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Connected vehicle real-time traveler information messages for freeway speed harmonization under adverse weather conditions: Trajectory level analysis using driving simulator

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ABSTRACT

This paper employed a high-fidelity driving simulator to investigate the impacts of the Wyoming Department of Transportation (WYDOT) Connected Vehicle (CV) Pilot's Traveler Information Messages (TIMs) on drivers' speed selection and the safety benefits of their speed harmonization. Three driving simulator experiment scenarios were developed to simulate the typical traffic and weather conditions on the rural Interstate 80 (I-80) in Wyoming. A total of 25 professional drivers from the WYDOT and trucking industry were recruited to participate in the driving simulator experiment. Participants' instantaneous speeds at various locations were collected to reveal the effects of CV TIMs on their speed selection. The results showed that average speed profiles under CV scenarios were generally lower than under baseline scenarios, particularly for winter conditions (snowy and severe weather). The variance of speed under CV scenarios was found to be significantly lower than the baseline scenarios, indicating that CV TIMs have the potential to harmonize the variations in speed. In addition, for the work zone driving simulator experiment, this research revealed that the mean time-to-collision (TTC) under baseline scenario is approximately 40 % lower than CV scenario, and the mean deceleration to avoid a crash (DRAC) under baseline scenario is approximately 19.3 % higher than CV scenario. These findings suggest that CV TIMs can reduce the risk of crashes. Research findings would provide the WYDOT with early insights into the effectiveness of CV TIMs, which could assist with developing more efficient transportation management strategies under adverse weather conditions.

1. Introduction

Interstate 80 (I-80) in Wyoming is one of the busiest freight and passenger corridors in the U.S., which is characterized as a challenging rural mountainous freeway corridor with harsh winter conditions such as low visibility and icy road surface from blowing snow or blizzard (WYDOT, 2019a). Despite the relatively low traffic demands in Wyoming, the fatality rates are always typically higher than the national level, particularly truck-related crashes (NHTSA, 2019). In 2014, heavy truck crash rate in Wyoming was 0.52 per million vehicle miles traveled (MVMT), which was ranked the first in the US (Weber and Murray, 2014). Besides, statistical results revealed that heavy truck-related crashes accounted for 6.9 percent of total crashes and 14.3 percent of fatal crashes in Wyoming in 2018 (WYDOT, 2019b). According to the National Highway Traffic Safety Administration (NHTSA), 94 percent of motor vehicle crashes were caused entirely or partially by driver-related errors (NHTSA, 2018). Among the driver-related errors, recognition errors (e.g., driver's inattention, distractions, and inadequate surveillance) and decision errors (e.g., speeding, misjudgment of gap or others' speed, false assumption of others' actions) were found to be the most critical causes to crashes, which accounted for approximately 41 percent and 33 percent of the total crashes in the US, respectively (NHTSA, 2018).

In practice, speed variation has been considered as a key Surrogate Measure of Safety (SMoS) for traffic crashes; a lower variation in speed means a smaller possibility of traffic collision (Moreno and Garcia, 2013; Li et al., 2013; Choudhary et al., 2018; Wali et al., 2019; Stipancic et al., 2019). This is especially significant to Wyoming I-80, where the mountainous terrain and the adverse weather events create considerable challenges to drivers controlling a vehicle, particularly heavy trucks (Gaweesh et al., 2019). In addition, the presence of slow-moving snowplows under snowy weather conditions brings the increased potential of rear-end crashes and near-crashes. In current practice, Variable Message Sign (VMS) has been proven as an effective

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freeway management strategy to minimize the potential of collisions on freeways under adverse weather conditions. VMS is one of the key components of Intelligent Transportation System (ITS), which is used to deliver real-time traveler information so that drivers can better make decisions in response to real-time roadway conditions such as congestion, crashes, and adverse weather (Dudek, 2004). For a VMS corridor, VMS signs are usually installed overhead or on the roadside to provide drivers with real-time traffic and weather events as well as advisory speed limits that were determined based on the prevailing weather and road conditions (Dudek, 2004). Nevertheless, in reality, the majority of rural freeway corridors are not equipped with VMS devices. In this condition, drivers are not able to receive such messages and have to adjust their speeds and driving behaviors individually based on their experiences and judgment, which tends to result in high variability in travel speeds that may cause traffic collisions. With this concern and given the safety benefits of the emerging Connected Vehicle (CV) technologies (Rahman and Abdel-Aty, 2018; Yue et al., 2018; Papadoulis et al., 2019), the U.S. Department of Transportation (USDOT) selected the Wyoming I-80 corridor to develop, test, and deploy a suite of CV applications that utilize Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) wireless communication technologies to deliver real-time Traveler Information Messages (TIMs) to drivers (Gopalakrishna et al., 2016a,b). The Wyoming CV TIMs were designed to assist drivers better recognizing the hazardous driving conditions and more reasonably manage their speed selection and acceleration/deceleration actions when driving under adverse weather conditions and thus eliminating potential speed variations. In comparison with traditional VMSs, CV-based TIMs can be implemented on a wider range of the freeway corridor with less infrastructure costs. Moreover, it is expected that CV drivers can receive real-time warnings or notifications in a more timely manner, thus allows more time to smoothly react to a hazardous situation.

To date, there have been several studies that evaluated the effectiveness of VMS and Variable Speed Limit (VSL) on Wyoming I-80 using empirical data (Sui and Young, 2014; Saha et al., 2015; Gaweesh and Ahmed, 2019). In general, their research revealed that VMS and VSL are efficient in reducing the speed variation as well as the number of crashes on the VMS/VSL corridors on Wyoming I-80 under adverse weather conditions. Nevertheless, since the Wyoming CV Pilot is still under the deployment and testing stage, the effectiveness of Wyoming's CV TIMs is still unexplored due to the lack of available field-collected traffic performance data. In comparison, a high-fidelity driving simulator allows for testing the impacts of various vehicle technologies and roadway and environmental characteristics on driving behavior in a controlled environment (Bella, 2008; Helman and Reed, 2015; Hussain et al., 2019; Zhao et al., 2019). With this consideration, this paper aims to assess the effectiveness of the Wyoming CV TIMs in terms of speed harmonization through a driving simulator experiment. The remainder of this paper is organized as follows: Section 2 presents a review of the state-of-the-art of speed harmonization; Section 3 provides a brief description of the TIMs developed by the Wyoming CV Pilot; afterward, Section 4 details the development of CV driving simulator testbed; then, Section 5 documents the statistical analysis of simulation results; finally, conclusions of this study and discussions on future works are summarized in Section 6.

2. Literature review

In current practice, the majority of speed harmonization research has been focused on addressing traffic congestion problems. In general, these researches concluded that using dynamic traffic management strategies to harmonize speed could efficiently alleviate freeway congestion (Ma and Shladover, 2016). For instance, Waller et al. (2009) assessed the impact of variable speed limits and peak-period shoulder use on freeway traffic operations and safety and concluded that although these strategies did not increase the throughput of the freeway system, they were found efficient in homogenizing traffic flow and create safer driving conditions. Talebopour et al. (2013) employed microsimulation modeling to evaluate the impacts of speed harmonization on traffic flow characteristics and safety. Simulation results indicated that the implementation of a reactive speed limit control strategy significantly improved traffic flow characteristics under congested conditions. Ackaah et al. (2016) assessed the harmonization potential of VSL systems using field collect speed data. The coefficient of variation was used to quantify the standard deviation of speed, and consistency was assessed by observing the consecutive dynamic changes in the displayed speed limits. Based on a real-word case study, it was found that a VSL system can reduce the speed differential and the consistency in the displayed speed limits.

