrate the cameras, the participants had to move a chessboard in-front of the cameras and their relative position was calculated.
3. World Coordinate System (WCS): To relate the eye tracking measurements to the real world, a world coordinate system was developed. The measurements of each object of the driving simulator to predefined reference points were measured to develop the WCS.
4. Profile: Personal profiles were developed for each test subject. This allowed the eye tracking software to create a personal profile with features like nostrils, ears, corners of the eyes and mouths, and centers of the eyes.

8.2 Limitations with the Eye Tracking System and Correction techniques

The eye tracking system is considered an efficient tool to detect the location were participants are focusing on within the tested scenarios. However, the eye tracking system might suffer from several limitations. Below are the main limitations encountered while utilizing the eye tracking system.

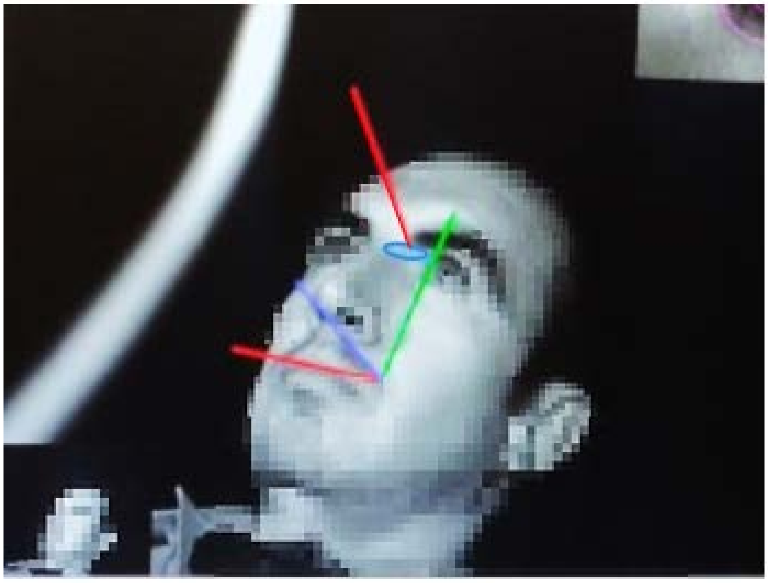
1. Noise Reductions

To reduce the noise in eye tracking data, filtration techniques must be used. Noise reduction was achieved by applying moving averages to smoothen the data where required.

2. Eye Tracking calibration

Since the simulator used for this study was a high-fidelity driving simulator with high degree of freedom, accidents or driving on bumps, lead to abrupt jolting and rattling of simulator vehicle that caused the eye tracking cameras to lose calibration as the cameras were attached to the driving simulator body. Thus, most of the scenarios played after the baseline scenario (as it had more accidents) had an error on eye calibration. To compensate this error, each of the eye tracking videos had to be reviewed individually, and the 3D world model had to be adjusted accordingly for each participant to make sure the participant's gaze intersected the correct objects. Figure 31-A shows an accurate eye tracking calibration, while Figure 31-B shows the shift in the eye detection location due to the calibration loss.

A- Subfigure A - Accurate eye identification



B- Subfigure B - Inaccurate eye identification

Figure 31 Picture Showing Before/After Calibration Loss

3. Track Loss

Track loss is a major issue encountered in eye tracking research. Track loss occurs when eye tracker cannot estimate the gaze position due to several reasons. In this driving simulator experiment, the main causes of track loss were loss of calibration due to accidents. To compensate for the track loss, the fixations were taken into account and any track loss that occurs between fixations were disregarded. Furthermore, modes of the closest world intersection (i.e. the closest intersection with any of the world objects) were taken to fill in all the track losses. This was further verified by comparing the glance durations obtained with video logs from the driving simulator.

Eye tracking data was collected on all nine participants who operated the simulator.

8.3 Eye Tracking Analysis for Highway Patrol

To visualize the eye tracking data, heat maps were plotted for the two different scenarios. The heat maps show how the eye glances are distributed throughout the different driving simulator objects. The close world intersection points on world model for x and y directions were extracted for all the scenarios. Python coding was done to obtain the heat maps. To obtain a smooth heat map a Gaussian kernel density estimation was performed with dispersion = 32 sigma. Once the heat plots were obtained, they were overlapped on the real-life picture of the driving simulator using certain reference points. Figure 32-A and Figure 32-B show the developed heat maps for the slippery road and the WZ scenarios, respectively.

A- Subfigure A - Slippery road surface scenario

B- Subfigure B - Work zone scenario

Figure 32 Heat map showing density of eye-tracking gaze points

From the generated heat maps, the participants had the highest number of glances on road, which is in line with the main driving task. The maximum number of glances were focused on the center screen. Some glances were distributed to the side-view mirrors and some to the rear-view mirrors. The glances were also distributed around the cluster. Apart from that the HMI also seemed to demand some glances. However, the frequency of these glances was small as the participant can see from the color coding. The location of the MDT seemed to cause track loss due to the large head movements it required.

From the heat maps it was seen that the WZ scenario seemed to have a higher number of glances around the CV HMI display. This might be because the WZ scenario had seven different CV notifications, whereas the slippery road scenario only had three different notifications. This heat map shows that the CV HMI display unit did induce several glances on the HMI causing a significant amount of distraction.

8.3.1 Descriptive Analysis for Eye Tracking Parameters for Slippery Road Scenario:

For the Slippery Road scenario, several SWIW) warnings were provided. First, an advisory 65 mph ahead notification was presented followed by an ice patch ahead notification, and an advisory 55 mph ahead notification. Table 10 represents the summary statistics of the glances for the slippery road surface scenario.

Table 10 Summary of HMI Glances during the Slippery Road Scenario

Modality	Mean HMI Glance Duration (s)	Std Dev of Glance Duration(s) on HMI	Mean of Total number of Glances on HMI across modalities	Maximum Glance Duration (s)
SREBeeps	0.55	0.38	33	2.35
SREVoice	0.59	0.33	31	1.76
SRSBeeps	0.64	0.45	34	3.95

A combined total of 833 glances were made on the HMI for all the participants, for the three CV modalities of slippery road scenario. The SRSBeeps modality seemed to demand the highest glance duration (0.64s on average), and had the highest standard deviation (0.45 seconds) among the three modalities followed by SREVoice (0.59 seconds on average). Similarly, for the number of glances, SREBeeps had the highest number of glances (34 glances on average) on the CV HMI display. SREVoice and SRSBeeps had almost equal number of glances on HMI. The maximum time spent glancing on the HMI was 3.95 seconds for SRSBeeps, 2.35 seconds for SREBeeps, and 1.76 seconds for SREVoice. Table 11 shows the mean glance duration and count of glances for the highway patrol participants.

Table 11 Mean Glance Duration and Count of Glances in the Slipper Road Scenario

Participant Number	Mean Glance Duration (s)	Average # of Glances
1	0.768	26.5
3	0.626	27
4	0.528	35.67
5	0.487	16.33
6	0.597	41.33
7	0.627	39.67
8	0.597	32.33
9	0.628	44
10	0.531	25.33

It is worth noting that participant 5 and participant 10 were found to have the mean glance durations (0.487 seconds and 0.531 seconds, respectively), and the mean number of glances on HMI (16.33 and 25.33 respectively), which were lower than the other participants and were the only participants who did not slip off the road. This might suggest that participants who spend less time glancing at the HMI are less distracted, which highlight the importance of getting familiar and used to the HMI and the CV system.

The eye tracking data was further analyzed to see if the HMI produces any distractions. NHTSA's guideline recommends that for any in-vehicle devices and any glances that lasts more than 2 seconds are considered a distraction. NHTSA, however, states that the guideline does not apply to emergency vehicles, including the law enforcement vehicles [126]. That is because, the law enforcement vehicles and other emergency vehicles need to perform tasks, such as entering GPS coordinates and looking up maps while driving. Nevertheless, to make sure that the HMI is safe for interaction, the recommendations of NHTSA for distraction (i.e. 2 seconds) is taken as a reference to evaluate distraction potential of the device. From the analysis of glance durations, five cases of distraction were observed. Four in the SRSBeeps modality and one in the SREBeeps modality for the slippery road scenario, as shown in Table 12. It was observed that most of the distractions occurred in small icons with beeps modality.

Table 12 Distraction Cases (HMI Glance Duration >2s) for Slippery Road Scenario

Participant	Modality	HMI Glance Duration (s)
6	Small Icons with Beeps (SRSBeeps)	3.95
7	Small Icons with Beeps (SRSBeeps)	2.3
8	Enlarged Icons with Beeps (SREBeeps)	2.35
9	Small Icons with Beeps (SRSBeeps)	2.27
8	Small Icons with Beeps (SRSBeeps)	2.35

Figure 33 shows the distribution of the glances with relatively longer durations. A total of 43 glances (5.16 percent of all glances) in the SBeeps modality had time greater than 1 second. Both SREBeeps (3.24 percent) and SREVoice (3.12 percent) seemed to have an equal number of glances with time greater than 1 second. SREVoice (0.72 percent) had the least number of glances greater than 1.5 second and no glances were greater than 2 seconds. The SRSBeeps modality seemed to demand the longest glance time with 12 glances being greater than 1.5 seconds (1.44 percent) and 4 glances being greater than 4 seconds (0.48 percent).

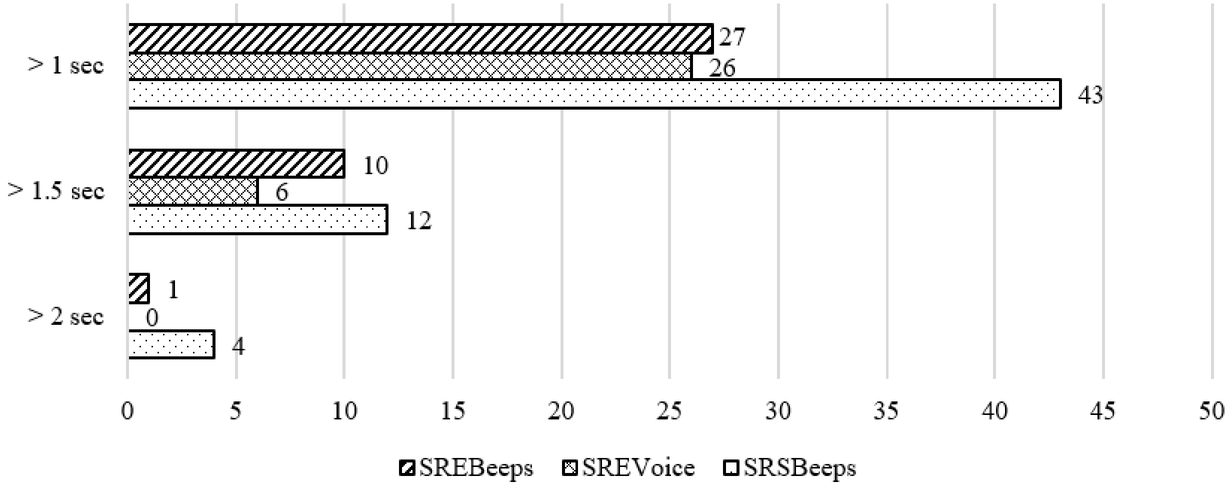


Figure 33 The Counts of Mean Glances for Times Greater than 1 second, 1.5 seconds, and 2 seconds for Slippery Road Scenario.

8.3.2 Descriptive Statistics for Work Zone Scenario

In the WZ senerio, the participants made a combined total of 990 glances on the CV HMI display. Table 13 shows that the WZSBeeps modality seemed to demand the highest glance duration (0.69s on average) and had the highest standard deviation (0.47s) among the three modalities, followed by SREVoice (0.65s on average). Similarly, for the number of glances, WZSBeeps had the highest number of glances (39 glances on average) on HMI whereas; WZEBeeps had the least number of glances. Out of the nine participants who drove the simulator, the highest amount of time spent glancing at the HMI was for WZSBeeps modality with one of the glances being as high as 4.17s.

Table 13 Summary of HMI Glances during the Work Zone Scenario

Modality	Mean (s)	SD Dev	Maximum
WZEBeeps	0.59	0.36	2.05
WZEVoice	0.65	0.40	2.45
WZSBeeps	0.69	0.47	4.17

Similarly, as shown in Table 14, the WZ scenario had nine cases of distraction, four in WZSBeeps modality, three in WZEVoice modality, and two in WZEBeeps modality. Participant number 4 seemed to be the most distracted with 6 instances of distraction and the highest time glancing on HMI being as high as 4.16secondsin WZSBeeps modality.

Table 14 Distraction Cases (HMI Glance Duration >2s)

Participant	Modality	HMI Glance Duration (s)
1	Small Icons with Beeps (WZSBeeps)	3.65 s
3	Enlarged Icons with Voice (WZEVoice)	2.45 s
4	Enlarged Icons with Beeps (WZEBeeps)	2.05 s
4	Enlarged Icons with Beeps (WZEBeeps)	2.03 s
4	Enlarged Icons with Voice (WZEVoice)	2.20 s
4	Small Icons with Beeps (WZSBeeps)	4.16 s
4	Small Icons with Beeps (WZSBeeps)	2.17 s
6	Small Icons with Beeps (WZSBeeps)	2.67 s
7	Small Icons with Beeps (WZSBeeps)	2.25 s

Figure 34 shows the HMI glances with relatively long glance durations (greater than one second). WZEVoice had almost the same number of glances with duration greater than one second as the WZSBeeps modality. WZEBeeps had the lowest number of glances greater than one second. Similarly, WZEBeeps had the least number of glances greater than 1.5 sec and only 2 glances greater than 2 seconds. WZEVoice and WZSBeeps had almost the equal number of glances greater than 1.5 second. WZSBeeps had the most distraction cases with five glances being greater than two seconds.

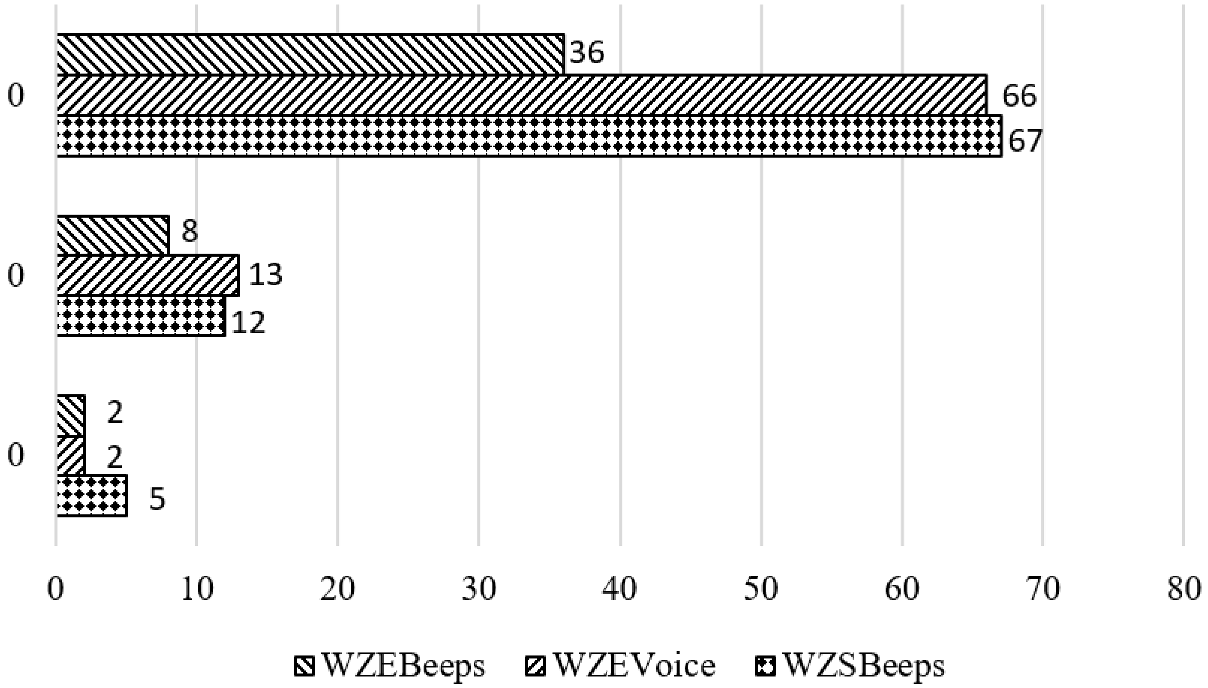
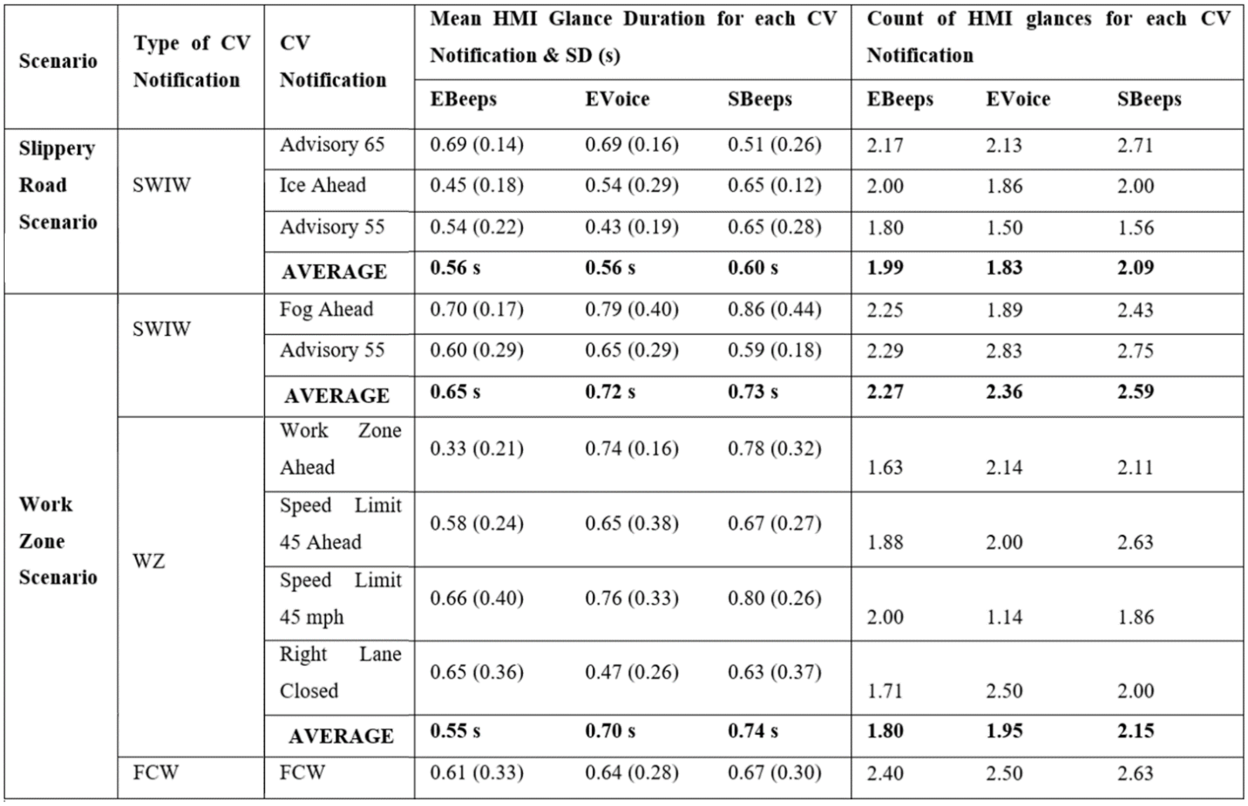


Figure 34 The Counts of Mean Glances for Times Greater than 1 second, 1.5 seconds and 2 seconds for the Work Zone Scenario.

Based on the 15 second rule recommended by Green (1999), a task time limit of 15 second was considered [127]. Table 15 shows the visual demands of each of the CV notifications for the two scenarios for different modalities. These glance durations were obtained based on a 15 second time interval after the notifications were played [127].