In comparison with congested urban freeways, the principle purpose of speed harmonization on low-volume rural freeways is to reduce the variances in speed, and thus reduce the likelihood of traffic collisions (Saha et al., 2015; Gaweesh and Ahmed, 2019). The safety benefits of speed harmonization are typically achieved by using VMS and/or VSL systems to change drivers' behavior under adverse weather conditions. Rama and Kulmala (2000) investigated the effects of VMSs that provide warnings about slippery road conditions and recommendations about the minimum headway time on driving speed and headways using field-collected traffic performance data. Results showed that slippery road condition warnings reduced the mean speed on slippery roads by 1 ± 2 km/h in addition to the decrease caused by the adverse road conditions, and the minimum headway sign decreased the proportion of headways shorter than 1.5 s for cars in car-following situations. Sui and Young (2014) developed a linear regression model to identify the impacts of VMS on driver speed behavior under different adverse weather conditions using field data. Modeling results indicated that VMS messages signs were effective at reducing drivers' speeds along rural freeway corridors from 5 mph to 20 mph. Carron (2015) examined the effectiveness of advisory VSL (prescriptive) and VMS (descriptive) messaging on reducing traffic speeds during inclement weather conditions. It was found that in addition to the speed reductions caused by adverse weather conditions, the presence of prescriptive and descriptive messages reduced the mean speeds by 9.5 mph and 2.5 mph, respectively. Zavareh et al. (2017) investigated the effects of displaying safety messages that contain risk level information on driving behavior based on traffic flow data collected from loop detectors. A comparison between the control group and experimental group revealed that the effects of high-risk messages were consistently related to safe adaptations; while the effects of messaging on rear-end conflicts were significant only in the fast lane at night time. Wu et al. (2018) assessed the effectiveness of real-time fog warning systems by quantifying drivers' speed adjustments under different roadway types, traffic conditions, and fog levels. The results suggested that VMS was beneficial to speed reduction before entering the fog area.

Recently, with the rapid evolution and deployment of CV technology, there have been numerous studies that assessed the impact of CV on harmonizing freeway speed and improving safety. Liu and Khattak (2016) and Khattak and Wail (2017) pointed out that when vehicles share their status (such as position and extreme driving motions) with other vehicles, driving actions could be better planned and hazards could be more timely identified, consequently create a safer driving environment. Yang and Rakha (2017) developed a feedback control speed harmonization algorithm to prevent the breakdown of a freeway bottleneck and thus reduce traffic congestion. Based on microsimulation, it was concluded that that the speed harmonization algorithm was effective in enhancing the bottleneck discharge rate (approximately 7% increases), and reduced the overall system delay by approximately 20 %. Ghiasi et al. (2017) proposed a Connected and Automated Vehicle (CAV) based trajectory-smoothing algorithm to harmonize traffic flow and improve mobility. Simulation analyses were performed to assess the algorithm performance, which showed that the

CAV-based speed harmonization algorithm led to smoother trajectories for both CAVs and regular vehicles that following CAVs. Similarly, Rahman et al. (2018) employed microsimulation to assess the effectiveness of CV technologies in adverse visibility conditions in terms of reducing the standard deviations of speed and headway. Simulation results showed that CV technologies significantly improved traffic operation and safety in fog conditions, particularly when CV market penetration rates were higher than 30 %. Tajalli and Hajbabaie (2018) developed a CV-based algorithm for dynamic speed harmonization in urban street networks to improve traffic operations and concluded that harmonizing the speed of vehicles in different links could regulate the movement of vehicles and thus lead to a smoother traffic flow, which eventually reduced the travel time and increase the average travel speed. Learn et al. (2018) developed a CAV-based speed harmonization algorithm, which dynamically adjusted vehicle speed recommendations to reduce speed differentials. Through field experiments, it was concluded that CAV-based speed harmonization algorithm has the potential to regulate traffic upstream of freeways bottleneck and reduce the oscillatory behavior of traffic. Park and Oh (2019) proposed a vehicle speed harmonization strategy aimed at minimizing inter-vehicle crash risk in CAV environments. Their vehicle speed control strategy consists of a risk assessment module, a risk map construction module, and a speed control module, which allows a CAV to adjust its speed based on the speeds of surrounding vehicles; eventually, reach the target speed determined by the risk map to minimize crash risk.

Nevertheless, since in current practice CV technology is still under testing or in early deployment stages, which might limit the availability of real-world traffic performance data in a CV environment. As a consequence, the majority of previous studies employed probe vehicle or microsimulation methods to assess the impact of CVs on speed harmonization. In comparison, using a driving simulator to assess the performance of CV technology has the advantages of lower costs (than probe vehicle experiment) and higher accuracy and reliability (than microsimulation modeling). Therefore, it has been considered as an effective tool for studying the impact of weather or new technologies on driver behavior (Kolisetty et al., 2006; Bella, 2008). Lee and Abdel-Aty (2008) employed a driving simulator to investigate the effect of VMS warning messages and VMS on driver speed behavior. It was found that when warning messages and VSLs were displayed, participants generally drove at a uniform speed and their variation in speed was reduced, which indicated that VMS warning messages and VSLs have the potential to reduce crash risk and improve efficiency on freeways. Gregoriades and Sutcliffe (2018) designed a driving simulator testbed to evaluate the effectiveness of various in-vehicle situation awareness systems and concluded that in-vehicle situation awareness systems enhanced drivers' awareness of risk situations and improve traffic performance in terms of headway and accident risk. Ali et al. (2018) pointed out that in a foreseeable future, CAVs will co-exist with human-driven vehicles, thus the evaluation of CAVs needs to take into consideration of the role of human factors, such as drivers understanding of traffic flow dynamics and effective operation in a CV or CAV environment. With this concern, Sharma et al. (2018) developed a series of driving simulator experiments to reveal the impacts of CAVs on driver performance. It was found that drivers in the CV environment posed a conservative driving behavior (e.g., maintain a longer waiting time and a larger spacing, select relatively larger gap sizes, increased lane-change duration, etc.) compared to the baseline condition. Previous research made by Yang et al. (2019) assessed the impact of Wyoming's CV-based VSL application on truck drivers' behavior under adverse weather conditions through driving simulator experiments. Results showed that CV-VSL technology led to lower average speeds and speed variances compared with baseline scenarios, indicating that CV-VSL warnings have the potential to reduce the risk of crashes under adverse weather conditions. Chang et al. (2019) also employed a driving simulator to evaluate the effectiveness of in-vehicle fog warning systems on driving performance and traffic safety in heavy fog conditions. Through multivariate analysis of variance, it was concluded that the fog warning system was beneficial to speed reduction before entering a fog area.

In summary, previous studies revealed that the safety benefits of speed harmonization were mostly stemmed from reductions in speed variance. While there is a decent amount of studies that looked into the effectiveness of VMS or VSL, there is not enough information about the impact of CV TIM on driver behavior, particularly, on freeway corridors without VMS or VSL systems. Also, the majority of existing speed harmonization research mostly focused on addressing freeway congestion in urban areas; there are limited studies on rural mountainous freeway particularly under adverse weather conditions.

3. Wyoming connected vehicle traveler information messages

Considering the unique traffic, challenging road geometric, and harsh weather conditions on I-80 in Wyoming, the WYDOT CV Pilot developed five on-board CV applications that will provide key TIMs to the drivers of equipped vehicles (Gopalakrishna et al., 2016a,b): Forward Collision Warning (FCW), Distress Notification (DN), Situational Awareness (SA), Work Zone Warnings (WZW), and Spot Weather Impact Warning (SWIW). These on-board CV applications aim at providing CV drivers with improved on-road messaging and advisory speed limits on the corridor, especially when adverse weather and work zones are present. A summary of each CV application, including its communication technology or technologies, the safety messages delivered by this application and expected safety benefits, are presented in Table 1.

Table 1
Overview of Wyoming CV applications and Expected Benefits (Adapted from Gopalakrishna et al., 2016a and Kitchener et al., 2018).

CV Application	Technology	Safety-Related Messages Delivered	Expected Safety Benefits
Forward Collision Warning (FCW)	V2V	An impending front-end collision with a CV ahead in the same traffic lane and direction of travel.	Improved safety through real-time warning of an impending rear-end collisions with a connected vehicle ahead.
Distress Notification (DN)	V2I & V2V	A distress notification will be sent to other CVs as well as Emergency Services or local Traffic Management Center to seek emergency help.	Improved safety through automated and/or manual incident involvement notification or dissemination of information to other road users.
Situational Awareness (SA)	I2V & V2I	Including road surface conditions such as icy or slick spot road surface; variable speed limits for existing road and weather conditions; road closure as well as the nearest parking or rest areas.	Improved safety through (near) real-time wide area alerts of conditions at downstream roadway segments or planned route.
Work Zones Warning (WZW)	I2V	Work zone ahead, distance to work zone, lane closure, and speed limit.	Improved safety through (near) real-time notification of unsafe work zones at specific locations on downstream roadway segments.
Spot Weather Impact Warning (SWIW)	I2V & V2I	A spot weather condition such as rain, snow, fog, strong wind, or severe weather ahead.	Improved safety through (near) real-time notification of unsafe conditions at specific points on downstream roadway segments.

Fig. 1. Driving simulator at WyoSafeSim.

4. Driving simulator experiment

4.1. Apparatus

The driving simulator experiment employed a motion-based high-fidelity driving simulator located at the University of Wyoming Driving Simulator Lab (WyoSafeSim), as illustrated in Fig. 1. The simulator has an open architecture software with a complete source code of the simulation creator tool. The open architecture offers a flexible tool that allows the development of driving scenarios and build roadways that mimic the actual environments. The driving simulator consists of both a passenger vehicle and a freight truck open cockpit cabs. The driving simulator's passenger vehicle cab is a 2004 Ford Fusion, and the freight truck cab is a 2000 Sterling AT9500 18-wheeler semi-trailer. Each cab is mounted on three degrees of freedom D-Box motion platform,

Table 2
Summary of the CV TIMs in the Driving Simulator Experiments.

CV TIM #	CV TIM Location (m)*	Message(s) delivered
Experiment #1: Work zone with FCW in fog		
1	2900	Fog Area ahead
2	3400	65 mph VSL
3	3900	Work Zone 1 mile ahead
4	4350	Work Zone 0.5 mile ahead and prepare to deduce speed to 45 mph
5	4700	Right lane closed
6	5000	Work Zone and 45 mph speed limit
7	7450 (Approximately)**	Forward Collision Warning(s)
8	7950	Regular speed limit of 75 mph
Experiment #2: Slippery road surface and DN due to snowy weather		
1	1850	Snowy weather
2	2600	Snowy weather with 65 mph VSL
3	3200	Icy surface with 55 mph VSL
4	3600	DN with 55 mph VSL
Experiment #3: Road closure due to accident in severe weather		
1	3150	Snowy weather with 65 mph VSL
2	3500	Severe weather with 45 mph VSL
3	5800	Accident ahead and road closed
4	6200	Rest Area ahead

Note:
* Location of a CV warning means the distance downstream from the starting point; distances are rounded to the nearest 50-m.
** Location of a FCW is dynamic and dependent on the relative speed and headway between the ego vehicle and leading/ subject vehicle.

comprising 4 electro-mechanical linear actuators. The motion base provides two rotational and one translational degree of freedom (roll, pitch, and heave). The provided motion cues immerse the driver into a real driving experience with kinematic changes in velocity and acceleration. The CV Human-Machine Interface (HMI) was mounted on the