Table 15 Visual Demand Metrics by CV Applications and Different CV Modalities



Scenario	Type of CV Notification	CV Notification	Mean HMI Glance Duration for each CV Notification & SD (s)			Count of HMI glances for each CV Notification		
			EBeeps	EVoice	SBeeps	EBeeps	EVoice	SBeeps
Slippery Road Scenario	SWIW	Advisory 65	0.69 (0.14)	0.69 (0.16)	0.51 (0.26)	2.17	2.13	2.71
		Ice Ahead	0.45 (0.18)	0.54 (0.29)	0.65 (0.12)	2.00	1.86	2.00
		Advisory 55	0.54 (0.22)	0.43 (0.19)	0.65 (0.28)	1.80	1.50	1.56
		AVERAGE	**0.56 s**	**0.56 s**	**0.60 s**	**1.99**	**1.83**	**2.09**
Work Zone Scenario	SWIW	Fog Ahead	0.70 (0.17)	0.79 (0.40)	0.86 (0.44)	2.25	1.89	2.43
		Advisory 55	0.60 (0.29)	0.65 (0.29)	0.59 (0.18)	2.29	2.83	2.75
		AVERAGE	**0.65 s**	**0.72 s**	**0.73 s**	**2.27**	**2.36**	**2.59**
	WZ	Work Zone Ahead	0.33 (0.21)	0.74 (0.16)	0.78 (0.32)	1.63	2.14	2.11
		Speed Limit 45 Ahead	0.58 (0.24)	0.65 (0.38)	0.67 (0.27)	1.88	2.00	2.63
		Speed Limit 45 mph	0.66 (0.40)	0.76 (0.33)	0.80 (0.26)	2.00	1.14	1.86
		Right Lane Closed	0.65 (0.36)	0.47 (0.26)	0.63 (0.37)	1.71	2.50	2.00
		AVERAGE	**0.55 s**	**0.70 s**	**0.74 s**	**1.80**	**1.95**	**2.15**
	FCW	FCW	0.61 (0.33)	0.64 (0.28)	0.67 (0.30)	2.40	2.50	2.63

For the slippery road scenario, three different SWIW were presented. Each of these notifications seemed to induce glances with duration below one second in each of the modality, and count of HMI glances about two per notification. Like previous results, although not significantly higher, SRSBeeps modality seemed to perform the worst. Both SREBeeps and SREVoice had similar results.

On the other hand, in the WZ scenario two SWIW notifications, four WZ notifications, and FCW notifications were provided. All the notifications induced glances with duration below one second in average with a count of about 2.5 glances per notification. WZSBeeps modality seemed to induce the highest glance duration for each of the notifications on average, whereas, WZEBeeps modality seemed to induce the lowest glance duration on average. Since the FCW notification is the same for all three modalities, no significant difference in mean glance time and count of glances was observed between the modalities, as expected.

To make sure that the CV warnings do not introduce higher amount of workload or distraction, they need to be compared with the non-CV baseline scenario. However, since no CV warnings are communicated in the baseline scenario, and it has no HMI, glances off-road were extracted for all the participants using the eye tracking system. Any time a driver was not paying attention to the road ahead, it increases the chance of an accident [44]. Thus, comparing with the non-CV scenario provides an ideal method to see how the CV warnings impacts safety in terms of workload/ distraction.

A one-way ANOVA was performed to compare the different modalities (CV and non-CV). For both the slippery road scenario and WZ scenario, there was no significant difference between the mean off-road glance time or the number of glances off road between the CV scenario and any of the CV modalities based on a one-way ANOVA. SBeeps modality had the highest number of glances off road, as well as the highest mean off-road glance rate in both the scenarios. baseline had the least number of glances per minute in both scenarios.

In terms of distraction (i.e. glances away from road greater than 2 seconds), the baseline scenario seemed to have the highest proportion of off-road glances greater than 2secondsfor both the scenarios with about 1.5 percent of total glances being greater than 2secondsin both cases. For the CV modalities in slippery road scenarios, SREBeeps had two cases of distraction, SRSBeeps had five cases whereas SREVoice modality had no distraction cases. On the other hand, for the WZ scenario, WZSBeeps was found to induce the longest off-road glances followed by WZEVoice modality.

8.3.3 Comparison of Visual/ Cognitive Demand of Different Modalities

A one-way ANOVA test was conducted to compare the mean HMI glance duration, standard deviation of glance duration on HMI, and number of glances on HMI for the different modalities. The results are shown below:

- **For the Slippery Road Scenario:**
- A one way ANOVA showed no statistical difference in the mean glance time between the four modalities $F_{(2,22)}=0.557$, p=0.581.
- Similarly, no statistical difference in standard deviation of glance time was found between the four modalities $F_{(2,22)}=1.389$, p=0.270.
- Similarly, no statistical difference in number of glances was found between the four modalities $F_{(2,22)}=0.165$, p=0.849.
- **For the Work Zone Scenario:**
- A one way ANOVA showed no statistical difference in the mean glance time between the four modalities $F_{(2,23)}=2.084$, p=0.147

- Similarly, no statistical difference in standard deviation of glance time was found between the four modalities $F_{(2,23)}$=1.342, p=0.81
- Similarly, no statistical difference in number of glances was found between the four modalities $F_{(2,23)}$=0.480, p=0.625.

A comparison between the visual behavior induced by different warnings types (i.e. SWIW, WZ and FCW) was done across the modalities and scenarios. A one-way ANOVA showed that the mean glance time ($F_{(2,49)}$ =0.448,p=0.641) and number of glances on HMI ($F_{(2,49)}$=0.904, p=0.412) induced by the SWIW notifications are not significantly different for any of the modality. For the WZW notifications, a significant difference was found between the glance duration on HMI ($F_{(2,23)}$ =4.032, p=0.032). A Bonferroni post hoc showed that both EBeeps and EVoice modalities invoked significantly lower glance duration on HMI than the SBeeps modality. There was no significant difference in the mean glance time on HMI between EBeeps and EVoice modalities. Similarly, no significant difference in HMI glance duration ($F_{(2,23)}$ =0.952,p=0.401) or number of glances on HMI ($F_{(2,23)}$=3.25, p=0.057) was found between the modalities for the FCW notification.

8.4 Dristraction and Workload Assessmnet Using Revealed Preference Survey Data

In addition to the quantitative analysis, a preference questionnaire survey was employed to gather information about the drivers' opinion on readability of the CV warnings, distraction potential of the CV HMI display, and ease of understanding the CV warnings. All these parameters directly or indirectly measure the distraction potential of the CV HMI system. The participants had to rank different CV warnings on a seven-point Likert Scale, where one represents negative perceptions, such as very low readability and extreme distraction, and seven represents positive perceptions such as very good readability and no distraction is encountered at all.

Figure 35 showed that most participants found the different CV HMI notifications easy to understand. The participants were asked to rate the clarity and ease of understanding of four different CV notification: Adverse weather notification, FCW notification, road surface notification, and WZ notification. The average score for the adverse weather and road surface notifications were 5.9, whereas the average score for the FCW and WZ notification was 6.3.

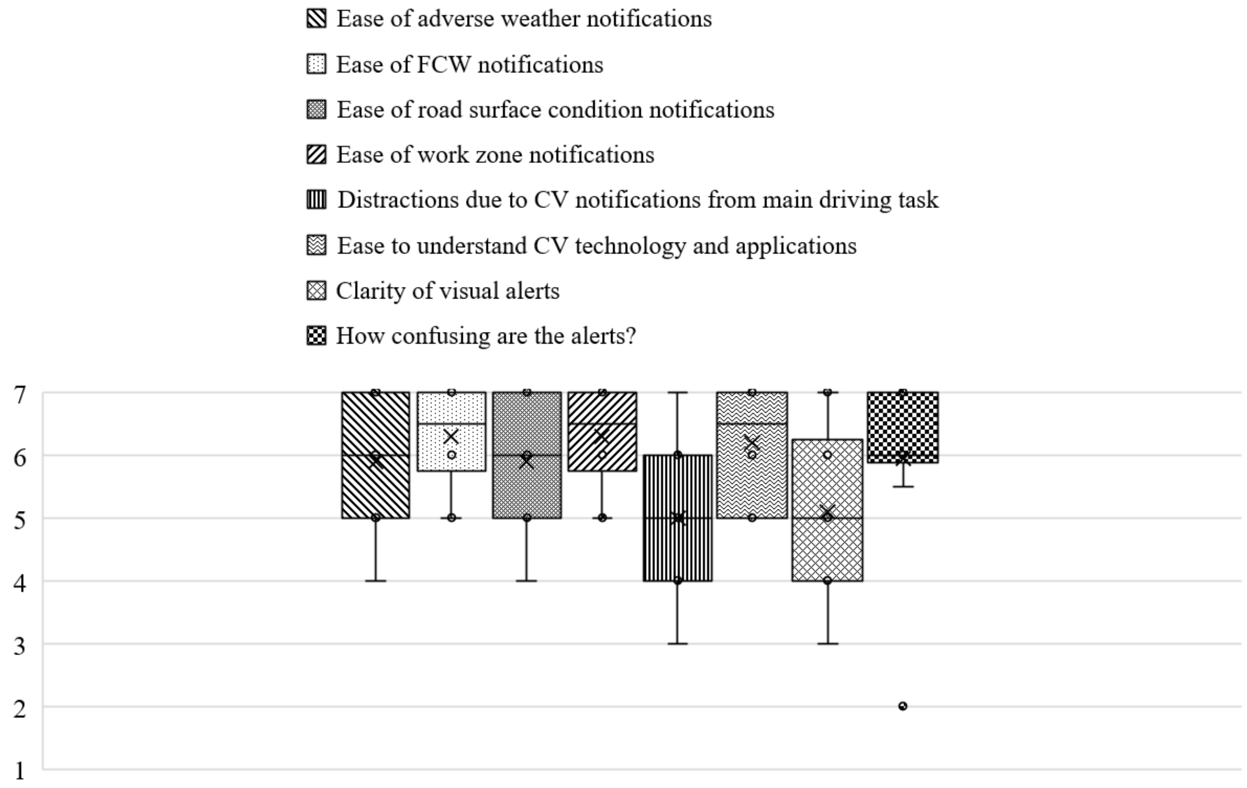


Figure 35 Driver Preferences in Seven-Point Likert Scale

Three questions regarding the readability of the CV HMI warning were asked to the participants:

1. How easy was it to understand the CV technology and applications?
2. Do you think the alerts among the different CV applications are confusing?
3. Do you think that the CV applications and the display unit are introducing any distraction from the main driving task?

For the first question, the participants ranked the CV technology and applications to be very easy to understand (average score 6.2). For the second question, 9 participants said that the CV alerts are not confusing, whereas 1 participant found the CV notifications to be extremely confusing. In terms of distraction introduced by CV warnings, the participants' ranked CV applications as being somewhat distracting to not distracting at all (score of 3 to 7). Three participants ranked the CV warnings as moderately distracting, four participants remained neutral, and three participants ranked the warnings as not distracting at all.

8.5 General Insights about the Distraction Introduced by the HMI for Highway Patrol

Although it is well known that long glances away from road is negative in terms of safety, it is important to take into consideration the experience of the driver, vehicle speed, and complexity of the road environment. In this study, the drivers were experienced highway officers who spend most of their time behind the wheels driving at high speeds under high workloads, and in complex road and weather conditions. This makes the results obtained from this study more unique than the results from other studies. Nevertheless, it is important to examine whether the HMI is detrimental to safety by distracting the driver from focusing fully on the driving task. Moreover, the study attempted to find the best HMI design with the least distraction potential.

From the heat maps created for data visualization, it was observed that the highest density of the gaze points was on the center of the road. The gaze points were centered mostly on the center of the screen. Some of the gazes were to the side-view and rear-view mirrors. The heat map plots also showed that some of the gaze points were distributed on the HMI. However, the frequency of these glances were very low.

The mean HMI glance duration for the slippery road scenario was observed to be 0.55 seconds, 0.59 seconds, and 0.64 seconds for Enlarged Beeps, Enlarged Voice and Small Beeps modalities, respectively. Similarly, for the WZ scenario, the mean HMI glances were 0.59s, 0.65s and 0.69s for Enlarged Icons with Beeps (EBeep), Enlarged Icons with Voice (EVoice), and Small Icon Beeps (SBeep) modalities, respectively. These values are close to the findings by Birrell and Fowkes (2014), who found an average glance duration of 0.43secondsfor an IVIS system [128].

For the slippery road scenario, the SBeeps modality seemed to perform the worst with highest mean glance duration (0.64 seconds), highest number of glances on HMI (34 on average), and highest maximum glance duration (3.95 seconds). The EVoice modality had the best results with the least standard deviation (0.33 seconds), least number of glances on HMI (31 on average) and no glances being greater than 2 seconds. From further analysis, it was found that four participants in the SBeeps modality had glances greater than 2 seconds (ranging from 2.3seconds to 3.95 seconds), and one participant from EBeeps had glance greater than 2 seconds (2.35 seconds). NHTSA guidelines recommend devices to be designed so than no glances away from the road are greater than 2 seconds [126]. Based on the guidelines, the SBeeps modality seemed to be the worst design with the highest distraction.

For the WZ Scenario, the SBeeps modality again had the highest mean HMI glance duration (0.69 seconds), highest standard deviation (0.47 secondss), highest number of glances (39 on average), and highest maximum glance duration (4.17 seconds). EBeeps seemed to have the best results with lowest mean HMI glance duration (0.59 seconds), lowest standard deviation (0.36 seconds), lowest number of glances on HMI (35.75), and lowest maximum glance duration (2.05 seconds). There were nine cases of distraction, five in SBeeps, two in EVoice, and two in EBeeps. Both SBeeps and EVoice seemed to induce more distraction compared to the EBeeps modality [126].

From the results, the SBeeps modality had the poorest performance among the three CV modalities. This might be because in the SBeeps modality, notifications are displayed as small icons that were accompanied by beeps. The participants need to look closer at the HMI to read and understand exactly what the notification is about. Therefore, this design has the highest visual demand.

Glance durations to an in-vehicle device depends on a number of factors, including the layout of the display unit, feature, means of interaction, as well as the position of the user interface [33]. Many studies have attributed the short durations to the effectiveness of user interface design [129] [130]. The short mean glance durations obtained in this study shows that the HMI developed in this study had a good design. The short glance, however, might also be because the participants in this study were experienced highway patrol officers who are trained to focus on multiple tasks at once. One recommendation might be to place the HMI to the users' line of sight, if possible (e.g., head-up display). This might result in even shorter glance durations and quicker reactions. This however might not be possible since modern highway vehicles are already crammed with several in-vehicle devices, and might not have enough space for another device (based on expert reviews and surveys).

According to literature, a higher number of glances to perform a task might be an indication of higher workload to read, understand, and process the information [130]. Comparing the slippery road and the WZ scenarios, it was observed that the WZ scenario had a slightly higher number of mean glances. This might be because, first the slippery road scenario had a relatively lower number of notifications due to which the HMI display unit was not clustered with notifications. The WZ scenario, on the other hand, had a high number of notifications that resulted in the HMI display unit being clustered with high number of notifications making it complex for the participant to distinguish the notifications. Moreover, the notifications in the WZ scenario was provided during a visually demanding condition with reduced visibility due to fog. This might have forced the driver to take shorter but a higher number of glances on the HMI.

The gaze plot analysis showed that the CV notifications were effective in drawing the concentration of drivers to the HMI. This resulted in the drivers shifting their attention shortly to the HMI display unit to read the CV notification. This made sure that the drivers were aware of the CV notifications. One of the most interesting results obtained from the gaze plot was when the driver seemed to be having a cognitive workload due to interaction with the dispatch unit. The CV notification seemed to alert the participant of the advisory speed limit for the encountered fog area.

Finally, the exposure to CV notifications seemed to introduce a higher number of mean off-road glance durations compared to the baseline scenario. This was not very apparent in the slippery road scenario. In the WZ scenario, however, the mean off-road glance rate for EVoice and SBeeps was almost double of the baseline. This result might be a concern since it signifies that the WZ application might have communicated too many notifications in a short time interval, and during a demanding road/weather condition. This finding suggests that the subject's attention might have been fragmented too often.

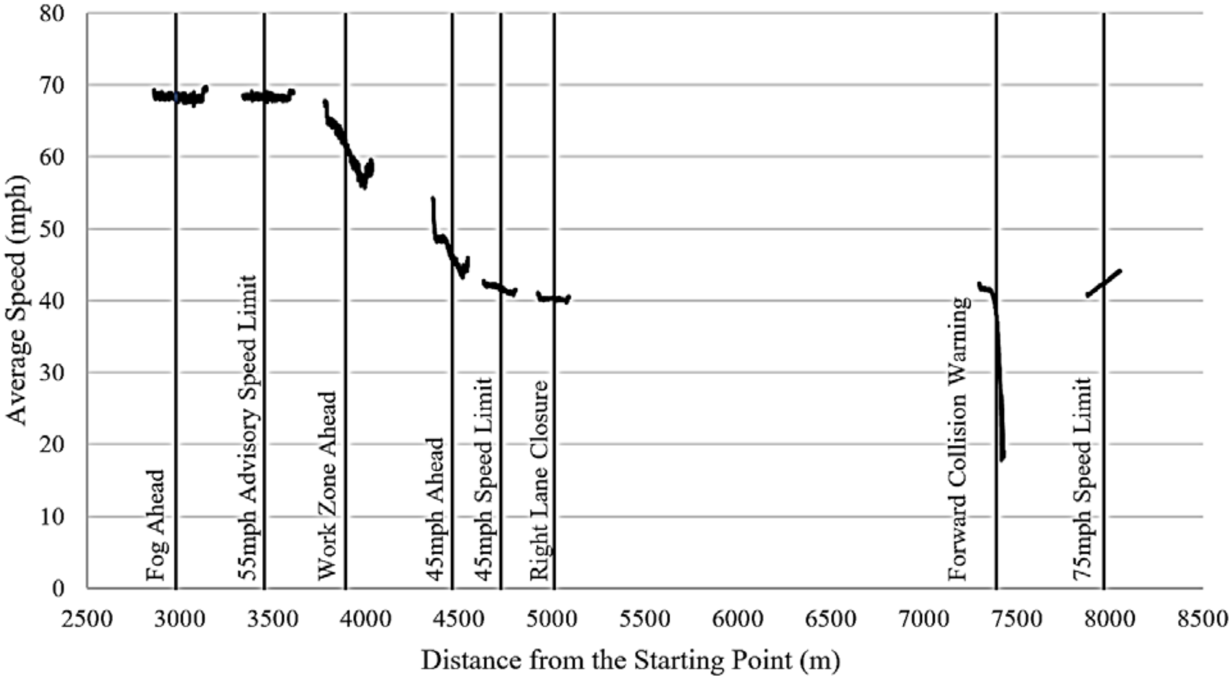
Moreover, from the preference surveys, it was observed that the CV HMI notifications were easy to understand. Although the adverse weather notifications had less distraction compared to the WZ notifications, the participants provided higher ratings to the FCW and WZ notifications based on clarity and ease of understanding. However, 3 out of 10 participants found the CV warnings to be moderately distracting. Additionally, the participants were asked about their comments on the CV application. The participants commented about the vocal alerts being distracting, especially when it was overlapped with the messages from dispatch. Moreover, the noise of siren and the cognitive workload the officers are in while attending an emergency scene reduces their ability to carry on with the notifications or even hear the vocal notifications. A beep, on the other hand, is alarming and the high-pitched sound is rarely missed.

8.6 Dristraction and Workload Assessmnet Using Vehicle Dynamics for Truck Drivers

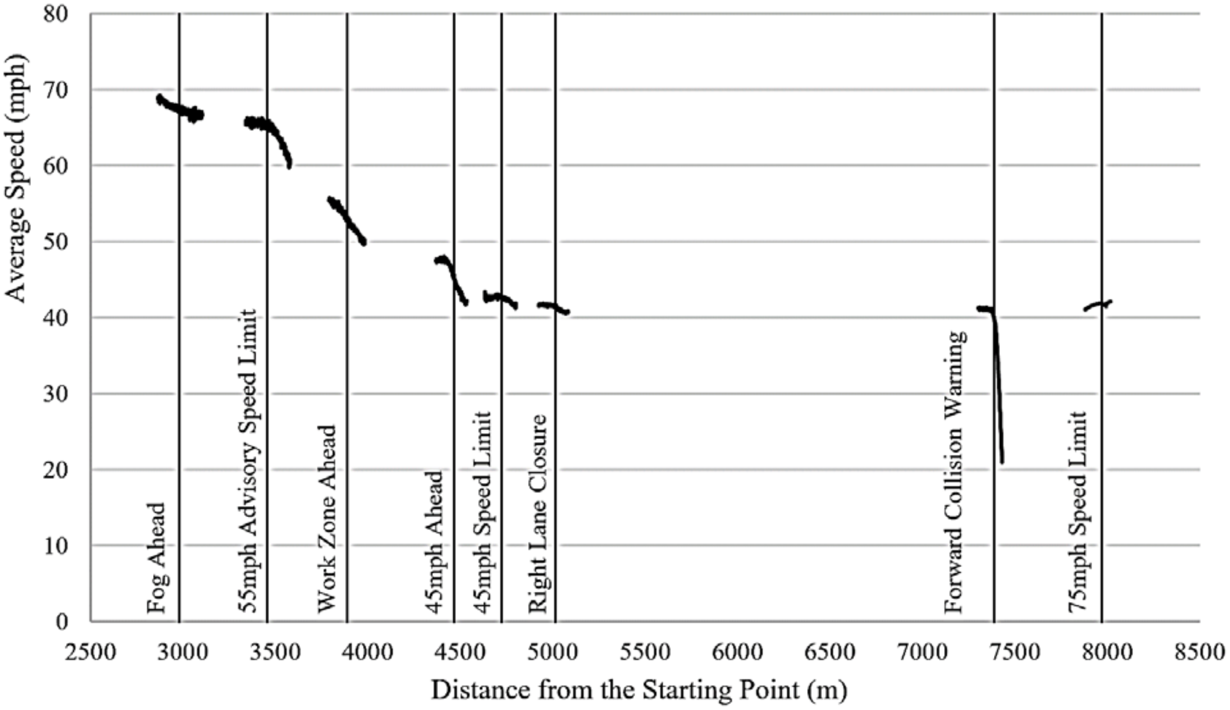
The simulator's SimObserver system was used to collect the quantitative driving performance data, such as the instantaneous speeds, acceleration/deceleration activities, lane change, and maintenance maneuvers. These data were further processed and reduced to compare the changes in performance before and after receiving the CV warnings. To quantitatively compare driver performance with and without CV HMI, this research analyzed the vehicle dynamics data five seconds before and after each CV warning for both baseline and CV scenarios. High definition videos of the entire experiment were reviewed to verify the results. Illustrations of the average longitudinal speed profile and lateral lane offset are presented in Figure 36 and Figure 37, respectively.

8.7 Descriptive statistics of the average speed.

Figure 36 illustrates the impacts of CV warnings on participants' longitudinal control of the vehicle. It can be seen that under the baseline scenario, participants maintained a relatively smooth speed profile prior to entering the advance area of the work zone, then sharp decreases in speed were found in the advance area of the WZ (i.e., the locations of CV warnings 3 and 4). In comparison, speed profiles under CV scenario displayed a gradual decreasing tend. It is necessary to point out that for the CV scenario, the variations of speed five seconds after most of the CV warnings were larger than the speed variations five seconds before the warning, as shown in Table 16 (i.e., CV warnings 2 to 8 for CV scenario versus. CV warnings 3, 4, and 7 for the baseline scenario).



A- Subfigure A - Speed trajectories for baseline scenario

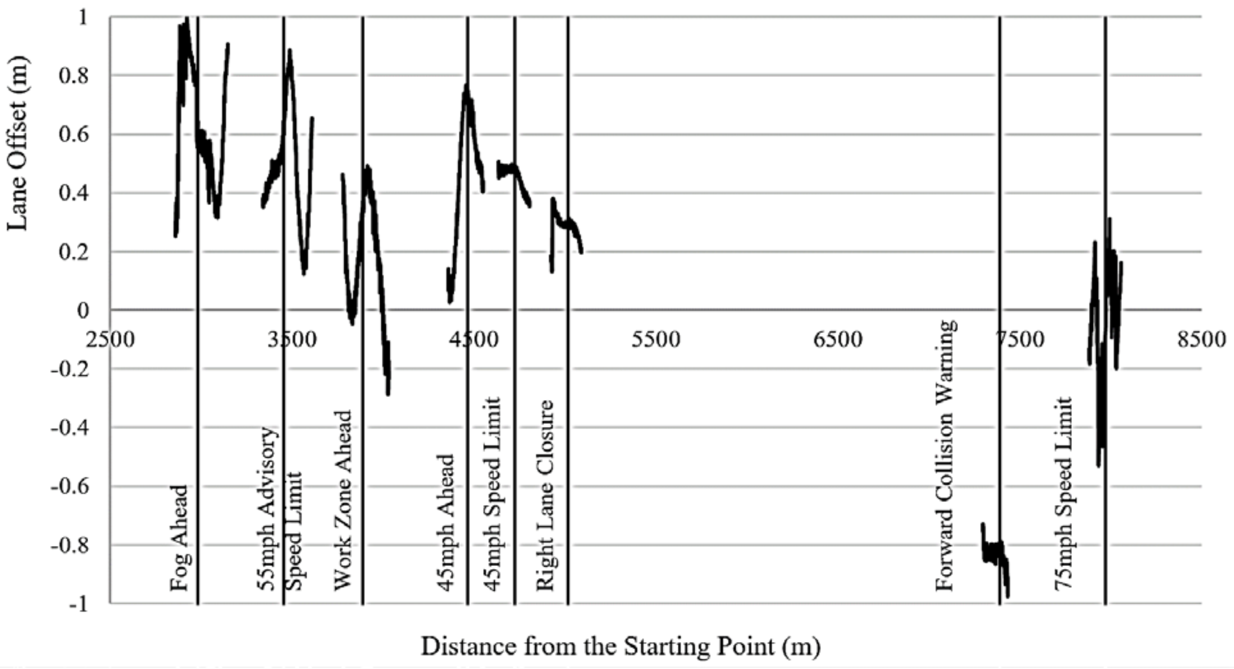


B- Subfigure B - Speed trajectories for CV work zone scenario

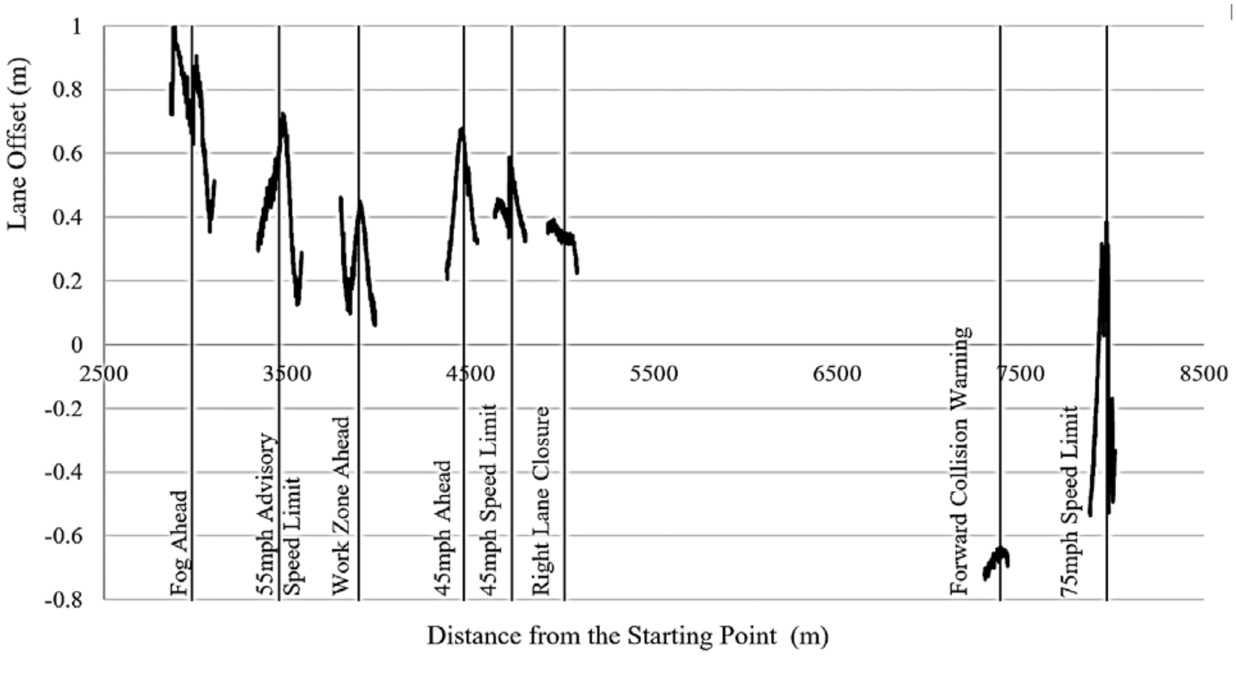
Figure 36 Speed Profile five-seconds Before and After each CV Warning

A significant speed reduction after the displaying the CV notification compared to the 5 seconds before the notification for the majority of the CV warnings. This significant reduction in speed was tested using a paired t-test, in which the test result was p-value = 0.03313. In comparison, under the baseline scenario, no significant changes in speed was found prior to the advance area of the active WZ (i.e., the location of CV warning 3). After entering the advance area of the WZ sharp reductions in speed were observed. These reductions in speed (under both the CV and baseline scenarios) are considered as expected and obligatory, since drivers need to be prepared to react to adverse weather events, traffic management strategies, and changes in traffic flow conditions while driving. Since no unexpected dramatic decrease in speed and deceleration was found during the experiment, it can be concluded that the CV HMI did not significantly affect participants' longitudinal control of the vehicle.

Figure 37 shows the impacts of CV warnings on participants' lateral control of the vehicle; it was found that the participants' lane keeping maneuvers under the CV scenario were similar to those under the baseline scenario, and the profiles of changes in lane offsets under CV scenario tended to be smaller. Comparisons of mean lane offsets five seconds before and after each CV warning are presented in Table 16, where it was found that the CV warnings did not introduce significant increases in lane offsets. In fact, the majority of CV warnings resulted in a reduced lane offset. A similar trend was observed for the baseline scenario, except in the vicinity of the CV warning #4 where the WZ was 0.5-mile ahead of the simulator vehicle. Using a paired t-test, it was concluded that changes of lane offsets at each CV warning under both CV and baseline scenarios were not significant, indicating that CV HMI did not significantly affect participants' lane keeping maneuver.



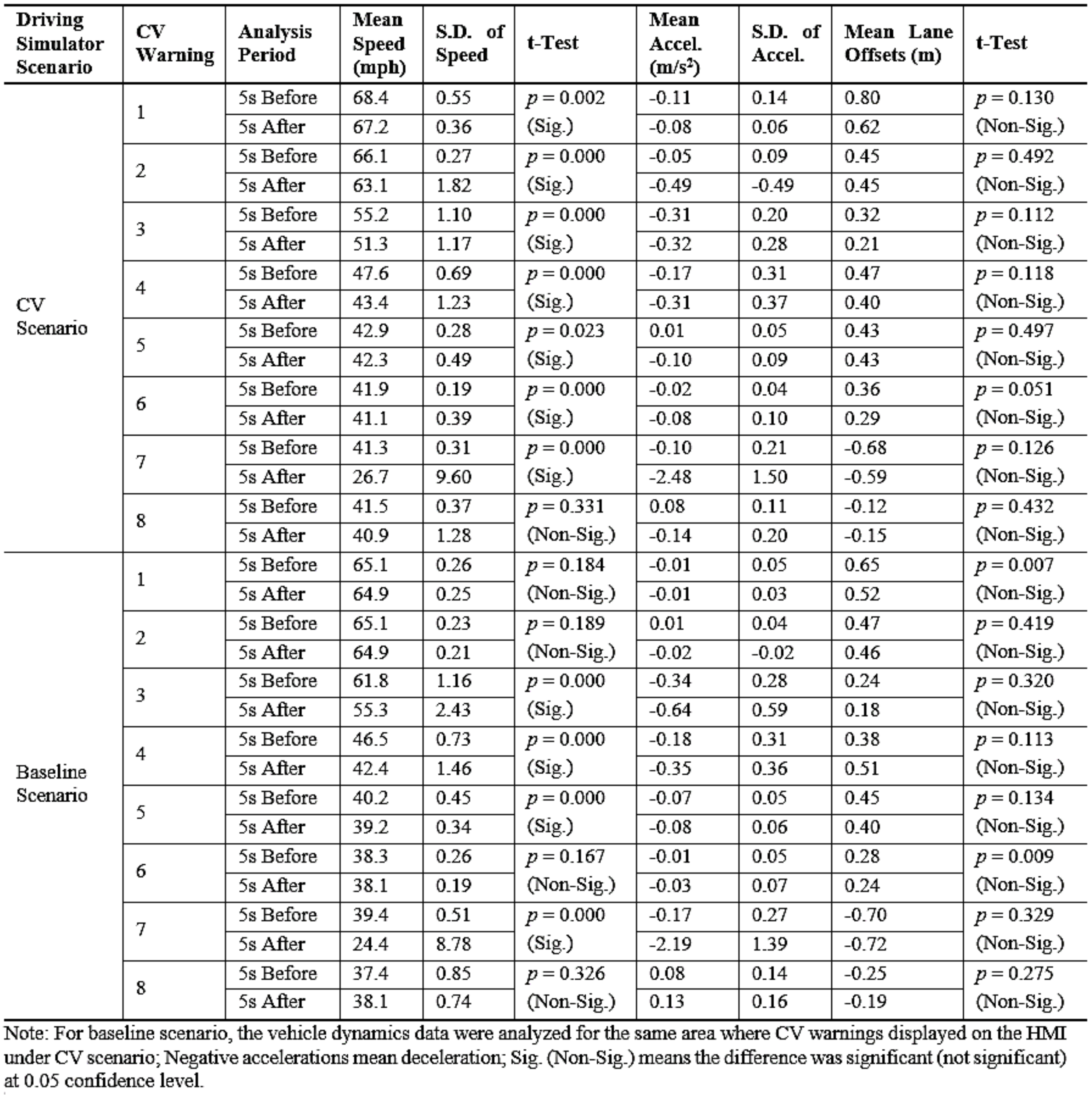
A- Subfigure A - Lane offsets for baseline scenario



B- Subfigure B - Lane offsets for CV work zone scenario

Figure 37 Lane offsets five-seconds before and after each CV warning

Table 16 Descriptive Statistics of Vehicle Dynamics five-seconds Before and After Each CV Warning



Driving Simulator Scenario	CV Warning	Analysis Period	Mean Speed (mph)	S.D. of Speed	t-Test	Mean Accel. (m/s^2)	S.D. of Accel.	Mean Lane Offsets (m)	t-Test
CV Scenario	1	5s Before	68.4	0.55	$p = 0.002$ (Sig.)	-0.11	0.14	0.80	$p = 0.130$ (Non-Sig.)
		5s After	67.2	0.36		-0.08	0.06	0.62	
	2	5s Before	66.1	0.27	$p = 0.000$ (Sig.)	-0.05	0.09	0.45	$p = 0.492$ (Non-Sig.)
		5s After	63.1	1.82		-0.49	-0.49	0.45	
	3	5s Before	55.2	1.10	$p = 0.000$ (Sig.)	-0.31	0.20	0.32	$p = 0.112$ (Non-Sig.)
		5s After	51.3	1.17		-0.32	0.28	0.21	
	4	5s Before	47.6	0.69	$p = 0.000$ (Sig.)	-0.17	0.31	0.47	$p = 0.118$ (Non-Sig.)
		5s After	43.4	1.23		-0.31	0.37	0.40	
	5	5s Before	42.9	0.28	$p = 0.023$ (Sig.)	0.01	0.05	0.43	$p = 0.497$ (Non-Sig.)
		5s After	42.3	0.49		-0.10	0.09	0.43	
	6	5s Before	41.9	0.19	$p = 0.000$ (Sig.)	-0.02	0.04	0.36	$p = 0.051$ (Non-Sig.)
		5s After	41.1	0.39		-0.08	0.10	0.29	
	7	5s Before	41.3	0.31	$p = 0.000$ (Sig.)	-0.10	0.21	-0.68	$p = 0.126$ (Non-Sig.)
		5s After	26.7	9.60		-2.48	1.50	-0.59	
	8	5s Before	41.5	0.37	$p = 0.331$ (Non-Sig.)	0.08	0.11	-0.12	$p = 0.432$ (Non-Sig.)
		5s After	40.9	1.28		-0.14	0.20	-0.15	
Baseline Scenario	1	5s Before	65.1	0.26	$p = 0.184$ (Non-Sig.)	-0.01	0.05	0.65	$p = 0.007$ (Non-Sig.)
		5s After	64.9	0.25		-0.01	0.03	0.52	
	2	5s Before	65.1	0.23	$p = 0.189$ (Non-Sig.)	0.01	0.04	0.47	$p = 0.419$ (Non-Sig.)
		5s After	64.9	0.21		-0.02	-0.02	0.46	
	3	5s Before	61.8	1.16	$p = 0.000$ (Sig.)	-0.34	0.28	0.24	$p = 0.320$ (Non-Sig.)
		5s After	55.3	2.43		-0.64	0.59	0.18	
	4	5s Before	46.5	0.73	$p = 0.000$ (Sig.)	-0.18	0.31	0.38	$p = 0.113$ (Non-Sig.)
		5s After	42.4	1.46		-0.35	0.36	0.51	
	5	5s Before	40.2	0.45	$p = 0.000$ (Sig.)	-0.07	0.05	0.45	$p = 0.134$ (Non-Sig.)
		5s After	39.2	0.34		-0.08	0.06	0.40	
	6	5s Before	38.3	0.26	$p = 0.167$ (Non-Sig.)	-0.01	0.05	0.28	$p = 0.009$ (Non-Sig.)
		5s After	38.1	0.19		-0.03	0.07	0.24	
	7	5s Before	39.4	0.51	$p = 0.000$ (Sig.)	-0.17	0.27	-0.70	$p = 0.329$ (Non-Sig.)
		5s After	24.4	8.78		-2.19	1.39	-0.72	
	8	5s Before	37.4	0.85	$p = 0.326$ (Non-Sig.)	0.08	0.14	-0.25	$p = 0.275$ (Non-Sig.)
		5s After	38.1	0.74		0.13	0.16	-0.19	

Note: For baseline scenario, the vehicle dynamics data were analyzed for the same area where CV warnings displayed on the HMI under CV scenario; Negative accelerations mean deceleration; Sig. (Non-Sig.) means the difference was significant (not significant) at 0.05 confidence level.

In addition to the quantitative analyzes, a revealed preference questionnaire survey was employed to gather drivers' qualitative opinions regarding the readability of the Pilot's CV warnings (i.e., ease of understanding), and distraction effects of the HMI after experiencing them in a simulated CV environment. Participants' subjective assessments on the ease of CV HMI, ease of various CV warnings, and distractions of CV warnings and HMI were documented using a seven-point Likert Scale, as illustrated in Figure 38. Note that Score 1 represents negative perceptions, such as not easy at all to understand, and extremely confusing/distracting” and Score 7 represents positive perceptions, such as very easy to understand” and not confusing/distracting at all”.