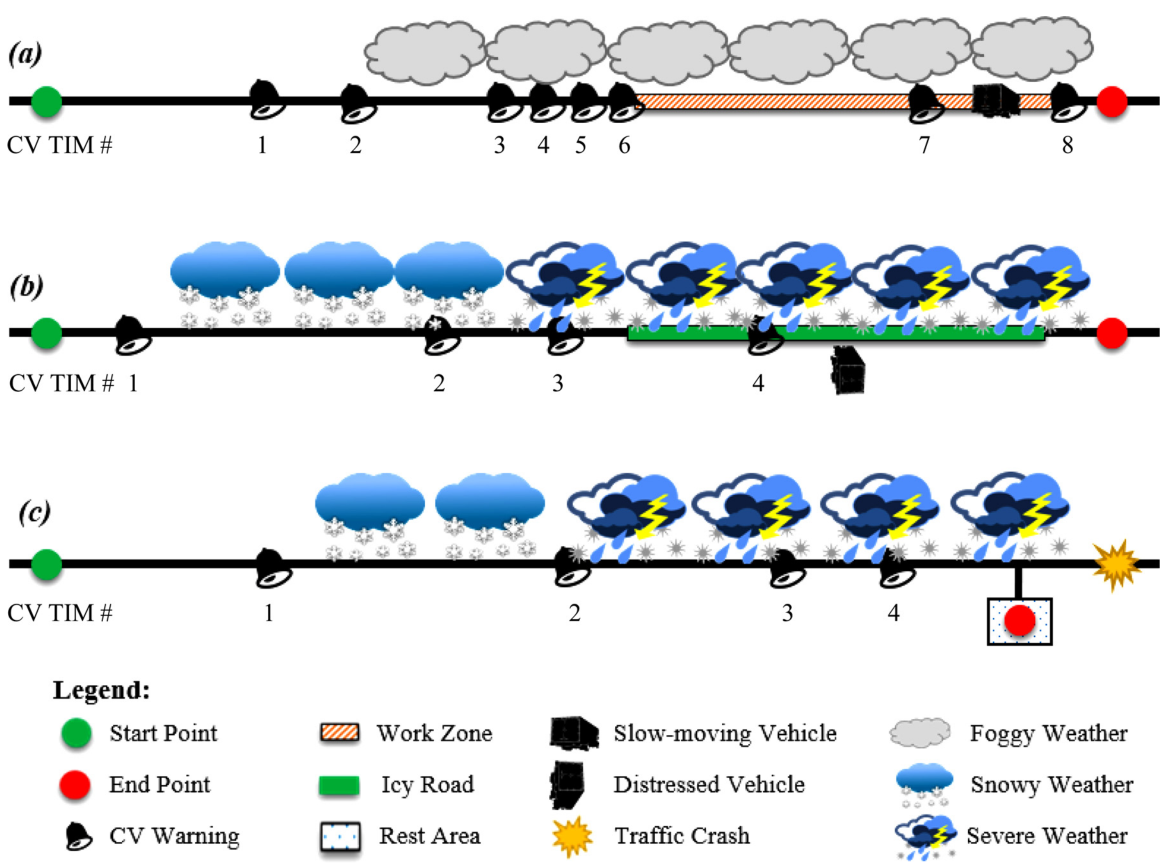


Fig. 2. Illustration of the driving simulator experiments (not to scale): (a) Experiment #1 - work zone with FCW in fog; (b) Experiment #2 - slippery road surface and DN due to snowy weather; (c) Experiment #3 - road closure due to accident in severe weather.

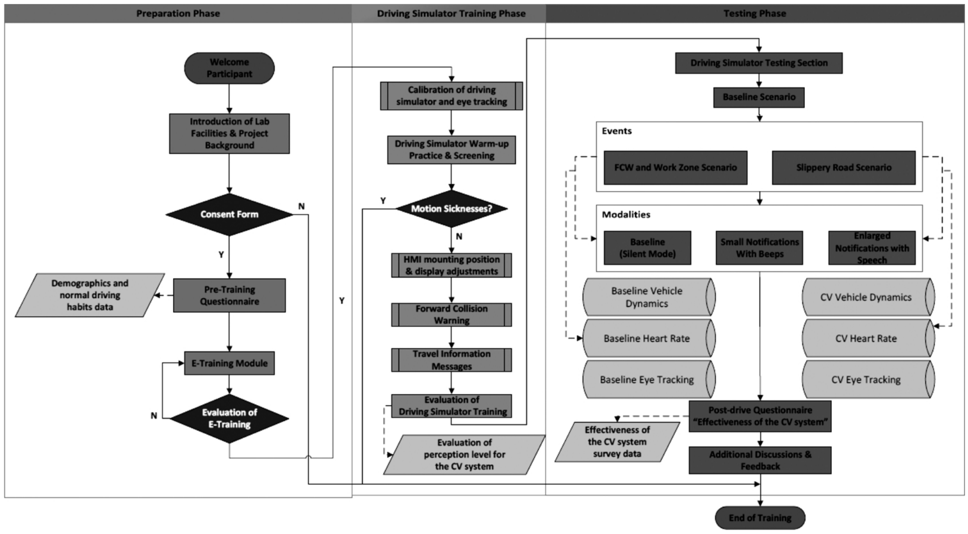
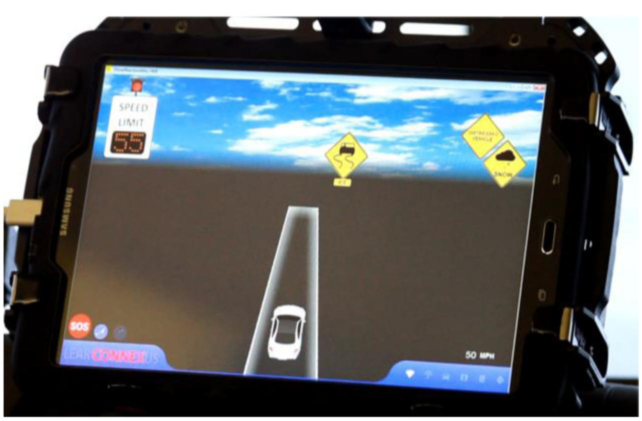


Fig. 3. Flow chart of the WYDOT CV pilot program driving simulator experiment.

(a)



(b)

Fig. 4. Illustration of driving simulator experiment at WyoSafeSim lab: (a) Simulator experiment scenario; (b) CV TIMs displayed on the HMI.

dashboard to provide participants with the received CV TIMs during the experiment. The simulator is equipped with a high definition SimObserver® system to capture and analyze digital video recordings for performance evaluation (i.e., raw data collected at a rate of 60 Hz). The system allows for capturing and playing back six synchronized views of a simulation experiment along with recorded driving data. According to the fidelity rating system provided by Wynne et al. (2019), this study utilized a high-fidelity simulator. The study showed that high-fidelity simulators have the potential of achieving valid results when speed and speed variation are the main measures pursued in the study.

4.2. Participants

Based on the literature review of the state-of-the-practice, it was found that the sample size for driving simulator studies is usually small (usually less than 25), which is mainly limited by the costs of the experiment (Wang and Wang, 2018; Gregoriades and Sutcliffe, 2018; Schleicher and Gelau, 2011; Kolisetty et al., 2006). In addition, this study is highly practice-focused, which acts in support of the WYDOT Connected Vehicle Pilot Deployment Program. Therefore, the selection of participants was mainly based on the expected users of the Wyoming CV Pilot. At this stage, the participants of the driving simulator experiment were professional snowplow truck and highway maintenance vehicle drivers from the WYDOT and commercial truck drivers from the trucking industry. These participants are not any regular drivers, but rather professional full-time truck drivers who will be piloting CV-equipped trucks under the umbrella of the Wyoming DOT CV Pilot. Their assessment and approval for the existing design of the CV TIMs and HMI design played a determining role in the success of the Pilot in accomplishing its goals. In a relevant context, inviting full-time professional truck drivers to participate in a driving simulator study is a tremendously costly and time-consuming process involving intensive preparations going behind the scenes to prepare the scenarios, coordinate with Pilot stakeholders, and conduct the study.

Knowing that the main goal of this study is to show whether the CV TIMs are effective or not, an initial sample size was identified using the sample size formula for binary output experiments. A confidence level of 90 % was determined to be used with a corresponding z-score of 1.65. However, it is hard to determine the population proportion in advance, it was estimated to be 10 %. This estimation was based on the known benefits of the CV highlighted in previous studies. Accordingly, it was expected to have a narrow standard deviation and the selected margin of error was 10 %. The sample size was calculated to be 22 participants for a population of 200 truck drivers that have the CV technology equipped in their trucks.

With all of these considerations, this study recruited 25 professional drivers with the majority holding Commercial Driver's License (CDL) to participate in the driving simulator experiment. Among the 25 participants, 20 participants drove the truck simulator and 5 drove the car simulator. Regarding the 5 participants for the passenger car, they were

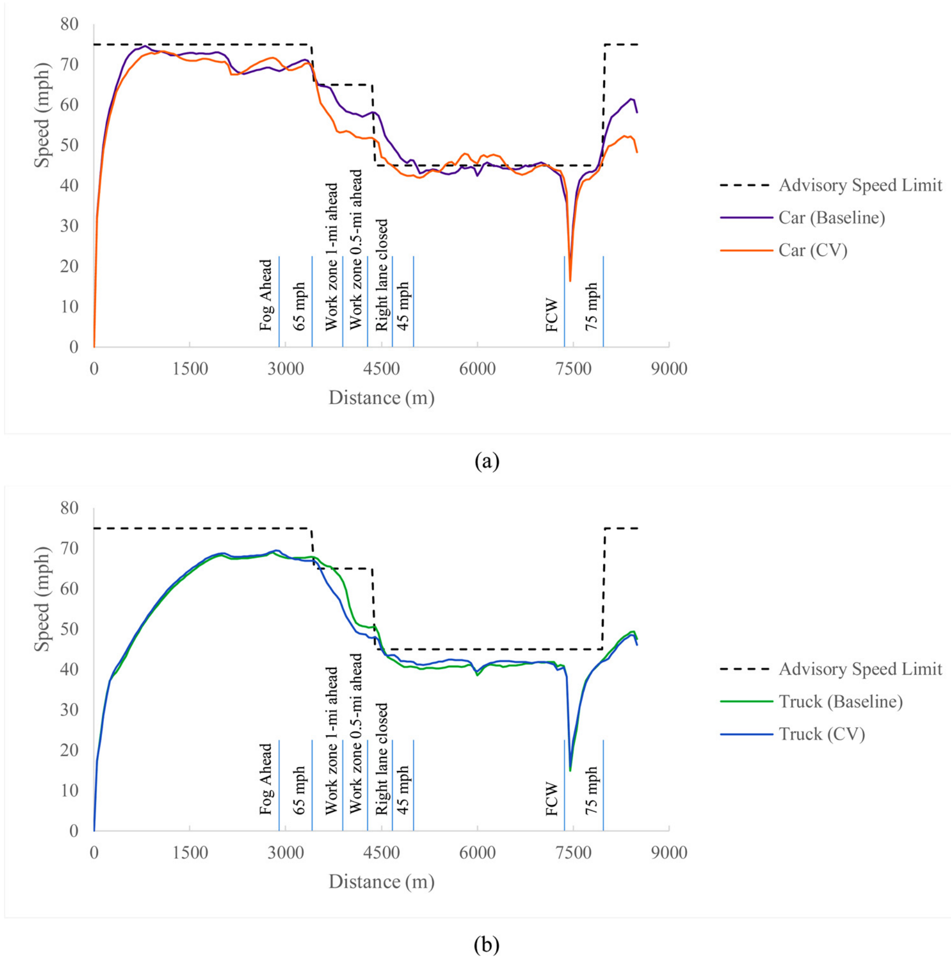


Fig. 5. Comparisons of simulated speed profiles for work zone driving simulator experiment under baseline and CV scenarios.

used as expert reviewers who helped in guiding the design and development of the Human Machine Interface, test and approve the training materials and simulation scenarios. Their results were presented to provide initial insights on the validity of the hypotheses.

The selection of participants considered a wide range of factors that might affect the acceptance and perception of CV technology, such as age, education level, driving experience, etc. Due to the fact that under the majority of conditions, these occupations are mostly dominated by male drivers; at this stage, this research only recruited male drivers from the WYDOT and trucking industry. Through the pre-drive survey questionnaire, it was summarized that their age ranged from 21 to 61 years (Mean = 42; S.D. = 10.3). Among the 25 participants, 14 graduated from high school, 9 have a college degree, and 2 have a postgraduate degree. All participants had a valid Commercial Driver's License (CDL) or class C driver's license with an average driving experience of 14.5 years (range from 0.5–36 years, S.D. = 11). Twenty-four of the participants reported they never had any ophthalmic surgery (1 participant had laser vision correction in 2006). All the participants were familiar with the driving environment on I-80 in Wyoming. During the driving simulator experiment, all the participants were in good health condition without vision, hearing, and emotional issues. The statistical verification of the sample size using t-distribution and a 95 % confidence level considering driving experience as the principal factor indicated a +/- 2.2 margin of error and a confidence interval of 10,20.

4.3. Development of driving simulator experiment scenarios

The driving simulator testbed was designed as a two-way four-lane freeway segment with a 75 mph speed limit to represent the basic operating conditions of I-80 in Wyoming. Three simulation scenarios were designed to simulate different real-world traffic and weather conditions on I-80-like freeway: (1) work zone with FCW in fog, (2) slippery road surface due to snowy weather, and (3) road closure due to accident in severe weather, respectively. The three driving simulator experiment scenarios were designed to reproduce the common traffic operation and weather conditions on the deployment corridor. To control for the potential impact of the ambient traffic on participants' driving behavior, the actual traffic volume and the average and standard deviation of speed of the ambient traffic, which were extracted from the roadside speed sensors installed on freeway I-80, were coded to the driving simulator scenarios to match the speed distributions similar to the Wyoming I-80 in alike adverse weather conditions. It is necessary to point out that this research used a fixed traffic volume to simulate the ambient traffic matching the traffic encountered on I-80 at the same weather conditions; while in specific locations (such as a work zone), traffic volumes were adjusted using dynamic sensors, which control traffic density. The selected traffic density is assigned within a specific circular region around the subject vehicle to simulate realistic surrounding ambient traffic.

The work zone driving simulator experiment aimed to test the Wyoming CV system's WZW and FCW applications. These CV applications are expected to help in avoiding potential collisions at a freeway work zone due to limited visibility caused by fog. The duration of this experiment scenario is approximately 7 min. The slippery road surface experiment aimed to test the Wyoming CV system's SWIW and DN applications; functions of these CV applications were to warn the participants to reduce speed before entering an icy road segment thus