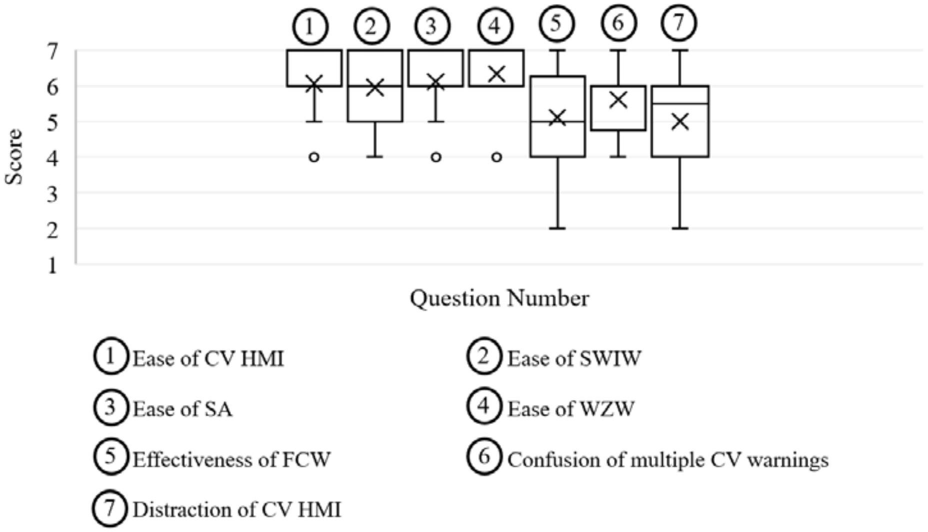


Figure 38 Participants’ Assessments on the Readability and Distraction of WYDOT CV HMI

Results show that the majority of participants found the Pilot CV HMI was easy to read, and the tested CV applications were easy to understand (average scores equal or greater than 6). The effectiveness of FCW was fairly good (an average score of 5.1). A reason to this relatively low score is that the participants are professional snowplow truck drivers who have very conservative driving behavior, such as always driving at a low speed and keeping a long following distance during the experiment, thus they could easily recognize a slowing-moving vehicle without the assistance of FCW. In terms of the distraction brought about by the CV warnings displayed on the HMI, the majority of participants ranked CV applications as not distracting (i.e., scores 5 to 7). Remarkably, 27 percent of participants ranked CV notifications as being more than moderately distracting (i.e., 12 percent found the CV warning distracting, while 15 percent found them neutral).

In reality, for non-autonomous vehicles, safe driving has been the principle task for the driver. As specified by NHTSA [51], the primary requirement of the in-vehicle HMI is to deliver desired traffic-related information while minimizing driver distraction. This is particularly critical during high workload situations (such as driving a heavy truck) or under adverse weather conditions when drivers need more response and reaction time to an un-expected event, since un-clear and/or over-loaded HMI information may distract driver and result in safety issues. Therefore, a robust CV

HMI design needs to effectively communicate warnings that drivers can effectively perceive. This indicates the content of CV warnings should be easily recognized, processed, and interpreted [131]. In view of these requirements for designing CV warning and HMI display, this research examined the effects of the CV HMI developed by the WYDOT CV Pilot on professional truck drivers' driving performance and cognitive distraction through a driving simulator experiment based on trajectory-level quantitative vehicle dynamics data and qualitative revealed-preference questionnaire survey.

Simulation results indicated that despite the variations of speed five seconds after most of the CV warnings was larger than the speed variations five seconds before the warning, these changes were considered as expected reactions to the prevalent weather and traffic conditions. In comparison with the baseline scenario, no unexpected dramatic changes in speed, acceleration, and lane offset was found at all the CV warning. This indicates that the Pilot CV warnings and HMI did not introduce significant impacts on participants' longitudinal and lateral control of the vehicle.

Nevertheless, based on the revealed-preference questionnaire survey results, it was found that more than a quarter of the participants indicated that distraction could be introduced by the Pilot CV HMI. Through the discussions with the participants after the experiment, this research summarized that participants generally thought the WZWs were more distractive compared to the other CV warnings. This was mainly because the frequency of displaying WZWs were higher than the other CV warnings. In addition, the majority of the WZWs were presented in combination with other information, such as speed limits or small-sized texts that increased participants' visual-workload to recognize the information delivered by a WZW. These WZWs were displayed on the HMI under a high-workload driving condition, since participants were approaching an active WZ under reduced visibility condition. Therefore, this research recommends that the amount of information per CV warning, the frequency (or time interval) of displaying successive CV warnings, and the modalities for displaying each CV warning (i.e., visual, audible, voice, or a combination of two or more modalities) need to be optimized based on a normal driver's ability of safely recognizing and reacting to the received CV warnings. This helps to minimize the cognitive distractions introduced by CV HMI and create a safer driving environment, which is considered as crucial for the success of the deployment of CV technology.

8.8 Dristraction and Workload Assessment Using Eye Tracking System for Truck Drivers

One obvious concern stems from the fact that the majority of the Pilot's CV applications rely on the visual HMI to display the content of the warnings calling drivers to divert their visual attention away from the driving scene. Eye tracking technology, widely used in the literature, provides a powerful tool to identify where a driver is looking within the visual scene.

Eye glance behavior in driving research is a complex and convoluted research field [39]. A solid analysis of the eye glance behavior predicates a multifaceted approach to capture the holistic effects of using in-vehicle technology on driver workload and distraction [39]. Before moving forward with the description of the dependent variables applied in this study (i.e., the eye tracking metrics), it is critical to start with laying the groundwork for the basic eye movement protocols:

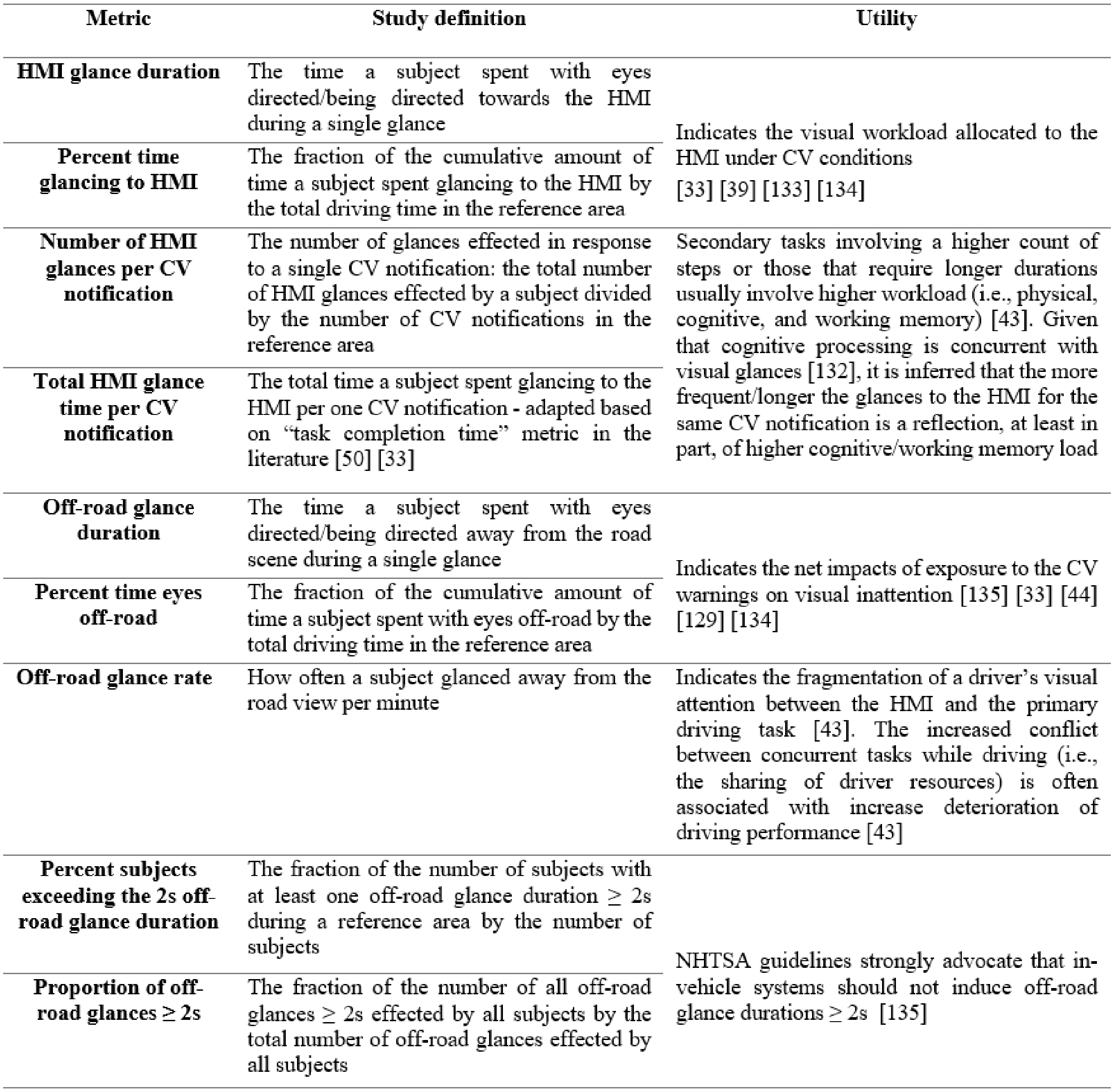
- Target: A target is a well-defined spatial region or object within the visual scene at which a driver may direct their gaze [33]. Since the prime focus of this study is to assess the impacts of the display of the CV warnings on the HMI, two sorts of glance are considered: glances to the HMI (labeled as HMI glances), and off-road glances. The analysis of the HMI glance behavior provides an understanding of the visual workload exclusively allocated to the HMI. On the other hand, off-road glances offer a medium to understand the net impacts of the introduction of the new in-vehicle technology, particularly by comparing with the baseline conditions. Off-road glances consist of all glances away from the road scene. Glances to the interior and exterior rear-view mirrors are beneficial to the safe operation of the vehicle [44],are viewed as directly relevant to the driving task, and therefore, were counted as part of on-road glances. Since the HMI is mounted on the vehicle's dashboard any glance to the HMI should be, at least in part, considered as an off-road glance.
- Fixation: A fixation is the duration of time occurring within a glance in which a driver's foveae (centers of the field of vision with highest visual acuity) fixate/concentrate on a particular point or location within an object (e.g., HMI, forward view, etc.). Research elucidates that it is during fixations that the extraction of visual information takes place [132]. Fixations are duration sensitive and generally vary between 100to 2000 millisecond for in-vehicle devices according to the provisions of the International Organization for Standardization' ISO 2014 standards (ISO) [33]. Fixations of less than 100ms are rare

[132]. In line with the ISO standard, glances identified in this study were based on fixations of minimum 100ms durations.

- Saccade: A saccade is used to denote the eye movements that occur between fixations on the same target [33], e.g., a driver fixates on the left side of the HMI and then fixates on the center of the HMI.
- Transition: Transitions are the eye movements that precede the fixations on a new target [33] [39] (e.g., a driver moves from the forward view towards the HMI)
- Dwell time: It is the total time spent with eyes directed towards a particular target: the sum of all fixations and saccades on the same target (e.g., HMI) [33] [39].
- Glance duration: Definitions can slightly vary in the literature, however, the most common definition, adopted in this study, is by the Society of Automotive Engineers - SAE J2396 [33]. A glance duration is the total time that starts from the point in time at which a driver begins directing their gaze toward the area of interest or target until the point in time at which the driver moves away from the area of interest [33] [39]. The concept of glance duration will be, henceforth, pivotal for the remainder of this chapter.

This study leverages multiple eye tracking metrics from/adapted from the literature to assess the visual and cognitive demands introduced by the display of the Pilot CV warnings. It is noteworthy that for the most part, eye tracking metrics in driving research, thus far, are based on secondary tasks that are often irrelevant to the primary driving task or are not well-equipped to evaluate the nature of CV HMI displays being investigated in this study. With this consideration in mind, some of the eye tracking metrics used in this study were slight adaptations of widely adopted metrics in the literature. Table 17 provides a definition of the eye-tracking metrics used in this study. All metrics were normalized either by the CV application being investigated (i.e., the WZW or SWIW application) or by the reference area where the CV warnings were communicated (i.e., the weather notifications area where the SWIW warnings were communicated or the WZ advance warning area where the WZW warnings were displayed).

Table 17 Definition of the Eye Tracking Metrics used in this Study



Metric	Study definition	Utility
HMI glance duration	The time a subject spent with eyes directed/being directed towards the HMI during a single glance	Indicates the visual workload allocated to the HMI under CV conditions [33] [39] [133] [134]
Percent time glancing to HMI	The fraction of the cumulative amount of time a subject spent glancing to the HMI by the total driving time in the reference area	
Number of HMI glances per CV notification	The number of glances effected in response to a single CV notification: the total number of HMI glances effected by a subject divided by the number of CV notifications in the reference area	Secondary tasks involving a higher count of steps or those that require longer durations usually involve higher workload (i.e., physical, cognitive, and working memory) [43]. Given that cognitive processing is concurrent with visual glances [132], it is inferred that the more frequent/longer the glances to the HMI for the same CV notification is a reflection, at least in part, of higher cognitive/working memory load
Total HMI glance time per CV notification	The total time a subject spent glancing to the HMI per one CV notification - adapted based on "task completion time" metric in the literature [50] [33]	
Off-road glance duration	The time a subject spent with eyes directed/being directed away from the road scene during a single glance	Indicates the net impacts of exposure to the CV warnings on visual inattention [135] [33] [44] [129] [134]
Percent time eyes off-road	The fraction of the cumulative amount of time a subject spent with eyes off-road by the total driving time in the reference area	
Off-road glance rate	How often a subject glanced away from the road view per minute	Indicates the fragmentation of a driver's visual attention between the HMI and the primary driving task [43]. The increased conflict between concurrent tasks while driving (i.e., the sharing of driver resources) is often associated with increase deterioration of driving performance [43]
Percent subjects exceeding the 2s off-road glance duration	The fraction of the number of subjects with at least one off-road glance duration $\geq$ 2s during a reference area by the number of subjects	NHTSA guidelines strongly advocate that in-vehicle systems should not induce off-road glance durations $\geq$ 2s [135]
Proportion of off-road glances $\geq$ 2s	The fraction of the number of all off-road glances $\geq$ 2s effected by all subjects by the total number of off-road glances effected by all subjects	

An algorithm was developed to identify the durations and the time stamps of both the glances of interest (glances to the HMI or off-road glances). The algorithm, in essence, uses the notion of a fixation to capture the off-road or HMI glances. The procedure behind the extraction of the HMI glances consists of the following steps (similar procedure for off-road glances):

1. Identifying the fixations that coincide with the HMI with a minimum duration of 100ms.
2. Identifying the total dwell time on the HMI per glance, by combining all consecutive saccades and fixations occurring within the same HMI glance

3. Determining the total glance duration by appending the dwell time with the leading transition duration to reach the HMI
4. Synchronizing the video recordings timing with the eye tracking time stamps
5. Subjectively validating that the algorithm-identified HMI glances are in agreement with the glance behavior observed in the video recordings. This step is not uncommon in the literature [132] and was applied in this study on multiple randomly selected glances for each driver that were discernable from the video recordings. This step aimed to ensure the validity of the algorithm and the accurate detection of glances.

While the procedure behind the extraction of glances is basic in nature, processing raw eye tracking data presented several challenges making the data reduction into a time-consuming and labor-intensive process. Loosely-defined algorithms are not uncommon in the literature and can produce an unusually high or low number of fixations, and thereof, misguide the analysis and interpretation of data [132]. All of the encountered challenges were dealt with according to or in the adaptation of common mitigation practices/procedures in eye tracking research. The following section describes the main hurdles that were encountered and how they were resolved in order to preserve the accuracy of the extracted eye tracking measurements.

- Track loss: the issue of track loss is well-encountered in eye tracking research [133]. This issue was encountered for several subjects in this study, and hence, could have impacted the quality of the findings if left unaddressed. Track losses are typically missing eye tracking readings and often take place when the eye-tracking system is unable to track the pupil, or the center of the corneal reflection, due a number of reasons, such as being partially obstructed by the subject’s eye lids or eyelashes or as a result of change in the illumination levels [133]. To remedy this issue: the following procedure was applied: 1) Track losses occurring prior to a fixation or between fixations on the same area of interest (off-road object or HMI) were disregarded since they have no impact on the final glance duration. 2) In line with the suggested corrections applied in [133], track losses (in addition to blinks) occurring within a fixation were incorporated into the overall fixation as long as the subject’s gaze was still maintained on the same area of interest.
- Fragmented fixations: The eye tracking software underlies a velocity-based method to identify fixations. Eye movements with an angular velocity lower than a certain threshold were identified as fixations (i.e., eyes are stabilized on a certain area), otherwise, they were

considered as saccades. Research demonstrates that this method is inclined to fail to accurately capture fixations at near-threshold velocities. As such, this method can fragment a single fixation into multiple distinct fixations [132]. In this study, this issue was manifested in the sense that the initial algorithm produced several fixations that were below the minimum 100ms duration threshold, and thereof, could not be considered as fixations. To remedy this issue, neighboring fixations groups were clustered into a single fixation as long the duration separation between the separate groups did not exceed 100ms. In a few occasions, the inability of the algorithm to detect overly-fragmented fixations warranted manual corrections. These corrections were performed following the review of eye glance behavior from the recorded video logs.

- Eye tracking data noise: erroneous readings were generally infrequent and did occur at random, which is in agreement with previous studies [132] [133]. Erroneous gaze locations were adjusted to match the identified region if the immediately before and after gaze points fell on the same region.

Eye tracking data was collected for all 20 participants. In total, 40 eye tracking data files were generated (2 scenarios per subject: baseline and CV). For unforeseen reasons, the collected data for four subjects were corrupt beyond repair and no data could be extracted from these files. Additionally, three data files affecting the baseline scenarios for three subjects were either corrupt or severely affected by track loss, and thus, no reliable measurements could be extracted. All in all, 16 participants presented high-quality data from the CV driving scenarios, and thus, were used in this study to measure the visual demands exclusive to the HMI. On the other hand, the analyses conducted to quantify the net impacts of exposure to the CV warnings in reference to the baseline scenario were limited to the 13 subjects with complete CV and baseline data sets.

Several data analyses were performed in this study comprised of descriptive and inferential statistics. Statistical testing was primarily conducted on the SPSS software and sought to 1) assess the individual and comparative visual/cognitive workload demands of the two CV applications and 2) the net impacts of exposure to the CV warnings by using the baseline conditions as a frame of reference. All tests were assessed at the 0.05 significance level. The performed tests consist of:

- Paired t-tests used to assess the differences in the subject’s visual behavior in response to the two CV applications being studied, and in comparison with the baseline conditions

- Two-way ANOVA tests applied to understand the overall effects of exposure to the CV warnings and the nature of the driving environment on the subjects' visual behavior
- Chi-squared tests for equality of proportions used to evaluate the changes in the proportion of the longer off-road glance durations following exposure to CV warnings

8.8.1.1 Description of the Drivers' Visual Behavior under the CV Environment

The SWIW consisted of two weather notifications communicated in clear weather conditions. During the weather notifications area (i.e., from the moment participants received the first weather warning until the moment of entering the reduced visibility area), the 16 participants, on average, spent 8.9 percent of the total time driving with their eyes directed/being directed towards the HMI. Each of the SWIW notification invoked on average 1.66 glances to the HMI (x 2 notifications) where the average single HMI glance duration took approximately 0.83 seconds to complete. This is the equivalent of 1.41 seconds total glance time per a single notification, on average.

On the other hand, the WZW application consisted of four WZ notifications communicated in the WZ advance warning area (i.e., the reference area for the WZW application). On average, the display of the WZW prompted the participants to spend 9.1 percent of the total driving time in the reference area glancing to the HMI. Moreover, the display of a single WZW notification on average induced 2.48 glances to the HMI (x 4 notifications) where each glance lasted approximately 1 second to complete. This is the equivalent of 2.68 second total glance time per single notification. These results are illustrated in Table 18.

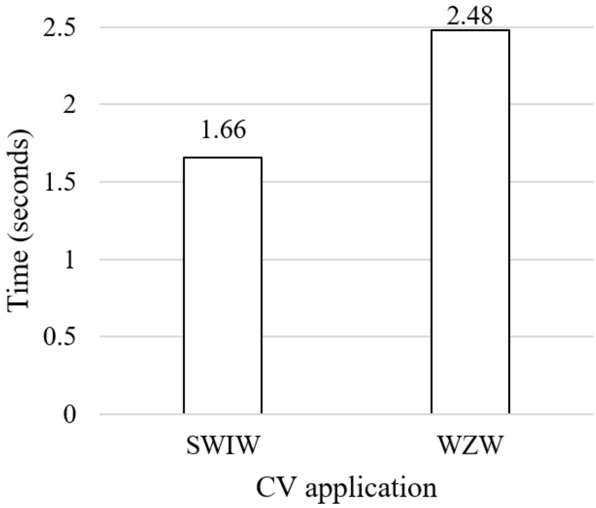
One of the common metrics in the literature is the task completion time [50]. Green (1999) argues that exclusively visual secondary tasks (e.g., reading GPS) should not induce task completion times that are more than 5 seconds in total. The 5 second demarcation is based on ratings for what drivers generally perceive as tasks that are safe to perform while driving [50]. In the case of this study, the total HMI glance time per CV notification could be viewed as the task completion time given the exclusive visual nature of the end user-HMI interaction. With this analogy in place, the two CV applications invoked total average glance durations per notification that are well below the recommended 5 second task completion time [50]. Therefore, the existing HMI design for two CV application seems to fall within the acceptable range of what is generally perceived as safe interaction from a user' perspective.

Table 18 Visual Demand Metrics by CV Application

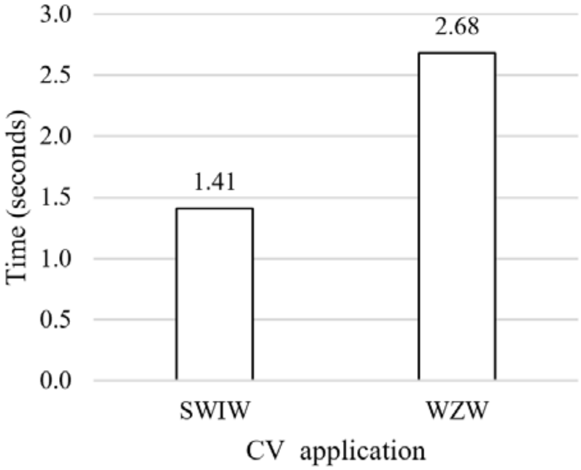
CV TIM	No. of CV TIMs	Mean HMI glance duration & (SD)	Percent time glancing to HMI (avg.)	Mean no. of HMI glances per CV TIMs	Total HMI glance time per CV TIMs (avg.)
SWIW	2	0.83s (0.26s)	8.87 percent	1.66	1.41
WZW	4	1.03s (0.26s)	9.11 percent	2.48	2.68

8.8.1.2 Comparison of the Visual/Cognitive Workload Demands by the CV Applications

The comparison between the visual behavior induced by the SWIW and WZW applications using the following normalized metrics reveals that: 1) the average single glance duration to the HMI in response to a WZW was 0.20 seconds longer than a single HMI glance duration due to a weather warning. Evidently, this marked difference in mean HMI glance duration between the two CV applications was found statistically significant using a paired t-test ($t_{(15)} = 2.52$, $p = 0.024$). 2) The WZW application prompted participants to effect more glances to the HMI per single notification in comparison with the SWIW application. Statistical significance using the paired t-test was also established ($t_{(15)} = 4.35$, $p < 0.001$). This result demonstrates that the display of a WZ notification required more glances to the HMI to extract and process the communicated information. 3) The total time spent glancing at the HMI in response to a single WZ notification was almost twofold of that of a weather notification. In other words, the display of a single WZ notification required nearly twice as much glance time in comparison with a weather notification, as Figure 39 illustrates. This result was also found statistically significant using a paired t test ($t_{(15)} = 4.34$, $p < 0.001$). This finding also highlights that the WZ notifications involved substantially higher visual/cognitive workload demands to locate, recognize, and process the displayed information.



A- Subfigure A - Mean Number of HMI glances per one CV notification



B- Subfigure B - Total time spent on HMI per one CV notification

Figure 39 Average number of glances and time spent on the HMI

8.8.1.3 Effects of Exposure to CV Warnings on Drivers' Visual/Cognitive Workload

Since no HMI glances exist in the baseline scenario, off-road glances were used instead to denote any time a driver is looking away from the road view. By comparing with the baseline conditions, off-road glance behavior offers an ideal medium to uncover the net safety impacts of exposure to the CV warnings, given that any time a driver is not acquiring visual information about the surrounding traffic environment entails an increased crash risk [44].

To put the HMI glances into perspective in the CV scenario, during the weather notifications area, 59 percent of all of the effected off-road glances by all subjects involved at least, in part, a glance to the HMI. Similarly, in the WZ advance warning area, 51 percent of all off-road glances were HMI glances, at least in part.

The display of the weather notifications on the HMI was not found to invoke a notable impact on the mean off-road glance duration in comparison with the baseline scenario. As Table 6-3 illustrates, the mean off-road glance duration slightly reduced from 0.86 seconds in the baseline conditions, to 0.83 seconds in the CV scenario (i.e., a reduction of 0.03 seconds following exposure to the weather warnings). No statistical significance could be detected using a paired t-test ($t_{(12)} = 0.27$, $p = 0.79$). Proceeding on this track the display of the weather notifications prompted participants to divert their visual resources away from the road view by an additional 10 percent of the total driving time in the reference area relative to the baseline conditions, as Table 19 highlights.

Table 19 Effects of Exposure to CV Warnings on the Percent Time Off-road

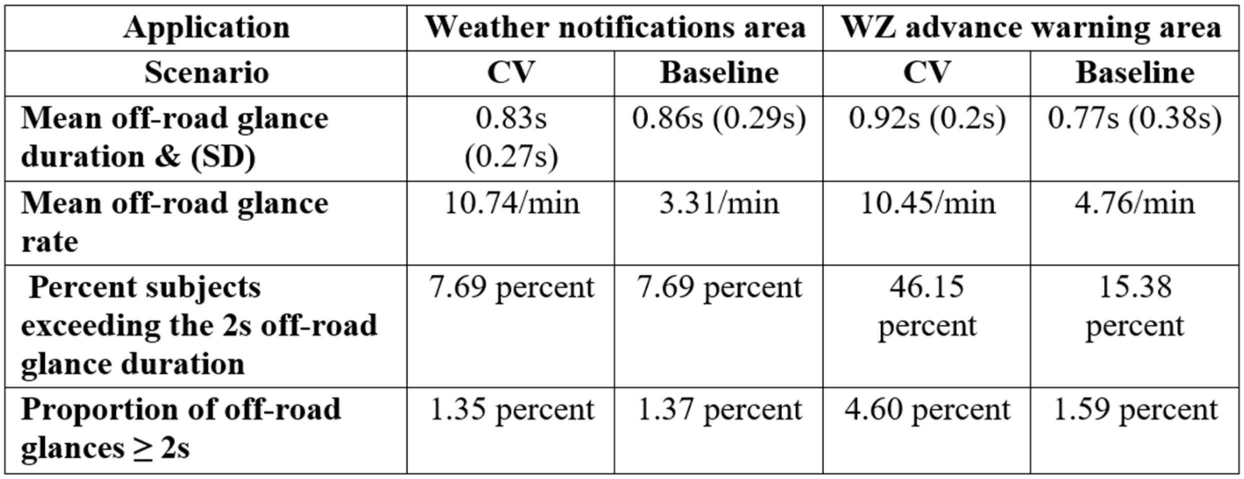
Scenario	Percent time eyes off-road	Percent time eyes on-road
Weather notification Area (CV scenario)	19.40 percent	80.60 percent
Weather notification Area (baseline Scenario)	5.90 percent	94.10 percent
WZ advance warning area (CV scenario)	14.50 percent	85.50 percent
WZ advance warning area (baseline Scenario)	4.60 percent	95.40 percent

The introduction of the WZW in the advance warning area brought about a more notable change in the mean off-road glance duration in comparison with the baseline scenario. The average off-road glance duration increased from 0.77 seconds in the baseline scenario, to 0.92 seconds in the CV scenario, or the equivalent increase of 0.15 seconds. This finding highlights a tendency towards slightly longer off-road glances as a result of exposure to the WZW. This result could be predicted given that HMI glances in response to the WZW, in the order of 1.03 seconds, were substantially higher than the mean off-road glance duration of 0.77 seconds in the baseline conditions. Nonetheless, no statistical significance could be detected between the mean off-road glance duration in the CV and baseline scenarios ($t(12) = 1.48$, $p = 0.16$). Alongside the relative increase in off-road glance durations, subjects spent substantially more cumulative time looking off-road when exposed to the CV WZW. The activation of the WZW triggered the allocation of an additional 13.5 percent of the total driving time towards glancing away from the road view. In other words, the percent time eyes off-road metric escalated by more than threefold on average following exposure to the WZW.

To examine the influence of the categorical variables, driving environment (normal driving conditions with clear visibility versus navigating a WZ advance warning area under reduced visibility), and the connectivity status (CV versus baseline conditions) on the mean off-road glance duration and the percent-time eyes off-road, two-way ANOVA tests were conducted for the two dependent variables, individually. No significance could be detected on the effects of the driving environment, connectivity status, or the interaction between the driving environment and the connectivity status on the mean off-road glance duration at the 0.05 level of significance. In addition, the driving environment factor was not found to carry a significant effect on the percent time eyes off-road metric ($F_{(1,25)} = 1.92$, $p = 0.173$). To the contrary, the connectivity factor had an extremely significant effect on the percent time eyes off-road metric ($F_{(1,25)} = 27.83$, $p < 0.0001$). This result corroborates earlier findings suggesting that exposure to both the weather and WZW triggered a marked increase in the percent time eyes off-road metric.

Under the baseline conditions where no CV warnings were communicated, the transition from the clear visibility conditions to the reduced visibility conditions, in which the WZ advance warning area was encountered, brought about a subtle change in the drivers' visual scanning behavior. As the transition occurred, the subjects elicited slightly shorter off-road glances (a mean reduction of 0.09 seconds) coupled with a slight increase in the off-road rate (an additional glance per minute). This subtle change highlights a natural tendency for the subjects to keep their eyes off-road for shorter durations in reduced visibility, in comparison to clear conditions to compensate for the reduction in the forward field of vision. Remarkably, the introduction of the CV warnings seemed to impede the subjects from maintaining their tendency to keep off-road glances at shorter durations under reduced visibility; exposure to the WZW application induced more off-road glances at relatively longer durations, as shown in Table 20.

Table 20 Visual Demand Using Off-Road Glance Metric



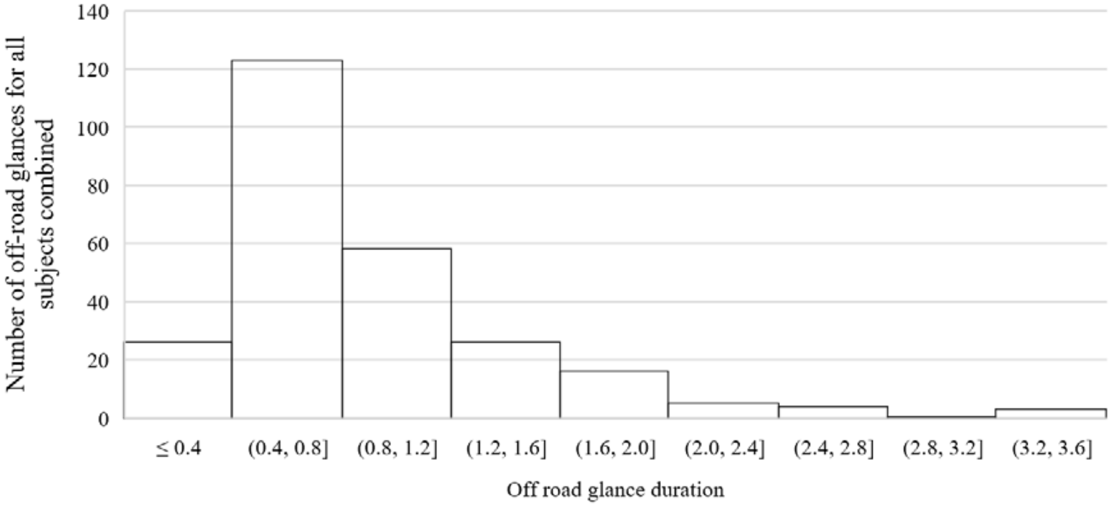
Application	Weather notifications area		WZ advance warning area	
Scenario	**CV**	**Baseline**	**CV**	**Baseline**
Mean off-road glance duration & (SD)	0.83s (0.27s)	0.86s (0.29s)	0.92s (0.2s)	0.77s (0.38s)
Mean off-road glance rate	10.74/min	3.31/min	10.45/min	4.76/min
Percent subjects exceeding the 2s off-road glance duration	7.69 percent	7.69 percent	46.15 percent	15.38 percent
Proportion of off-road glances ≥ 2s	1.35 percent	1.37 percent	4.60 percent	1.59 percent

8.8.1.4 Impacts of Exposure to CV Warnings on Visual Distraction

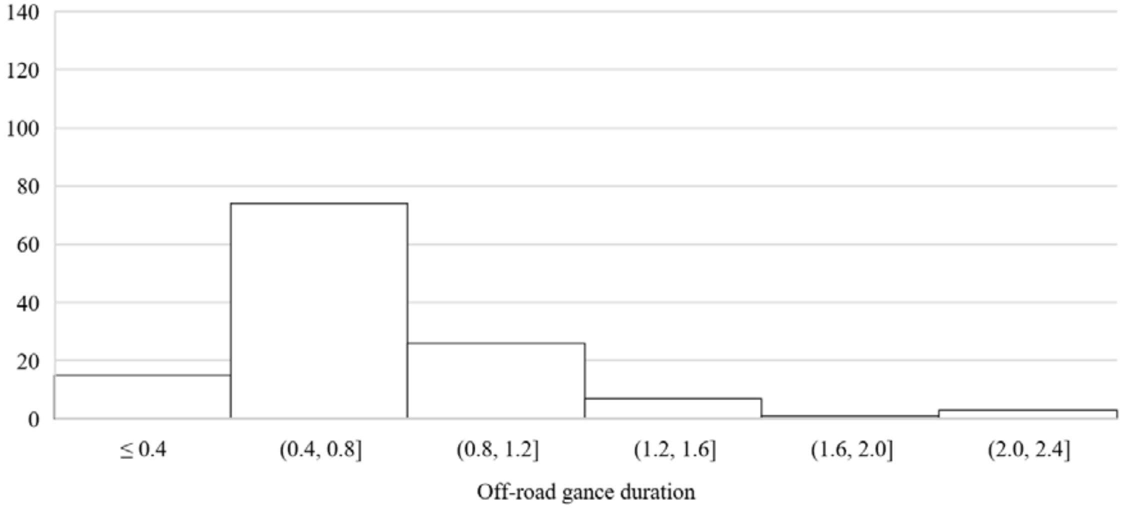
Using the NHTSA’s off-road glance benchmark for measuring distraction, the proportion of glances exceeding 2 seconds from the total number of off-road glances effected by all subjects (i.e., the proportion of off-road glances ≥ 2 seconds) has remained unchanged following exposure to the weather warnings. In addition, the number of participants exceeding the 2 seconds threshold (i.e., percent subjects exceeding the 2 second off-road glance duration) also remained unchanged following exposure to the CV weather warnings. Only one participant effected an off-road glance duration exceeding the 2 second threshold under the baseline conditions in the weather notifications area, and the same was also true under CV conditions.

Conversely, exposure to the WZW notifications has almost tripled the proportion of off-road glances exceeding 2 seconds from the total number of all off-road glances effected by all subjects. Moreover, the number of subjects exceeding the 2 second threshold was also tripled following exposure to the CV WZW (two subjects in the baseline conditions versus six subjects in the CV scenario). This substantial increase in the percent subjects exceeding the 2 second threshold could be alarming since it reveals that nearly half of the participants (46 percent of all participants), when exposed to the WZW in the WZ advance warning area, exceeded the 2 second off-road glance durations used by NHTSA to designate potentially unsafe glance durations. To further visualize the impacts of exposure to the CV WZW on the subjects’ visual behavior, histograms of all off-road glance durations effected by the 13 subjects were plotted for both the CV and baseline conditions in the WZ advance warning area.

Figure 40 shows the off-road glances with durations ranging between 0.4secondsand 0.8seconds remain the most common off-road glance durations in both CV and baseline conditions. However, the display of the CV WZW seems to have augmented both the frequency and proportion of the longer off-road glance durations. Markedly, exposure to the CV WZW ushered record-breaking off-road glance durations of more than 3 second.



A- Subfigure A - CV scenario - WZ advance warning area



B- Subfigure B - baseline scenario - WZ advance warning area

Figure 40 Distribution of all Off-road Glance Durations in the Work Zone Advance Warning Area

Upon closer review of the off-road glance durations, it was recognized that three subjects exceeded the 3 second mark in the WZ advance warning area, where all of these off-road glances were found partly or fully HMI glances. To validate whether exposure to the CV WZW has increased the proportion of longer off-road glances, a chi-squared for equality of proportions test was conducted using a two-by-two contingency table of the off-road glance frequencies classified according to the 1secondsduration mark as used in [134]. The test revealed that the proportion of off-road glances exceeding the 1 second mark in the WZ advance warning area from the total number of off-road glances effected by all subjects was significantly higher in the CV scenario comparative to the baseline scenario (χ^2 (1,387) =11.98, $p < 0.001$). It is noteworthy that the proportion of off-road glances exceeding the 1 second mark did not significantly differ as a result of exposure to the CV weather warnings (χ^2 (1,147) =0.57, $p < 0.45$).

In light of the significant increase in the proportion of the longer off-road glances as a result of exposure to the CV WZW, it is important to note that a marked increase in the off-road glance rate (number of off-road glances per unit time) also took place. The off-road glance rate has more than doubled because of the introduction of the WZW highlighting an increased diversion of the subjects' visual attention away from the primary driving task in the WZ advance warning area.

8.9 General Insights about the Distraction Introduced by the HMI for Truck Drivers

The mean HMI glance durations were determined in the order of 0.83 seconds and 1.03 second in response to the weather and WZW, respectively. The mean glance durations for both CV applications fall well within the typical range of glance durations for in-vehicle devices, according to the literature. According to Birrell and Fowkes (2014), in-vehicles devices typically result in glances to the devices ranging between 0.8 second and 1.1 second [129]. By the same token, the reported mean HMI glance durations are comparable to the range of glance durations to effect secondary visual or visual/manual in-cab tasks for truck drivers (e.g., 1.42s to compare posted speed with speedometer, 1.20s to read clock, 1.10s to adjust radio volume up/down, etc.) [50].

Glance duration to an in-vehicle device is highly dependent on the design of the visual elements, display features, and the position of the user interface in reference to a driver's line of sight [33]. It is not uncommon in literature to report substantially shorter off-road glance durations comparative to the values reported in this study. As an example, one study assessed the visual demands induced by a smart driving aid device communicating eco-driving and real-time safety information via a dashboard-mounted smartphone device and reported brief glance durations in the order of 0.43 second on average. The study attributed the short durations to the effectiveness of the user interface design [129]. Another study investigated the mean glance durations to a personal navigation device and reported mean glance durations of 0.76 second [135]. The core of this discussion is that well-designed user interfaces can result in brief glance durations. In this context, it is recommended to adjust the CV applications and HMI displays in the sense that improves the relative visibility of each of the warnings, and thus, helps drivers shorten the amount of time to extract information. Another recommendation could be placing the HMI closer to the users' line of sight, if possible, (e.g., head-up display) in such a way that requires little gaze transition time for the drivers to land their eyes on the HMI.

Wierwille and Tijerina present the crash risk induced by an in-vehicle system as a linear function of exposure to the system where the exposure factor was defined as the product of the mean glance duration to the system, glance frequency/rate, and how often the system is used [136]. In light of the potential distraction uncovered from the WZW, it is vital that the WZW application be re-evaluated in terms of both the display fashion of the warnings and the amount of information communicated.

The comparison between the visual demands of the two CV applications revealed that the WZW applications invoked significantly more glances per CV notification. It is generally adopted in the literature that higher number of glances to perform an in-vehicle task is an indication of higher workload to extract and process the information [137] [33]. Moreover, HMI glances, in response to the WZW, were notably longer than HMI glances for a weather warning (with statistical significance). Taken together, the WZW application seemed to invoke higher cognitive and visual workload from the drivers to locate, extract, and process the HMI-communicated information. It is noteworthy to reiterate that the WZW application presented two notifications with two items of information that appeared to require longer visual and cognitive processing time.