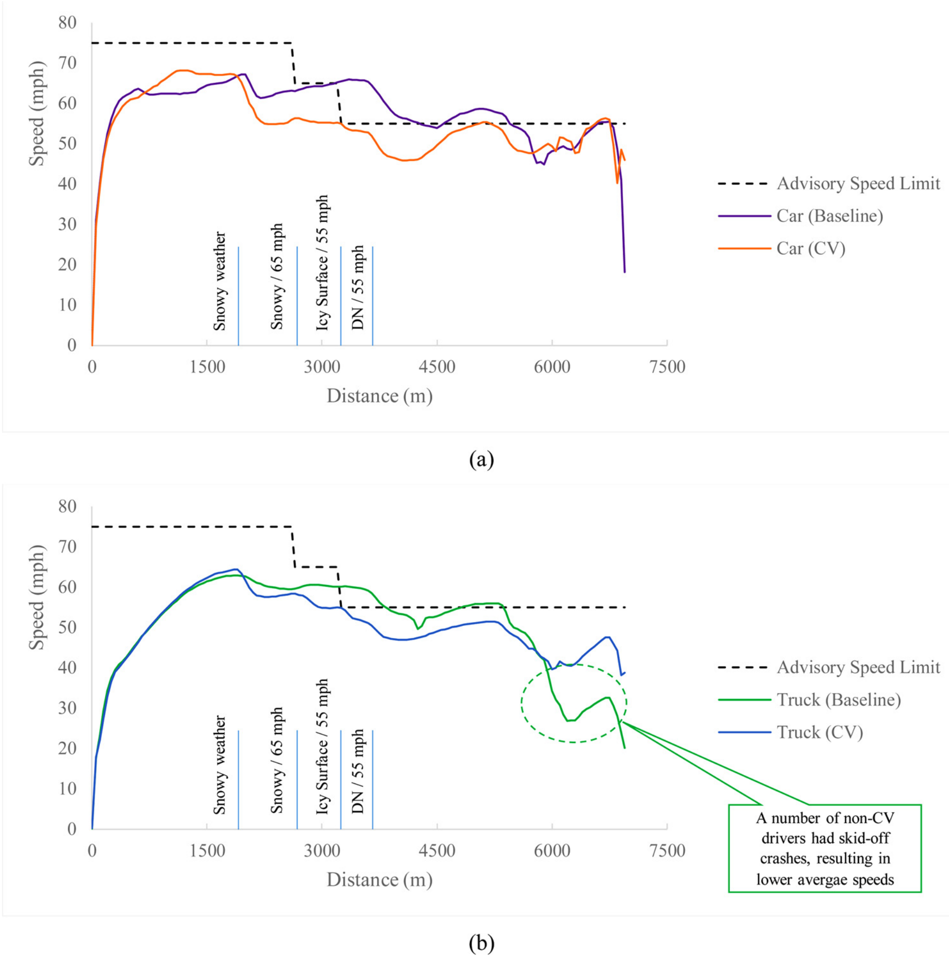


Fig. 6. Comparisons of simulated speed profiles for slippery road surface driving simulator experiment under baseline and CV scenarios.

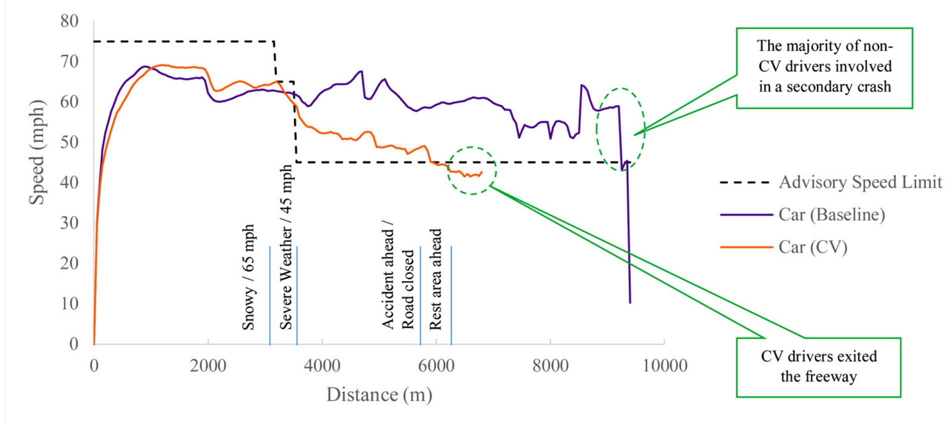
avoiding skidding off the travel lane or being involved in a secondary crash. The duration of this experiment scenario is approximately 5 min. The road closure experiment scenario aimed to test Wyoming CV system's SWIW and SA applications, which provided participants with real-time road closure notification due to an incident and provided information about the nearest rest area to help participants avoid being jammed on the closed freeway or involve in a secondary crash. Duration of this experiment scenario is approximately 9 min. The full training program and experiment design could be found in Ahmed et al. (2019).

The content and location of each CV TIM in the driving simulator experiments were determined based on the WYDOT CV Pilot Concept of Operation (Gopalakrishna et al., 2016a,b), typical work zone layout recommended by WYDOT (WYDOT, 2011), the Federal Highway Administration (FHWA) "Manual on Uniform Traffic Control Devices for Streets and Highways" (MUTCD) (FHWA, 2009), as well as the research team's real-world driving experience on Wyoming I-80. The speed limits were also determined based on the typical posted VSL on Wyoming I-80 under similar weather events. It is worth noting that adequate perception and reaction time was provided to heavy truck drivers, so they could adjust their speeds, exit the freeway, and/ or change lanes in a timely fashion. The location and timing of FCW were based on the SAE standards and TTC for light vehicles and heavy trucks. For Baseline scenarios, participants could only see the roadside signs; for CV scenarios, participants could see both the in-vehicle CV TIMs and the roadside signs. It is worth mentioning that in adverse weather conditions such as fog, participants were able to see and hear the CV TIMs before they could discern the information from physical roadway signs due to limited visibility. Fig. 2 illustrates the driving simulator experiment scenarios with the location of each CV TIM for each experiment; detailed location of each CV TIM and the message(s) delivered by the CV TIM during are listed in Table 2.

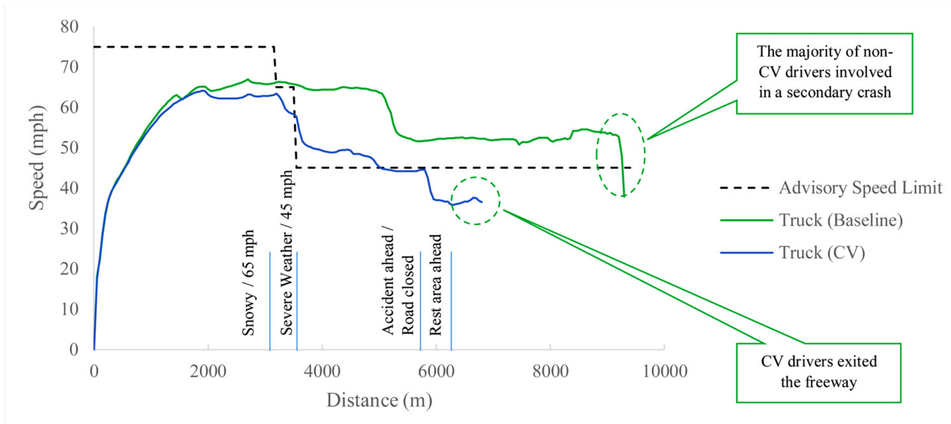
In an attempt to minimize potential distractions introduced by the HMI, the setup of HMI and the TIMs displayed on HMI were designed based on the FHWA's guidelines of using standard messages for in-vehicle safety systems (Richard et al., 2015). Through an expert review and the research project panel recommendations, the HMI was mounted on the central dashboard of the simulator vehicle (Gopalakrishna et al., 2016a,b; Raddaoui and Ahmed, 2019; Raddaoui* and Ahmed, 2020). The developed CV TIMs were further categorized into four priority levels to assist drivers better recognizing the urgency of a received warning: FCW, Speed Limit (including VSL), Critical Warnings, and Advisory Warnings (Ahmed et al., 2019). Critical Warnings were defined as situations that would significantly affect a driver's operation of a vehicle (such as a sudden reduction in visibility, work zone, etc.). Advisory Warnings aimed to provide advisory information to draw drivers' awareness while driving. When a CV received multiple TIMs from the roadside units (RSUs) or other CVs, TIMs that have a higher priority was displayed on the left side of the HMI to allow drivers more easily read the TIM(s).

4.4. Experiment procedure

The driving simulator experiment was designed as a pre-post-test study with all the participants required to drive each simulation scenario with two test runs; the baseline scenario (i.e., no CV TIMs) and the CV scenario. Prior to the experiment, a proposal that detailed potential risks to participants and procedures of protecting the privacy and confidentiality of the participants was approved by the University



(a)



(b)

Fig. 7. Comparisons of simulated speed profiles for road closure driving simulator experiment under baseline and CV scenarios.