The contrast between the SWIW and WZW visual/cognitive demands is consistent with what one would expect given that 1) the SWIW application consisted of fewer notifications being communicated and overlaid on the HMI, and thereof resulting in an uncluttered HMI layout, whereas, the WZW application with more warnings increased the visual clutter on the HMI due to the multiple relatively small-sized icons being overlaid next to each other. 2) Unlike the weather warnings, the WZWs were communicated during visually-demanding conditions consisting of a work zone, in addition to a reduced visibility driving environment. As a result, subjects may have been compelled to distribute their visual and cognitive resources between the demanding driving task and the display of the CV notifications. This is largely attestable in view of the higher glance frequency per CV notification for the WZW application relative to its’ SWIW counterpart.

One notable finding of this study is that under baseline conditions, the transition from clear/normal conditions to the more visually-demanding conditions (WZ advance warning area at reduced visibility), drivers seemed to subtly adapt their eyes off-road/on-road glance strategy to suit the visual workload demands of the driving task. This was manifested by slightly shorter off-road glances effected more frequently under the visually demanding conditions. This natural response acts in the compensation of the increased workload demands from the driving environment and is consistent with findings from the literature [137] [50]. Interestingly, the introduction of the WZWs appeared to inhibit this tendency by inducing more frequent off-road glances at relatively longer durations. This result could be acknowledged considering that the WZW application presented drivers with multiple notifications during a short window of time. Each notification was accompanied with relatively intrusive audible beeps calling the subjects to divert their attention away from the road view. With this in view, the reduced visibility environment may have compelled the subjects to seek safety-beneficial information about the traffic environment from the HMI, as opposed to directly extracting information from the road view, given the limited sight distance due to fog.

Although minor differences in the mean off-road glace durations were detected for the two CV applications in comparison with their corresponding baseline scenarios, no statistical significance was established. These findings are also consistent with the findings reported in a study by Horrey and Wickens (2007). The study elaborated that the mean off-road glance duration is largely unrelated to the complexity of the performed in-vehicle task. On the contrary, more complex tasks are associated with an increased proportion of prolonged off-road glances [138]. Against the slight increase in the overall mean off-road glance durations, exposure to the demanding WZWs, unlike the weather notifications, not only induced a higher proportion of eyes off-road time but also significantly increased the proportion of off-road glances exceeding both the 2 second and 1 second thresholds. This is in addition to unlocking an unprecedented range of off-road glance durations exceeding 3 second. This being the case, it is important not to underrate the effects of the challenging roadway and weather conditions as contributors to the heavy workload demands taking place in the presence of the WZWs. As a consequence, it is highly recommended that all CV applications be designed/reevaluated to ensure that the amount of information communicated on the HMI is commensurate with the workload demands imposed from the driving environment, given the nature of the HMI-present CV warnings. In other words, the HMI algorithm should be able to identify the difficulty of the driving task, and adjust the HMI displays and the amount of information communicated in the way that both benefits the driver under the difficult driving environment and suits the driver's needs primarily with regards to scanning the traffic environment for potential hazards.

Finally, the exposure to the CV warnings has more than doubled the off-road glance rate for the two CV applications. This result is particularly of concern for the WZ application since it not only involved more notifications communicated during demanding driving conditions but also induced relatively longer off-road glances. This finding highlights an increased fragmentation in the subjects' visual/cognitive attention, as a result of exposure to the CV WZWs. Scattering drivers' visual resources in real-life could carry serious safety risks, particularly under difficult driving environments and complex in-cabin environments where the vast array of in-vehicle secondary tasks and systems all compete for the truck drivers' allocation of visual/cognitive resources.

CHAPTER 9. CONCLUSIONS AND LESSONS LEARNED IN SUPPORT OF THE WYOMING DOT CONNECTED VEHICLE PILOT

This study highlights the key conclusions and lessons that were drawn in support of the enhancement of the HMI design and user experience (UX) for the WYDOT CV Pilot’s end users. These lessons focus on both the promising aspects, as well as the identified limitations of the evaluated designs. A multi-pronged approach underpins the drawn lessons that are of essence to the HMI and UX design. The approach used in this study consists of:

- Drawing lessons from the state-of-the-art and the state-of-the-practice relevant to automotive systems including HMI and UX evaluation and design practices.
- 2) Bringing together the research insights from the driving simulator experiments on participants’ behavior in response to the Pilot’s CV applications.
- 3) Conducting surveys with the Pilot's leading stakeholder, the WYDOT to inform the HMI and UX design enhancements.

Figure 41 and Figure 42 presents the existing HMI layouts used for truck drivers and highway patrol, in which the display screen size was the difference between them. All in all, the qualitative and quantitative research approach led to the development of well-supported actionable recommendations to ameliorate and address potential limitations of the Pilot’s HMI design and UX. These recommendations are being fed back into the development and enhancement process, allowing rapid improvements to be applied to the HMI displays and algorithms. Notably, the recommendations discussed in this study were approved for immediate and future implementation by the WYDOT via a survey that the research team conducted internally.

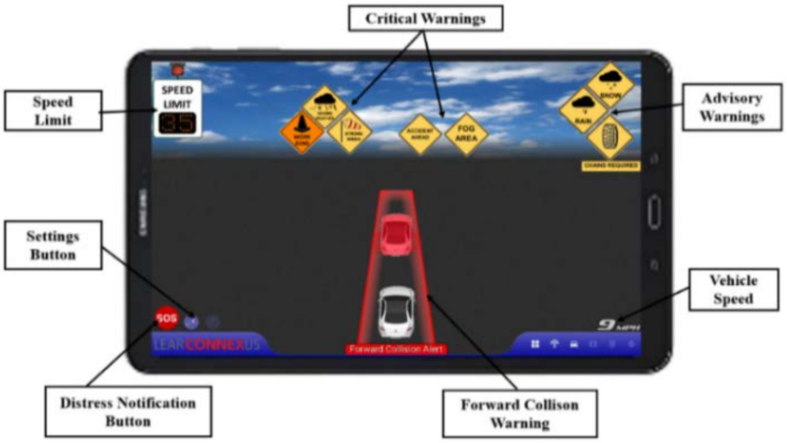


Figure 41 HMI Layout for Truck Drivers

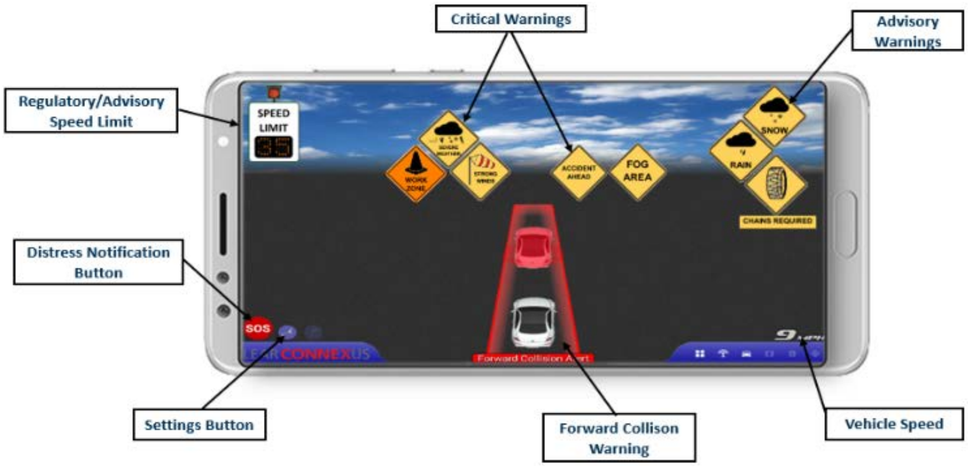


Figure 42 HMI layout for Wyoming Highway Patrol

9.1 Key Lessons Learned

HMI design will play a consequential role in determining the overall outcomes of the CV deployment. A robust HMI design has three key functional requirements:

- Effectively communicates warnings that drivers can effectively perceive.
- Delivers message content that is easily recognized, processed, and interpreted.
- Prompts the appropriate driver response against the forewarned conditions.

9.1.1 Package the Training Program Specific to the End User

Since different end users, such as truck drivers and the highway patrol, have different driving conditions, different driving environment, and different behavior, it is important to package the training program specific to the end user. The highway patrol troopers are highly skilled and confident about their driving skills. Therefore, the difficulty level of the scenarios needs to match the difficult driving environments the highway patrol drive every day. This includes high speed driving, attending accident scenes, performing secondary task while driving, as well as driving in adverse road and weather conditions. From the study, it was also observed that the highway patrol is highly demanding, and the scenarios developed needs to be working perfectly without any glitches. Apart from the driving scenarios, the E-training module needs to be packaged specifically for different end users as well. The same E-training module cannot be used both for truck drivers and highway patrol. For example, for the highway patrol the most important warnings could be a FCW and speed limits warnings, whereas, for the trucks the most important warnings could be WZ notifications. Similarly, truck drivers have specific warnings, such as chains required, ,o light trailers, or parking availability notifications, which are not required by highway patrol. Also, since the training is long and takes about three hours to complete, it needs to be attractive and interactive to draw the participants' attention. Different approaches should be used in the training, such as part-task approach or variable priority approach where different components of the system are focused at different components of the system at different times. Moreover, the job of the highway patrol require them to drive at high speeds. Thus, they cannot be mandated to follow each and every regulation, as well as advisory warnings. Warnings Should Be Clearly Visible and Timely Accessible to Drivers

Given the possibility that warnings may go unnoticed by drivers, particularly under visually demanding and high-noise environments, such as a truck cabin and a patrol car, leveraging multimodal warning displays is crucial [33]. A report by the USDOT on driver-vehicle interfaces recommends the use of both audible warnings and visual displays for all status, information, cautionary, and imminent warnings [33]. It is noteworthy that multimodal display for in-cabin safety systems is also a common practice in the truck manufacturing industry. In line with the design guideline, the Pilot-implemented HMI is capable of communicating warnings via the visual and audible modalities. Unsurprisingly, the multimodal HMI display received strong approval from the CV-equipped truck drivers participating in the Pilot's stakeholder education and training activities.

Furthermore, the display of visual warnings on the HMI must be made conspicuous and accessible to drivers in a timely manner. Convoluted HMIs overloading drivers with information may obstruct drivers' ability to effectively and timely extract information and act upon it [139]. Among the widely adopted usability heuristics of user interface design, by Nielsen, is the “Aesthetic and Minimalist Design” heuristic, articulating that every additional piece of information on a user interface competes with other present items of information, which reduces their respective visibility to the user [140]. Markedly, the limited effectiveness of the Pilot’s CV early lane closure warning in prompting early lane merging behavior among truck drivers, while approaching a WZ lane closure area, is a case in point. The study revealed that 40 percent of the participants effected the lane merge only following the static road lane closure sign and not as soon as the early CV lane closure warning was communicated, thus suggesting, that some drivers may have been unable to extract or process the information communicated on the HMI. Upon further usability review of the scenario, it was recognized that the early WZ lane closure warning notification may have lacked proper visibility. The early lane closure warning was overlaid on the HMI main screen, already cluttered with three other notifications informing participants of an upcoming work zone, the WZ speed limit, and the presence of adverse weather, all displayed close to each other in relatively small-sized icons, as Figure 43 illustrates. In addition, as illustrated in the previous chapter, WZWs were found to require long and frequent off-road glance durations to extract information from the HMI. To enhance the relative visibility and timely accessibility of warnings to drivers, design guidelines by NHTSA (2016) recommend that high-priority alerts be displayed in a salient manner, in the sense that occupies the entire visual display for a specified duration. In light of the limited effectiveness of the early lane closure warning, a five-second full-screen/large-sized display of high priority warnings preceding their overlay on the main screen, when appropriate, was recommended and adopted for future implementation [141]. The five-second large-sized display is intended to adequately accommodate the average driver perception-reaction time [142] and maximize drivers’ ability to timely extract information. The automobile manufacturer, Mercedes Benz, displays traffic regulation signs on the on-board display for five-seconds on its’ X-Class 2017 model [143]. Table 21 illustrates the recommended display process for high-priority warnings.

Figure 43 Small-Sized Overlay of the Lane Closure Warning

Table 21 Recommended Display Process for Priority Warnings

Display Phase	Description	View
Phase 1	Initial State	
Phase 2	New warning displayed in a salient fashion for five-seconds	
Phase 3	Warning is then overlaid on the main screen	

Taking all these ideas into consideration, the second phase of the project was performed, this time with highway patrol officers as the participants. Like the experiment on truck drivers, two different scenarios were tested; one with the CV disabled and one with the CV enabled. However, this time, three different modalities were tested to communicate the CV warnings; small icons with beeps, englared icons with beeps, and enlarged icons with voice. From different analysis with the vehicle dynamics data, all three CV modalities seemed to perform almost the same way. However, when looked into the distraction potential of each of these modalities, it was observed that the enlarged icons with beeps performed much better than the two other modalities. This was because the enlarged icons were much easier to look at than the small icons. The enlarged icons would pop up on the entire screen and stay enlarged for five-seconds before going back into the background. This was enough for the participants to look at and understand even when under extreme workload. Regarding which audible sound they preferred, the patrol officers recommended using beeps instead of voice. This was because, the voice would sometimes interfere with the sound of the dispatch. Also, the beeps were more alarming than the voice.

9.1.2 Warnings Should Be Easily Recognized and Processed

One of the key Pilot activities has been training and educating the various Pilot's stakeholders. The training of the CV-equipped truck drivers and highway patrol primarily sought to instill an appropriate understanding of the CV technology, including how to use the HMI and respond to the various CV warnings [144]. Overall, the training program enhanced the drivers' understanding of how to use the HMI and respond to the CV warnings [145]. Moreover, participants found the CV warnings displayed on the HMI easy to understand [145]. In part, this could be explained by the use of standard visual warnings from/adapted from the MUTCD [122]. In this regard, FHWA guidelines for driver-vehicles interfaces, strongly recommend the use of standard message formats and familiar messages such as those provided in the MUTCD [49]. This is because drivers who are unfamiliar with non-standard messages are susceptible to misinterpreting their meanings. This guideline corroborates Nielsen's second usability heuristic for user interface design "Match between the System and the Real-World" suggesting that effective user interfaces leverage users' existing schemas from real-world objects and experiences when interacting with the user [140].

Moreover, drivers performing an action in response to a CV warning should feel confident when doing so. As such, warnings should be definitive in nature. When a driver's response is expected, it is essential that warnings communicate all the relative aspects of the hazard necessary for the driver's interpretation and action. Message content should not only warn the driver about a potential problem, but also convey an action element, its level of instruction (permissive, advisory, prohibited, etc.), the affected audience, if the hazard involves a subgroup of the road users, in addition to the location of or distance to the condition or action. Evidently, driving simulator studies on the impacts of the Pilot's weather notifications on truck drivers' found that communicating an advance fog warning did not result in noticeable speed reduction on the part of the participants, whereas, pairing the fog warning with the appropriate advisory speed, i.e., the action element, triggered a marked reduction in speed [123].

All in all, it is crucial that CV warnings are easy to use, and of definitive nature in the sense that drivers should not experience any confusion or ambiguity when interpreting the warnings. While MUTCD based and static signs are generally easy to recognize, one of the identified limitations is their occasional inadequacy in conveying definitive and dynamic message content tailored to the instant needs of drivers in evolving situations. Lack of clear instruction may trigger confusion in the mind of the driver or at the very least increase the cognitive workload to the driver. Markedly, one of the CV-equipped truck drivers participating in the stakeholder training and education activities reported that the experimented re-routing notifications were not easy to understand. In this connection, Intel's research on CV HMI shows that communicating information to users should be a balanced activity, where the amount of information should be determined according to the context. For example, Intel's research shows that when the driver needs to consider re-routing due to road activities, more information is desired by the users [146]. Taken together, these findings led to the recommendation of consolidating the Pilot's rerouting notifications by explicitly stating the expected action from the drivers and potentially guiding the drivers to the location of the exit within the context of real-time navigation guidance [141].

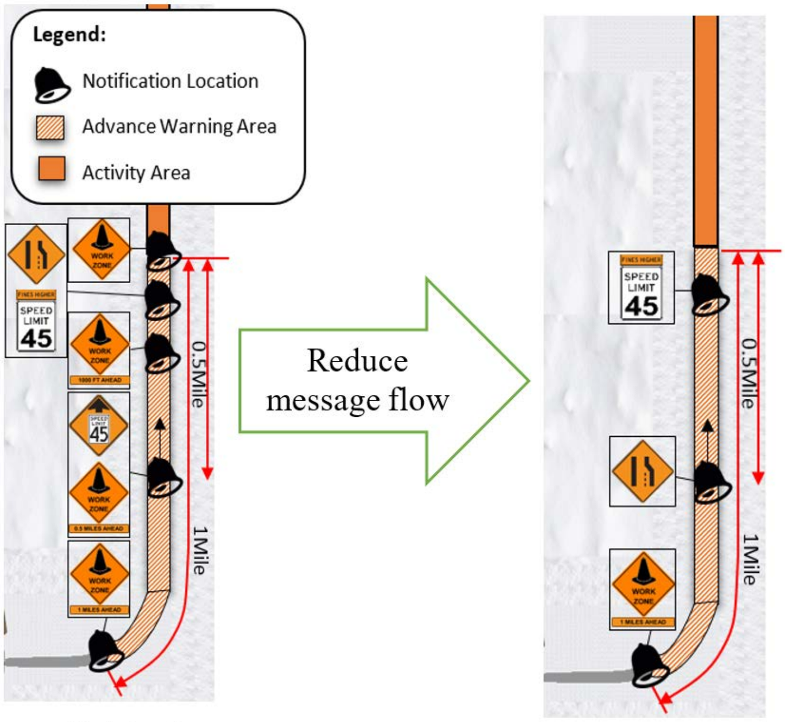
9.1.3 Ensure Appropriate Driver Response against Forewarned Conditions

Prompting appropriate driver response against forewarned conditions is the ultimate step in an effective HMI-driver interaction process. An appropriate driver response is at the core of what connected driving is all about. Driving simulator usability studies substantiated several promising results in terms of driver response [145]. In general, it was found that the trained participants well adhered to the CV warnings [145]. Some of the key benefits confirmed, as a result of participants' exposure to the CV warnings in relation to the Pilot's performance measures, include increased variable speed limit adherence under adverse weather conditions [147], gradual reduction in speed accompanied by smoother braking responses in reduced visibility [123], lower speed variability in the WZ advance warning area in reduced visibility [123], early lane merging behavior toward the open lane when approaching the WZ lane closure, and better braking responses when provided with a FCW [123]. It is noteworthy that merging well in advance of the lane closure in work zones is a behavior the USDOT highly recommends for truck drivers.

9.1.4 Support the Safety of the Drive

9.1.4.1 Minimize Driver Distraction and Nuisance

The communication of CV warnings on the HMI should not impede drivers from maintaining awareness of the immediate surrounding environment. Striking a balance between effectively communicating information, which increases drivers’ situational awareness while minimizing potential adverse impacts, such as driver nuisance and distraction, should be focal to the HMI development process [48] [49] [33]. The studies conducted on the impacts of the Pilot’s CV WZWs on truck driver and highway patrol behavior revealed that distraction may have affected participants as a result of the display of the CV notification. As part of designing for the worst-case scenario approach, participants (both truck drivers and highway patrol) had to navigate the WZ under reduced visibility conditions mimicking conditions commonly experienced on Wyoming’s I-80. In such circumstances, drivers’ attention seems to have been scattered between the demanding driving task and the HMI. Overall, exposure to the CV WZWs triggered a notable increase in the percent time few participants spent driving off-lane in the advance warning area, especially for truck drivers. Additionally, 27 percent of the participants in the stakeholder training and education activities suggested that the display of the Pilot’s CV notifications could be distracting [122]. Upon a closer usability evaluation of the Pilot’s WZ application, it was recognized that the application presents numerous notifications over a short period, where each notification may contain more than one item of information. Over-communicating information over the short time window compelled the participants to frequently divert their attention away from the forward scene for durations that may undermine the safety of drivers. In view of the potential distraction uncovered from the WZ notifications, NHTSA’ tutorials on HMI design provide insights to counteract driver distraction and overload [33]. In demanding driving conditions, a robust HMI should not over-communicate information beyond drivers’ safe capacity to handle information. This is best accomplished by controlling the message flow rate to the driver, and limiting the display to time-critical warnings and those of higher safety or operational relevance [33]. In line with the guidelines, a WZ application consisting of fewer notifications with the higher safety relevance was recommended. This recommendation was adopted for immediate implementation [148] [141]. Figure 44 illustrates the recommended design. Aside from distraction, low-priority messages displayed frequently may annoy and disturb drivers, particularly if they are redundant or easily extracted from the driving environment [33] [49]. With fewer notifications, the recommended design is expected to lower the redundancy of the WZWs with the static road signs, thus reducing the potential of driver nuisance [141].



Original

Recommended

Figure 44 Recommended Enhancement to the Work Zone Application

9.1.4.2 Design of HMI to Handle Critical Situations and Emergencies

Designing an intelligent HMI capable of supporting drivers in critical situations is all important. During emergencies, effective HMIs should communicate clear instructions to vehicle occupants on how they should behave and what to expect. Weast (2017) elaborates; “If the situation requires, the HMI should also give additional context for what should or will be happening next, for example, passengers should exit the vehicle and wait for another vehicle in a safe location.” [149]. It is not uncommon for Wyoming’s I-80 to experience large-scale crash pileups in adverse road and weather conditions. On April 16, 2015, a multi-vehicle crash resulting in multiple injuries occurred on Wyoming’s I-80 during a blizzard and reduced visibility conditions [150]. Numerous drivers (mostly commercial trucks) were involved in secondary crashes occurring in three crash sequences, while others vehicles were stranded in queues behind the pileup scene [150]. In the event of a similar context, it is plausible that few CV drivers may end up in the situation where no routing option or parking area exists ahead of them, given the infrequent access to alternative routes and rest areas on the rural I-80 corridor [151].

In such a scenario, what instructions should the HMI communicate to stranded drivers, (e.g., reduce your speed, find a safe location to park, exit the vehicle if in danger, and wait for instructions from emergency services). Figure 45 illustrates the aftermath of the pileup crash that occurred in 2015. These considerations, while not critical at present considering the low penetration rate of CV vehicles [152], were raised to the Pilot team for thoughtful assessment. To minimize the likelihood of this scenario affecting a greater number of drivers in the future, it was recommended to implement an HMI-embedded algorithm capable of identifying the optimal routing options according to drivers' location, alternative routes availability, and parking availability as soon as road closure information is broadcast to the vehicles [141]. In the same context, it was recommended that the HMI should inform vehicle occupants attempting to request assistance via the DN application in case the distress signals could not be broadcast to the emergency services [141]. Although the parking, rerouting, and rest area notifications might not be of importance to the highway patrol, since they need to the accident scene itself, messages, such as "distressed vehicles" ahead and other FCW, might be of help for the highway patrol.

Figure 45 Aftermath of the April 16th, 2015 Pileup on Wyoming's I-80 (Source: Wyoming Highway Patrol)

9.1.4.3 Craft a Thoughtful UX Propelling Acceptance and Adoption in the Long Haul

Propelling real-world tangible safety benefits could only be accelerated through widespread adoption of CV technology. This predicates strong approval and support from the various stakeholders involved in the decision-making process, including the end users and the private sector adopters. The implemented technology should be of marked utility to each of the individual stakeholders, such as increased safety and convenience for truck drivers and highway patrol troopers, and improved fleet operations for trucking companies. Early findings suggest that the WYDOT CV Pilot has promising potential to garner widespread adoption among both truck drivers and highway patrol. The majority of the CV-equipped drivers participating in the stakeholder education and training activities recognized the Pilot's CV applications for being effective for the real-world with strong potential to improve their safety while driving on Wyoming's I-80 [123] [122]. It is noteworthy also that a sizable proportion of the CV-equipped drivers had a neutral or negative attitude on whether they will become dependent on the Pilot's CV applications for their safety while driving on I-80; only 42 percent of the participants pointed out that they are likely to depend on the CV technology upon full implementation [122]. Therefore, to derive maximal safety benefits, HMI and UX should be thoughtfully crafted to garner user trust and approval [141].

9.1.4.4 Deliver Stakeholder-Tailored Implementation

Addressing stakeholders' needs early on is a critical part of the CV HMI development and implementation. The Pilot's participants from the trucking and freight industry alone, bring differing needs, regulations, and preferences for CV HMI integration within their truck fleet. For instance, some of the stakeholders' regulations prohibit the use of in-cabin visual warnings, which suggests that alternative display modalities are needed. Through the use of surveys, the research team is learning about the needs and regulations for the Pilot's stakeholders and will draw lessons to provide stakeholder-tailored HMI implementation to the extent possible.

9.1.4.5 Adapt the HMI to End Users' Needs

User experience should be at the forefront of every stage in the design process. Weast (2017) stresses that designing for user trust is the key to widespread adoption: "at the end of the day, connected vehicles must behave, react, and communicate in ways that passengers, pedestrians and other drivers are comfortable with." [149]. Inappropriate integration of the HMI may ultimately deter end-users from using the system altogether, as few participants pointed out in the stakeholder training and education activities [122]. To solve this problem, HMI design should be tailored to the individual needs and goals of the diverse demographics of the CV-equipped drivers. As an illustration, a study found that nearly half of the surveyed truck drivers would rather see WZ signs be placed as far as three to five miles in advance of the work zone. In this respect, one of the Pilot's features for the WZ application is the early lane closure warning communicated well ahead of the lane closure zone. Driving simulator experimentation attests to the potential of this feature in prompting early lane merging behavior among truck drivers, a behavior expected to reduce late and forced merging behavior by truck drivers at lane closure zones [123].

In the same direction, the majority of the CV-equipped drivers participating in the stakeholder training and education activities reported that CV technology would provide the highest benefits under poor visibility compared with other conditions (daytime, nighttime, slippery road, and vision blocked). [122]. These findings warrant an in-depth evaluation of drivers' needs and preferences under various conditions, (e.g., which warnings could be appropriate under certain conditions and may be eliminated in other contexts such as clear weather conditions due to nuisance or redundancy considerations [141]).

With many truck drivers on the US roadways being non-native speakers, a key question raised by the CV Pilot team is how safely Limited English Proficiency (LEP) truck drivers will be able to use and interact with the HMI in the Standard English format. While federal regulations stipulate that all commercial motor vehicle drivers must be able to sufficiently converse with the public and understand traffic signs and signals in the English language, LEP violations are a common occurrence [153] [154]. Between 2002 and 2007 there were 39,265 inspections with reported LEP violations. In addition, LEP truck drivers are significantly more involved in crashes and unsafe driving violations compared to their non-LEP counterparts [153]. With this in view, WYDOT is contemplating integrating other languages for HMI settings and speech warnings. Stakeholder surveys for the participating freight companies will aid in determining the optimal approach.

9.1.4.6 User/Owner Customizability

The premise of allowing a certain level of customizability is that preferences vary from one driver to another as to what information they desire and the amount of information they would like to see [139]. Thoughtful consideration of the elements of customizability can promote improved driver response and approval. A one-size fits all design cannot match the needs and preferences of all drivers. For example, since the truck cabins has enough space, a bigger tablet sized HMI display was recommended, whereas, for the highway patrol who have a very crowded cabin with limited space and a lot of distracting in-vehicle devices, a small phone sized HMI display was recommended. Enabling on-demand, user-personalized, and straightforward HMI design and UX communicating information according to the present needs of the situation and drivers' preferences is the key to acquiring strong approval [139]. The majority of participants in the stakeholder education and training activities (mostly CV-equipped truck drivers) viewed the re-routing notifications along with the FCW warnings to be of utmost effectiveness for the real-world, compared with the other CV notifications, such as adverse weather and WZ notifications. On the other hand, the highway patrol found the FCW to be the most useful in the real world followed by adverse weather and WZ notifications. This finding suggests that drivers, at varying degrees of preferences, do not want to be exposed to all sorts of information unless there is a clear safety benefit or a direct impact on their safety and operations, such as being involved in a crash or stranded due to a road closure. In this regard, one available element of customizability for the Pilot's HMI is the option to select/unselect the CV applications for which users would like to receive warnings [141]. Other elements of user-configurable settings that may benefit drivers if implemented include the ability to 1) select how far in advance drivers would like to be notified of adverse conditions; this feature is availed by the WYDOT 511 traveler information service mobile app [155], and 2) filter out warnings based on their level of impact on the driver [141].

9.1.4.7 Create a Cohesive User Experience

With increased connectivity with the physical and digital worlds, vehicles have become crammed with various types of in-vehicle systems, most of which require physical, cognitive, and visual interactions from the driver. Commercial trucks can be crammed with a myriad of in-cabin systems from navigation systems, dispatch communication, and infotainment systems to ADAS, and potentially over-the-air diagnostic and payment technologies whereas the highway patrol vehicles are crammed with devices such as the radar, MDT, radio, as well as sirens. The addition of the CV HMI with no coordination with the existing in-cabin systems may subject drivers to increased distraction and give rise to a disturbing and non-cohesive user experience [156]. For example, it would be inappropriate to alert drivers of a nearby restaurant or a gas station when navigating a WZ activity area or in case a FCW is impending. To solve this problem, merging all systems into a single processing unit or a centralized architecture managing the display of all information issued from the various in-vehicle systems in a coordinated and seamless fashion is highly-recommended. If appropriate, integrating the CV HMI display within existing systems (e.g., mirroring the screen on CarPlay or Android Auto, etc.) could be considered. Moreover, commercial truck drivers often receive over-the-air updates on traffic and road conditions via dispatch communications, navigation systems, or other road and weather in-vehicle systems (e.g., Sirius XM). It is plausible that drivers on I-80, with the implementation of CV technology, may receive multiple redundant or conflicting information from the different in-vehicle systems, subjecting drivers to increased confusion, distraction, and annoyance. With low tolerance for nuisance and false alarms, it is critical that HMI integration for the Pilot’s fleet partners be achieved in coordination with their existing ADAS, navigation, and dispatch systems. It is noteworthy that in the long run, WYDOT intends to integrate CV warnings within third-party navigation apps, which may reduce the issues associated with implementing a stand-alone CV HMI.

REFERENCES

[1] USDOT, “Connected Vehicles: Benefits, Roles, Outcomes,” *U.S. Dep. Transp.*

[2] USDOT, “20 Questions About Connected Vehicles,” *U.S. Department of Transportation*. .

[3] Wyoming Department of Transportation, “Wyoming DOT Connected Vehicle Pilot.” .

[4] Wyoming Department of Transportation, “Wyoming’s 2018 Report on Traffic Crashes,” 2019.

[5] P. D. Saha Promothes and R. Young, *Weather-based safety analysis for the effectiveness of rural vsl corridors*. 2014.

[6] National Highway Traffic Safety Administration, “Distracted driving 2009,” 2010.

[7] C. Yager, S. Dinakar, T. K. Ferris, and S. M, “Emergency Vehicle Operator On-Board Device Distractions,” *Texas A&M Transp. Inst. Tech. Rep.*, 2015.

[8] NBC News, “April Blizzard Causes 70-Vehicle Pile-Up on Wyoming Interstate,” 2015.

[9] C. Hill and G. Krueger, “ITS ePrimer - Module 13 : Connected Vehicles,” *U.S. Dep. Transp.*

[10] NHTSA, “Quick Facts 2016 Fatality Rate per Quick Facts 2016,” *U.S. Dep. Transp.*, pp. 1–6, 2016.

[11] NHTSA, “Traffic Safety Facts,” *U.S. Dep. Transp.*, no. February, pp. 2–3, 2015.

[12] USDOT, “Connected Vehicle Benefits.” .

[13] NHTSA, “Vehicle-to-Vehicle Communication,” *U.S. Department of Transportation*. .

[14] USDOT, “Vehicle-to-Infrastructure (V2I) Resources,” *U.S. Department of Transportation*. .

[15] VTTI, “V2X Data Infrastructure,” *Virginia Tech Transp. Inst.*

[16] B. Wassom, “DSRC vs. 5GLTE: Which Will It Be for Connected Vehicles,” *Wards Auto*, 2018.

[17] P. Brinckerhoff and C. for A. Research, “Connected Vehicle Infostructure Plan,” *Michigan Dep. Transp.*, 2012.

[18] W. Jack, “FULLY CONNECTED VEHICLES: REINVENTING DRIVING FOR A SAFER WORLD,” *IOT @ Intel - Intel Blogs*, 2017.

[19] I. Kimley-Horn and Associates and Noblis., “Traffic Management Centers in a Connected Vehicle Environment,” *Univ. Virgina*, 2013.

[20] FHWA, “Work Zone Facts and Statistics,” *U.S. Dep. Transp.*

[21] Federal Highway Administration, “Trucking Safely Through Work Zones - Safety,” 2014. .

[22] J. G. Pigman and K. R. Agent, “Highway Accidents in Construction and Maintenance Work Zones,” *Transp. Res. Rec.*, vol. 1270, pp. 12–21, 1986.

[23] Federal Motor Carrier Safety Administration, “Large Truck and Bus Crash Facts 2017,” 2019.

[24] FHWA, “Manual on Uniform Traffic Control Devices for Streets and Highways,” 2009.

[25] J. Wang, W. E. Hughes, F. M. Council, and J. F. Paniati, “Investigation of highway work zone crashes: What we know and what we don’t know,” *Transp. Res. Rec.*, vol. 1529, pp. 54–62, 1996.

[26] A. Ghasemzadeh and M. M. Ahmed, “Exploring factors contributing to injury severity at

work zones considering adverse weather conditions," *IATSS Res.*, 2018.

[27] X. Wei, X. Shu, B. Huang, E. L. Taylor, and H. Chen, "Analyzing Traffic Crash Severity in Work Zones under Different Light Conditions," *J. Adv. Transp.*, vol. 2017, 2017.

[28] S. Hallmark, A. Mudgal, T. Stout, and W. Bo, "Behavior Study of Merge Practices for Drivers at Work Zone Closures," *InTrans Proj. 09-359. Iowa State Univ. Inst. Transp.*, no. June, 2011.

[29] W. C. Zech, S. B. Mohan, and J. Dmochowski, "Evaluation of Messages on Changeable Message Signs as a Speed Control Measure in Highway Work Zones," *Pract. Period. Struct. Des. Constr. ASCE*, vol. 13, no. 1, pp. 11–18, 2008.

[30] Y. Li and Y. Bai, "Effectiveness of temporary traffic control measures in highway work zones," *Saf. Sci.*, vol. 47, pp. 453–458, 2009.

[31] D. Datta, C. Hartner, and L. Grillo, "Evaluation of The Dynamic Late Lane Merge System at Freeway Construction Work Zones," *Res. Rep. RC-1500. Michigan Dep. Transp.*, 2007.

[32] P. T. V. Benekohal, R. F., Shim, E., Resende, "Truck Drivers' Concerns in Work Zones: Travel Characteristics and Accident Experiences.," *Transp. Res. Rec.*, vol. 1509, pp. 55–64, 1995.

[33] J. S. et al Campbell, J. L., Brown, J. L., Graving, "Human Factors Design Guidance For Driver-Vehicle Interfaces," *NHTSA, U.S. Dep. Transp. Rep. no. DOT HS 812 360.*, 2016.

[34] Q. Li, L. Yu, and F. Qiao, "Impacts of P2V Wireless Communication on Safety and Environment in Work zones through Driving Simulator Tests," *Proc. 26th Annu. Conf. Int. Chinese Transp. Prof. Assoc. (ICTPA), Tampa, FL*, no. May, 2013.

[35] F. Qiao, R. Rahman, Q. Li, and L. Yu, "Smart Phone Based Forward Collision Warning Messages in Work Zones to Enhance Safety and Reduce Emissions," *94th Transp. Res. Board Annu. Meet.*, vol. 94, no. January, 2015.

[36] R. Rahman, F. Qiao, Q. Li, L. Yu, P.-H. Kuo, and B. Transportation Research, "Smart Phone Based Forward Collision Warning Messages in Work Zones to Enhance Safety and Reduce Emissions," *Present. 94th Annu. Meet. Transp. Res. Board, Washington, D.C., 2014*, 2015.

[37] B. You, F. Qiao, and L. Yu, "Drivers' Reaction of Warning Messages in Work Zone Termination Areas with Left Turn," *J. Transp. Technol.*, vol. 6, pp. 139–147, 2016.

[38] C. Castro, *Human Factors of Visual and Cognitive Performance in Driving*. CRC Press, 2009.

[39] J. A. Mcclafferty and J. M. Hankey, "Comparing Three Methods of Eye-Glance Transition Coding," 2016.

[40] C. Spence and C. Ho, "Crossmodal Information Processing in Driving Performance in Driving," in *Human Factors of Visal and Cognitive*, 2009.

[41] "Distracted Driving." .

[42] J. Engstrom and E. Johansson, "Effects of visual and cognitive load in real and simulated motorway driving," *Transp. Res. Part F*, vol. 8, pp. 97–120, 2005.

[43] L. Angell, P. a. Auflick, D. Kochnar, L. Tijerina, and W. Biever, "Driver Workload Metrics Project Task 2 Final Report," *NHTSA, US Dep. Transp. Rep. no. DOT HS 810 635*, no. report no. DOT HS 810 635, 2006.

[44] S. G. Klauer, T. A. Dingus, V. L. Neale, J. D. Sudweeks, and D. J. Ramsey, "The Impact of Driver Inattention On Near-Crash / Crash Risk : An Analysis Using the 100-Car Naturalistic

Driving Study Data," *NHTSA, US Dep. Transp. Rep. no. DOT HS 810 594*, no. April, 2006.

[45] FMCSA, "The Large Truck Crash Causation Study - Analysis Brief," *Fed. Mot. Carr. Saf. Adminsitration, U.S. Dep. Transp. Publ. No. FMCSA-RRA-07-017*, 2007.

[46] R. E. Lianeras, J. P. Singer, and R. Bowers-Carnahn, "Assessment of Truck Driver Distraction Problem and Research Needs," 2005.

[47] J. Brown, M. McCallum, J. Campbell, and C. Richard, "Integrated Vehicle-Based Safety System Heavy Truck Driver-Vehicle Interface (DVI) Specifications," 2007.

[48] M. François, F. Osiurak, A. Fort, P. Crave, and J. Navarro, "Automotive HMI design and participatory user involvement: review and perspectives," *Ergonomics*, vol. 60, no. 4, pp. 541–552, 2017.

[49] C. M. Richard, J. F. Morgan, P. L. Bacon, J. S. Graving, G. Divekar, and M. G. Litchy, "Multiple Sources of Safety Information from V2V and V2I: Redundancy, Decision Making, and Trust—Safety Message Design Report," *Publ. FHWA-HRT-15-007. FHWA, U.S. Dep. Transp.*, no. November, 2015.

[50] P. Green, "Visual and Task Demands of Driver Information Systems," *Univ. Michigan Transp. Res. Inst. (UMTRI). Rep. no. UMTRI-98-16*, 1999.

[51] NHTSA, "Technology Applications For Traffic Safety Programs: A Primer," Washington DC, 2009.

[52] J. L. Campbell *et al.*, "Human Factors Design Guidance for Driver-Vehicle Interfaces," Washington, DC, 2016.

[53] P. Gáspár, Z. Szalay, and S. Aradi, "Highly Automated Vehicle Systems. Report No. 978-963-313-173-2," Badapest, 2014.

[54] C. Sentouh, J.-C. Popieul, S. Debernard, and S. Boverie, "Human-Machine Interaction in Automated Vehicle: The ABV Project," *IFAC Proc. Vol.*, vol. 47, no. 3, pp. 6344–6349, 2014.

[55] M. L. Cummings, R. M. Kilgore, E. Wang, L. Tijerina, and D. S. Kochhar, "Effects of single versus multiple warnings on driver performance," *Hum. Factors*, vol. 49, no. 6, pp. 1097–1106, 2007.