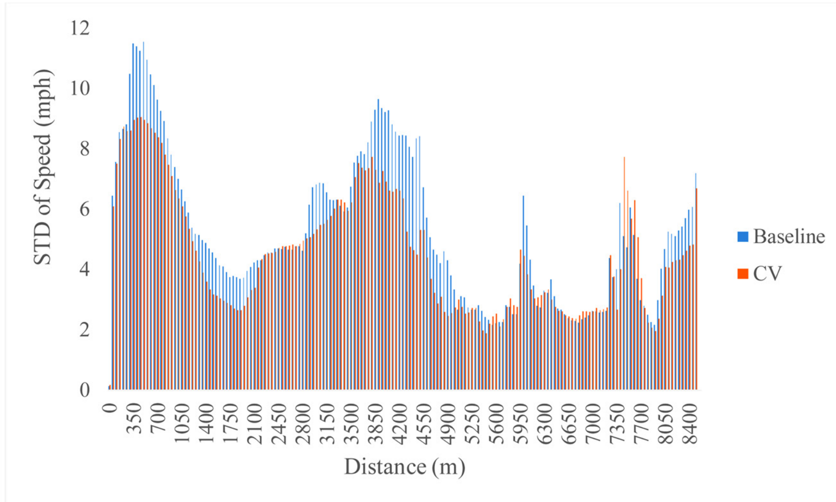
of Wyoming Institutional Review Board (IRB). In addition, participants were requested to read and sign a consent form, which had the similar content as the proposal approved by IRB. During the experiment, participants were provided a 10-min warm-up driving practice, which aimed to let participants get familiar with the operation of the driving simulator. This warm-up practice also aimed at screening if a participant gets motion sick due to driving the simulator. Participants could quit the experiment anytime during the experiment if they start to get motion sickness, feel uncomfortable, or simply do not wish to continue. Participants were also provided with trainings on both the basic concept of the Wyoming CV system and a hands-on operation of the driving simulator in a CV environment. In addition, participants were instructed to follow their normal driving habits during the entire experiment. Fig. 3 shows a detailed procedure for the different steps followed to conduct the driving simulator experiment.

During the experiment, each participant drove each scenario two times; one with the HMI turned-on and the other one with the HMI turned-off. For each participant, the sequence of these six scenarios was unordered and randomly assigned to eliminate the potential impact of any learning effect on the experiment results. Moreover, the surroundings such as terrain, vegetation, etc., within the scenarios were varied between the base condition and the CV scenarios. Fig. 4 illustrates the driving simulator experiment at the WyoSafeSim lab.

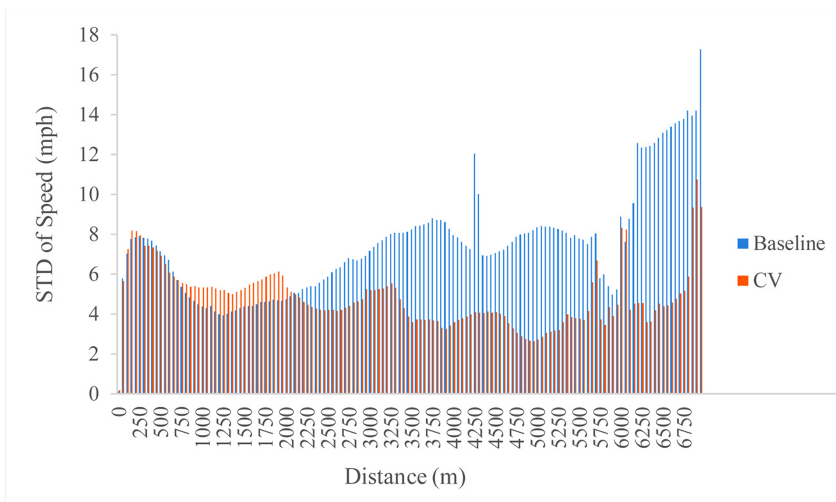
5. Simulation results

The simulated vehicle kinematics and driver behavior data were collected throughout the driving simulator experiment using the SimObserver® system. To reveal the impact of CV TIMs on drivers' speed adaptation behavior, this study extracted participants' instantaneous speeds at various locations to plot the speed profiles, one time under baseline (i.e., no CV TIMs) and another time with the Wyoming CV scenarios, as illustrated in Figs. 5–7. The speed data presented in this paper were the average instantaneous speed of all the participants every 50 m for each testing scenario. The speed data interception in units of 50 m was determined based on a trade-off between the data resolution for plotting the speed profile and costs for extracting these instantaneous speeds. Since the typical perception time of a regular driver is approximately 1.5 s (Dozza, 2013; Wang et al., 2016; AASHTO, 2018), thus a distance of 50 m, which approximately equals to the distance traveled on freeway during the perception time, was employed to investigate a driver's reaction to CV TIMs (Lee and Abdel-Aty, 2008; Yang et al., 2019). Since all the participants were provided sufficient warm-up practice to get familiar with the operation of the driving simulator and training on the concept as well as appropriate reactions to the Wyoming CV TIMs before participating in the driving simulator experiment, this research assumed that the speed changes were caused by the CV TIMs.

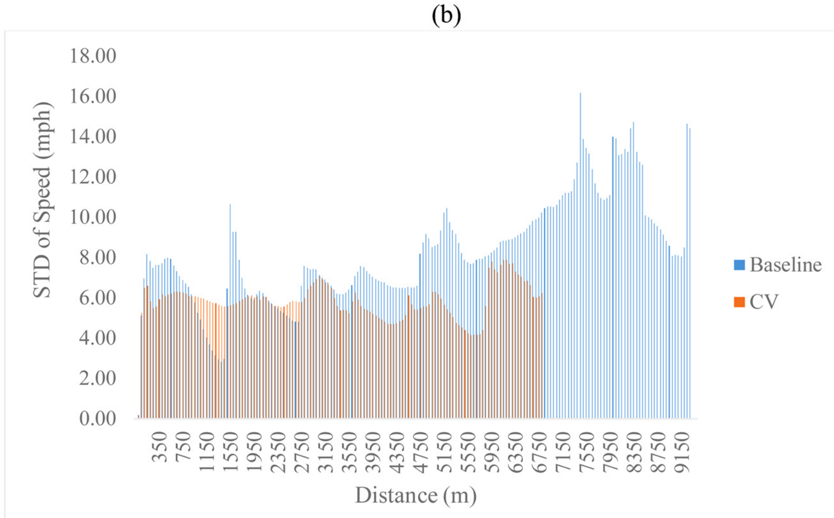
Based on the driving simulator experiment results, it was found that for all the three experiments, generally speaking participants' speed profiles under CV scenarios were lower than their counterparts under baseline scenarios. Under the majority of conditions, both passenger car and truck participants' speed profiles were below the advisory speed limits displayed on the CV HMI, indicating that participants typically complied with the CV TIMs, particularly the advisory speed limits. It is worth to mention that during the driving simulator experiments, there were much more participants involved in crashes (i.e., skid-off accidents on the icy surface road segment, and secondary crashes on the



(a)



(b)



(c)

Fig. 8. Comparisons of the standard deviations of speeds under baseline and CV scenarios: (a) Experiment #1; (b) Experiment #2; (c) Experiment #3.

closed road) under baseline scenarios than under CV scenarios, which were mainly caused by the inappropriate selection of speeds for the condition, as highlighted in Figs. 6 and 7.