[56] G. Fitch, D. Bowman, and R. Llaneras, "Distracted Driver Performance to Multiple Alerts in a Multiple-Conflict Scenario," *Hum Factors*, vol. 56, pp. 1497–1505, Dec. 2014.

[57] G. Jakus, C. Dicke, and J. Sodnik, "A user study of auditory, head-up and multi-modal displays in vehicles," *Appl. Ergon.*, vol. 46, Aug. 2014.

[58] F. Naujoks, Y. Forster, K. Wiedemann, and A. Neukum, "Improving Usefulness of Automated Driving by Lowering Primary Task Interference through HMI Design," *J. Adv. Transp.*, vol. 2017, pp. 1–12, Aug. 2017.

[59] P. Konstantopoulos, P. Chapman, and D. Crundall, "Driver's visual attention as a function of driving experience and visibility. Using a driving simulator to explore drivers' eye movements in day, night and rain driving," *Accid. Anal. Prev.*, vol. 42, pp. 827–834, May 2010.

[60] G. K. Kountouriotis, R. M. Wilkie, P. H. Gardner, and N. Merat, "Looking and thinking when driving: The impact of gaze and cognitive load on steering," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 34, pp. 108–121, 2015.

[61] T. Louw and N. Merat, "Are you in the loop? Using gaze dispersion to understand driver visual attention during vehicle automation," *Transp. Res. Part C Emerg. Technol.*, vol. 76,

pp. 35–50, Mar. 2017.

[62] Volvo, "VOLVO VN Operator's Manual," 2010.

[63] Daimler, "Detroit Assurance - Radar System - Camera System," 2016.

[64] Kenworth, "T680 & T880," 2013.

[65] C. M. Richard, J. L. Campbell, and L. Brown, "A Procedure for Developing Warning Message Prioritization Rules in Integrated Collision Warning Systems for Heavy Trucks," *Proc. Hum. Factors Ergon. Soc. 52nd Annu. Meet.*, pp. 1860–1864, 2008.

[66] J. L. Campbell, C. M. Richard, J. L. Brown, and M. McCallum, "Crash Warning System Interfaces : Human Factors Insights and Lessons Learned," *NHTSA, U.S. Dep. Transp. Rep. no. DOT HS 810 697*, no. January, 2007.

[67] J. Wan, C. Wu, and Y. Zhang, "Effects of lead time of verbal collision warning messages on driving behavior in connected vehicle settings," *J. Safety Res.*, vol. 58, pp. 89–98, 2016.

[68] Wikipedia, "Highway patrol," *Wikipedia*. .

[69] Wyoming Highway Patrol, "Field Operations." .

[70] E. Filtness and A. & Lenné, "Assessment of police subjective workload and preference for using a voice-based interface during simulated driving," 2013.

[71] T. C. Lansdown, N. Brook-Carter, T. Kersloot, and N. Brook-carter, "Distraction from multiple in-vehicle secondary tasks: vehicle performance and mental workload implications," 2007.

[72] K. L. Young and P. M. Salmon, "Examining the relationship between driver distraction and driving errors: A discussion of theory, studies and methods," *Saf. Sci.*, vol. 50, pp. 165–174, 2012.

[73] NHTSA, "Distracted Driving in Fatal Crashes, 2017," 2019.

[74] NHTSA, "Distracted Driving 2016," 2018.

[75] J. Citrowske *et al.*, "Distracted Driving by Law Enforcement Officers Resulting in Auto Liability Claims Identification of the Issues and Recommendations for Implementation of a Loss Control Program," 2011.

[76] C. Missikpode, C. Peek-Asa, T. Young, and C. Hamann, "Does crash risk increase when emergency vehicles are driving with lights and sirens?," *Accid. Anal. Prev.*, vol. 113, pp. 257–262, Apr. 2018.

[77] G. S. Anderson, A. Courtney, D. Plecas, and C. Chamberlin, "Multi-tasking Behaviors of General Duty Police Officers," *Police Pract. Res.*, vol. 6, no. 1, pp. 39–48, 2005.

[78] National Highway Traffic Safety Administration (NHTSA), "FARS Analytic Reference Guide 1975 to 2008," Washington, DC, 2009.

[79] E. Y. Noh, "Characteristics of Law Enforcement Officers' Fatalities in Motor Vehicle Crashes," 2011.

[80] S. E. Wolfe, J. Rojek, G. Alpert, H. Tiesman, and S. James, "Characteristics of officer-involved vehicle collisions in California.," *Polic. An Int. J. Police Strateg. Manag.*, vol. 38, no. 3, pp. 458–477, 2015.

[81] G. Carrick, S. Srinivasan, and S. S. Washburn, "Law Enforcement Vehicle Crashes in Florida: Descriptive Analysis and Characterization," *Transp. Res. Rec. J. Transp. Res. Board*, vol. No. 2182, pp. 40–47, 2010.

[82] USDOT, "Connected Vehicle Pilot Deployment Program : Phase 2 Deployment Outreach

Plan, Version 3 -WYDOT," *DOT Natl. Transp. Integr. Search - ROSA P*, 2018.

[83] B. Reaves, "Police Vehicle Pursuits, 2012-2013," 2017.

[84] Cheyenne Police Department, "Cheyenne Police Department 2016 Annnual Report," 2016.

[85] Wyoming Highway Patrol, "Patrol News." .

[86] R. Kuncyté, C. Laberge-Nadeau, T. G. Crainic, and J. A. Read, "Organisation of truck-driver training for the transportation of dangerous goods in Europe and North America," *Accid. Anal. Prev.*, vol. 35, no. 2, pp. 191–200, 2003.

[87] S. A. Gargoum, A. M. Kim, H. Zhang, and T. Z. Qiu, "Towards establishing effective commercial driver training standards: Analysis of industry opinions from Alberta," *Can. J. Civ. Eng.*, vol. 44, no. 11, pp. 899–910, 2017.

[88] J. Morgan, S. Tidwell, A. Medina, and M. Blanco, "On the training and testing of entry-level commercial motor vehicle drivers," *Accid. Anal. Prev.*, vol. 43, pp. 1400–1407, Jul. 2011.

[89] P. Hirsch, M. A. Choukou, and F. Bellavance, "Transfer of training in basic control skills from truck simulator to real truck," *Transp. Res. Rec.*, vol. 2637, no. 1, pp. 67–73, 2017.

[90] P. Chapman, G. Underwood, and K. Roberts, "Visual search patterns in trained and untrained novice drivers.," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 5, no. 2, pp. 157–167, 2002.

[91] A. K. Pradhan, D. L. Fisher, and A. Pollatsek, "Risk perception training for novice drivers: Evaluating duration of effects of training on a driving simulator," *Transp. Res. Rec.*, no. 1969, pp. 58–64, 2006.

[92] D. Fisher, A. Pollatsek, and A. Pradhan, "Can novice drivers be trained to scan for information that will reduce their likelihood of a crash?," *Inj. Prev.*, vol. 12 Suppl 1, pp. i25-9, Jul. 2006.

[93] D. Fisher *et al.*, "Use of a Fixed-Base Driving Simulator to Evaluate the Effects of Experience and PC-Based Risk Awareness Training on Drivers' Decisions," *Hum. Factors*, vol. 44, pp. 287–302, Feb. 2002.

[94] T. Rosenbloom, A. Shahar, A. Elharar, and O. Danino, "Risk perception of driving as a function of advanced training aimed at recognizing and handling risks in demanding driving situations," *Accid. Anal. Prev.*, vol. 40, pp. 697–703, Apr. 2008.

[95] G. Walker, N. Stanton, T. Kazi, P. Salmon, and D. Jenkins, "Does advanced driver training improve situation awareness?," *Appl. Ergon.*, vol. 40, pp. 678–687, Aug. 2008.

[96] V. Beanland, N. Goode, P. Salmon, and M. Lenné, "Is there a case for driver training? A review of the efficacy of pre- and post-licence driver training," *Saf. Sci.*, vol. 51, pp. 127–137, Jan. 2013.

[97] D. Begg and R. Brookland., "Participation in Driver Edu- cation/Training Courses during Graduated Driver Licen- sing, and the Effect of a Time-Discount on Subsequent Traffic Offenses: Findings from the New Zealand Drivers Study," *J. Safety Res.*, vol. 55, pp. 13–20, 2015.

[98] A. Petersen, R. Barrett, and S. Morrison, "Driver-training and emergency brake performance in cars with antilock braking systems," *Saf. Sci.*, vol. 44, pp. 905–917, Dec. 2006.

[99] N. Stanton, G. Walker, M. Young, T. Kazi, and M. Salmon, "Changing drivers' minds: The evaluation of an advanced driver coaching system," *Ergonomics*, vol. 50, pp. 1209–1234,

Sep. 2007.

[100] R. Isler, N. Starkey, and A. Williamson, "Video-based road commentary training improves hazard perception of young drivers in a dual task," *Accid. Anal. Prev.*, vol. 41, pp. 445–452, Jun. 2009.

[101] R. Isler, N. Starkey, and P. Sheppard, "Effects of higher-order driving skill training on young, inexperienced drivers' on-road driving performance," *Accid. Anal. Prev.*, vol. 43, pp. 1818–1827, Sep. 2011.

[102] D. Crundall, B. Andrews, E. Loon, and P. Chapman, "Commentary training improves responsiveness to hazards in a driving simulator," *Accid. Anal. Prev.*, vol. 42, pp. 2117–2124, Nov. 2010.

[103] Y. Wang, W. Zhang, and G. Salvendy, "Effects of a Simulation-Based Training Intervention on Novice Drivers' Hazard Handling Performance," *Traffic Inj. Prev.*, vol. 11, pp. 16–24, Feb. 2010.

[104] N. Goode, P. M. Salmon, and M. G. Lenné, "Simulation-based driver and vehicle crew training: Applications, efficacy and future directions," *Appl. Ergon.*, vol. 44, no. 3, pp. 435–444, 2013.

[105] T. Petzoldt, T. Weiß, T. Franke, J. Krems, and M. Bannert, "Can driver education be improved by computer based training of cognitive skills?," *Accid. Anal. Prev.*, vol. 50, Jan. 2013.

[106] E. Bart and A. Reep, "Culture of progressive longitudinal training in the public transit industry," *Transp. Res. Rec.*, no. 2328, pp. 40–46, 2013.

[107] L. Tijerina, "Key human factors research needs in intelligent vehicle-highway system crash avoidance," *Transp. Res. Rec.*, vol. 1485, pp. 1–9, 1995.

[108] W. Payre, J. Cestac, N. T. Dang, F. Vienne, and P. Delhomme, "Impact of training and in-vehicle task performance on manual control recovery in an automated car," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 46, pp. 216–227, 2017.

[109] National Highway Traffic Safety Administration; International Association of Directors of Law Enforcement Standards and Training (IADLEST), "Law Enforcement Driver Training Reference Guide," 2007.

[110] NAPD, "National Academy for Professional Driving," 2018. .

[111] "Wyoming Law Enforcement Academy," 2018. .

[112] S. MASTROFSKI and R. B. PARKS, "Improving Observational Studies of Police," vol. 28, no. 3, 1990.

[113] Wyoming Department of Transportation, "Pavement Marking Manual," 2012.

[114] Alliance of Automobile Manufacturers, "Statement of Principles, Criteria and Verification Procedures on Driver Interactions with Advanced In- Vehicle Information and Communication Systems," 2006.

[115] A. R. Bowers, A. J. Mandel, R. B. Goldstein, and E. Peli, "Driving with Hemianopia, II: Lane Position and Steering in a Driving Simulator," *Invest. Ophthalmol. Vis. Sci.*, vol. 51, no. 12, pp. 6605–6613, 2010.

[116] H. Klee and E. Radwan, "Assessment of the Use of a Driving Simulator for Traffic Engineering Studies," *Cent. Adv. Transp. Syst. Simulation, Univ. Cent. Florida*, 2004.

[117] V. G. et al. Kitchener, Fred, Rhonda Young, Mohamed Ahmed, Guangchuan Yang, Sherif Gaweesh, Deepak Gopalakrishna, "Connected Vehicle Pilot Deployment Program Phase 2,

Performance Measurement and Evaluation Support Plan-ICF/Wyoming. No. FHWA-JPO-16-290.," United States, 2018.

[118] M. Ahmed and M. Abdel-Aty, "A data fusion framework for real-time risk assessment on freeways," *Transp. Res. Part C Emerg. Technol.*, vol. 26, pp. 203–213, 2013.

[119] M. Ahmed and M. Abdel-Aty, "Application of stochastic gradient boosting technique to enhance reliability of real-time risk assessment," *Transp. Res. Rec.*, no. 2386, pp. 26–34, 2013.

[120] R. Yu, M. Abdel-Aty, and M. Ahmed, "Bayesian random effect models incorporating real-time weather and traffic data to investigate mountainous freeway hazardous factors," *Accid. Anal. Prev.*, vol. 50, pp. 371–376, 2013.

[121] S. M. Gaweesh and M. M. Ahmed, "Evaluating the safety effectiveness of a weather-based variable speed limit for a rural mountainous freeway in Wyoming," *J. Transp. Saf. Secur.*, vol. 0, no. 0, pp. 1–26, 2019.

[122] M. M. Ahmed, G. Yang, and S. Gaweesh, "Assessment of Connected Vehicle Human Machine Interface Using a High-Fidelity Driving Simulator: Preliminary Findings from the Assessment of Connected Vehicle Deployment Program," *98th Transp. Res. Board Annu. Meet.*, 2019.

[123] O. Raddaoui, S. Gaweesh, and M. M. Ahmed, "Evaluation of Connected Vehicle Real-Time Weather and Work Zone Warnings on the Behavior of Truck Drivers : A Driving Simulator Study," 2019.

[124] K. D. Kusano and H. C. Gabler, "Safety benefits of forward collision warning, brake assist, and autonomous braking systems in rear-end collisions," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1546–1555, 2012.

[125] Smart Eye AB, "User Manual Smart Eye." Gothenburg, pp. 1–19, 2002.

[126] NHTSA, "Visual-Manual NHTSA Driver Distraction Guidelines," 2010.

[127] P. Green, "The 15-second rule for driver information systems," *Am. Conf. Proc.*, Jan. 1999.

[128] A. Aksjonov, P. Nedoma, V. Vodovozov, and E. Petlenkov, "A Method for Detection and Evaluation of Driver Distraction Induced by In-Vehicle Information Systems," *IECON 2018 - 44th Annu. Conf. IEEE Ind. Electron. Soc.*, no. October, pp. 4513–4518, 2018.

[129] S. A. Birrell and M. Fowkes, "Glance behaviours when using an in-vehicle smart driving aid: A real-world, on-road driving study," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 22, pp. 113–125, 2014.

[130] A. Morris, S. Reed, R. Welsh, L. Brown, and S. Birrell, "Studying the Effects of In-vehicle Information Systems on Driver Visual Behaviour – Implications for Design," in *IRCOBI Conference*, 2013.

[131] O. Radddaoui and M. Ahmed, *User Experience and Human Machine Interface design for connected heavy trucks: lessons learned in support of the Wyoming DOT Connected Vehicle Pilot*. 2019.

[132] D. D. Salvucci and J. H. Goldberg, "Identifying Fixations and Saccades in Eye-Tracking Protocols," *Proc. Eye Track. Res. Appl. Symp.*, pp. 71–78, 2000.

[133] S. M. Munn and J. B. Pelz, "Fixation identification in dynamic scenes : Comparing an automated algorithm to manual coding," *Proc. 5th Symp. Appl. Percept. Graph. Vis.*, 2008.

[134] A. Morando, T. Victor, and M. Dozza, "A reference model for driver attention in automation : Glance behavior changes during lateral and longitudinal assistance," *IEEE*

Trans. Intell. Transp. Syst., pp. 1–11, 2018.

[135] A. Morris, S. Reed, R. Welsh, L. Brown, and S. Birrell, "Studying the Effects of In-vehicle Information Systems on Driver Visual Behaviour – Implications for Design," *Int. Res. Counc. Biomech. Inj. (IRCOBI 2013)*, pp. 11–13, 2013.

[136] W. W. Wierwille and L. Tijerina, "Modelling the Relationship Between Driver In-Vehicle Visual Demands and Accident Occurrence," *Vis. Veh. -VI*, 1998.

[137] B. Metz, N. Schomig, and H.-P. Kruger, "Attention duting Visual Secondary tasks in driving.pdf," *Transp. Res. Part F*, vol. 14, pp. 369–380, 2011.

[138] W. J. Horrey and C. D. Wickens, "In-Vehicle Glance Duration: Distributions, Tails, and Model of Crash Risk," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1, 2007.

[139] C. Bush, "Eyes off the road," *Vehicle Electronics Magazine*, 2018. .

[140] J. Nielsen, "No Title," *10 Usability Heuristics for User Interface Design*, 1994. .

[141] O. Raddaoui and M. M. Ahmed, "User Experience and Human Machine Interface design for connected heavy trucks : lessons learned in support of the Wyoming DOT Connected Vehicle Pilot User Experience and Human Machine Interface design for connected heavy trucks : lessons learned in suppor," *To be Publ. ITS Am. Proc.*, 2019.

[142] R. J. Koppa, "Traffic Flow Theory," *Chapter 3 Gartner, N.H., Messer, C.J. Rathi, A.K. (Eds). Traffic Flow Theory Transp. Res. Board Monogr. Natl. Res. Counc. Washingt. DC 2000*, 2001.

[143] M. Benz, "X-Class," *X-Class Operating Instructions*, 2017. .

[144] F. Kitchener, R. Young, M. Ahmed, G. Yang, and Y. Gaweesh, "Connected Vehicle Pilot Deployment Program Phase 2 Updated Performance Measurement and Evaluation Support Plan – Wyoming," *U.S. Dep. Transp. Fed. Highw. Adminsitration*, 2018.

[145] M. M. Ahmed, G. Yang, and S. Gaweesh, "Development and Assessment of a Connected Vehicle Training Program for Truck Drivers," *Transp. Res. Rec.*, 2019.

[146] J. Weast, "Trusting The Rise: Four Capabilities at the Heart of Connected Vehicles," *IOT @ Intel - Intel Blogs*, 2016. .

[147] G. Yang, M. M. Ahmed, and S. Gaweesh, "Impact of Variable Speed Limit in a Connected Vehicle Environment on Truck Driver Behavior under Adverse Weather Conditions: Driving Simulator Study," *Transp. Res. Rec.*, vol. 2673, no. 7, pp. 132–142, 2019.

[148] B. Subedi, S. Gaweesh, M. Ahmed, and G. Yang, "CONNECTED VEHICLE TECHNOLOGY TO PROTECT THE SAFETY OF HIGHWAY PATROL TROOPERS: TRAINING FRAMEWORK AND LESSONS LEARNED FROM THE WYOMING CONNECTED VEHICLE PILOT," *Transp. Res. Rec.*

[149] J. Weast, "Intersections of Trust: HMI Use Cases for Connected Vehicles," *IOT@Intel - Intel Blogs*, 2017. .

[150] W. H. Patrol, "No Title," **Update for I 80 multi-vehicle crash between Cheyenne and Laramie* - Facebook Post*, 2015. .

[151] Wyoming Department of Transportation, "Wyoming Truck Parking Wyoming Truck Parking."

[152] M. M. Ahmed, G. Yang, G. Sherif, R. K. Young, and F. Kitchener, "Performance Measurement and System Evaluation of Wyoming Connected Vehicle Deployment Program: Planning and Pre-deployment Conditions," *Accept. Present. Transp. Res. Board 98th Annu. Meet.*, 2019.

[153] L. Nixon, Julie, C. Stevenson, M. Yeh, and I. Bartinique, “A Preliminary Review of English Proficiency and Safe Commercial Vehicle Operation,” 2011.

[154] M. McCoy, “Danger Ahead? Truckers Who Can’t Read AR Roadway Signs a Common Problem,” *KARK Local News*, 2018.

[155] Wyoming Department of Transportation, “Wyoming 511 Mobile App For Android.”

[156] J. Weast, “Building Trust in Connected Vehicles: Active Safety Systems Must Converge With in-Vehicle Infotainment,” *IOT @ Intel - Intel Blogs*, 2017. .