In addition to the graphical comparisons of the speed profiles, this research also presents a descriptive analysis of standard deviation of speeds for each experiment under baseline and CV scenarios, as

Table 3
Comparisons of Participants' Mean Speeds under Baseline and CV Scenarios at Various Locations.

Driving Simulator Experiment	Speed Data Observation Location*(m)	Speed Limit (mph)	Baseline Scenario		CV Scenario		% Change	*t*-Value	*p*-Value	Sig.**
			Speed (mph)	S.D.	Speed (mph)	S.D.				
Work zone with FCW in fog	2900	75	68.2	6.2	69.6	5.1	2.1%	−0.8719	0.3878	No
	3100	75	67.9	6.9	67.7	5.5	−0.3%	0.1133	0.9103	No
	3400	65	68.2	5.9	67.5	6.2	−1.0%	0.4089	0.6844	No
	3600	65	65.7	7.8	62.4	7.5	−5.0%	1.5248	0.1339	No
	3900	65	61.3	9.6	54.6	6.9	−10.9%	2.8336	0.0069	Yes
	4100	65	52.9	8.8	49.9	6.6	−5.7%	1.3636	0.1795	No
	4350	45	51.7	8.1	48.4	4.7	−6.4%	1.7619	0.0859	No
	4550	45	45.5	6.7	44.1	5.3	−3.1%	0.8194	0.4167	No
	4700	45	43.3	4.7	43.7	3.2	0.9%	−0.3517	0.7267	No
	4900	45	41.5	4.3	42.1	2.5	1.5%	−0.6031	0.5499	No
	5000	45	41.5	3.3	42.0	2.7	1.2%	−0.5863	0.5605	No
	5200	45	40.9	2.7	41.5	2.6	1.5%	−0.8003	0.4274	No
	7450	45	15.5	5.1	16.1	7.7	3.9%	−0.3248	0.7469	No
	7650	45	36.0	3.7	35.4	5.1	−1.7%	0.4761	0.6363	No
	7950	75	43.2	3.0	42.6	2.4	−1.4%	0.7808	0.4388	No
	8150	75	47.6	5.2	45.7	4.2	−4.0%	1.4212	0.1619	No
Slippery road surface and DN due to snowy weather	1850	75	63.6	4.7	64.8	6.0	1.89%	−0.7872	0.4352	No
	2050	75	63.1	4.9	59.9	5.1	−5.07%	2.2622	0.0282	Yes
	2600	65	60.9	6.3	58.0	4.2	−4.76%	1.915	0.0623	No***
	2800	65	61.7	6.8	57.1	4.6	−7.46%	2.8015	0.0076	Yes
	3200	55	61.4	7.9	55.0	5.4	−10.42%	3.344	0.0017	Yes
	3400	55	61.5	8.1	52.4	4.3	−14.80%	4.9615	0.0000	Yes
	3600	55	60.8	8.5	51.4	3.7	−15.46%	5.0699	0.0000	Yes
	3800	55	57.1	8.7	47.7	3.7	−16.46%	4.9713	0.0000	Yes
Road closure due to accident in severe weather	3150	65	65.5	6.9	63.4	6.8	−3.2%	1.0839	0.2838	No
	3350	65	65.5	6.2	60.0	5.6	−8.4%	3.2916	0.0019	Yes
	3500	45	65.1	6.3	58.6	5.4	−10.0%	3.9168	0.0003	Yes
	3700	45	63.9	7.3	51.5	5.9	−19.4%	6.6055	0.0000	Yes
	5800	45	52.9	7.9	45.3	4.4	−14.4%	4.202	0.0001	Yes
	6000	45	53.3	8.4	38.3	7.4	−28.1%	6.6996	0.0000	Yes
	6200	45	53.5	8.8	37.8	7.9	−29.4%	6.6380	0.0000	Yes
	6400	45	53.7	9.1	37.3	7.2	−30.5%	7.0666	0.0000	Yes

Note:
* Speed data observation location means distance from the starting point.
** Two sample *t*-test at 0.05 significance level.
*** significant at 0.1 significance level.

Table 4
Analysis of Variance for the Standard Deviations of Simulated Speeds.

Driving Simulator Experiment	Scenario	# of Observations*	Mean	Std. Dev.	Degree of Freedom		*F*-Stat.	*p*-Value	Sig.**
					Between Group	Within Group			
Work zone with FCW in fog	Baseline	171	5.2844	2.4511	1	340	8.4374	0.0039	Yes
	CV	171	4.5818	1.9992					
Slippery road surface and DN due to snowy weather	Baseline	140	7.5009	2.7213	1	278	103.8736	0.0000	Yes
	CV	140	4.8292	1.4883					
Road closure due to accident in severe weather	Baseline	187	8.2842	2.6415	1	322	108.8870	0.0000	Yes
	CV	137	5.8211	0.9379					

Note:
* Number of spot speed data observation locations for each simulation scenario (one observation location per 50 m);
** One-way ANOVA at 0.05 significance level; Std. Dev. = Standard Deviation; F-Stat. = F-Statistic Test.

Table 5
Descriptive Statistics of TTC and MDRAC for the Work Zone Driving Simulator Experiment.

SMoS	Simulation Scenario	Minimum	Maximum	Mean	Standard Deviation
TTC (s)	Baseline	0.60	1.02	0.77	0.11
	CV	0.70	1.18	1.08	0.23
MDRAC (m/s^2)	Baseline	3.58	5.12	4.36	1.14
	CV	3.52	4.39	3.52	0.71

Note: TTC threshold is 1.5 s, MDRAC threshold is 3.4 m/s^2.

illustrated in Fig. 8. The standard deviation of speeds has been widely used as a SMoS; a larger standard deviation of speeds indicates a higher risk of crash. Results show that under the majority of conditions, the standard deviation of speeds under CV scenarios were lower compared to baseline scenarios, particularly under winter snowy or severe weather conditions (i.e., Experiments 2 and 3).

To figure out the effects of CV TIMs on speed harmonization, the two-sample *t*-test was utilized to reveal the difference of speed profiles under baseline and CV scenarios, and the analysis of variance (ANOVA) test was employed to identify the variations of speed between the baseline and CV scenarios.

Adequate perception and reaction time (PRT) should be provided to

Table 6
Analysis of Variance for the Standard Deviations of TTC and MDRAC for the Work Zone Driving Simulator Experiment.

SMoS	Attribute	Sum of Squares	Degree of Freedom	Mean Squares	F-value	Sig.
TTC (s)	Between	0.9575	1	0.9575	29.68	< 0.0001
	Within	1.226	38	0.0323		
MDRAC (m/s^2)	Between	6.952	1	6.952	14.72	< 0.0001
	Within	18.897	40	0.472		

drivers to enable a safe response to a received CV TIM. From an analysis perspective, this indicates that it is necessary to determine a location to measure speed changes that can capture a participant's reaction to a CV TIM. Previous research had revealed that a 200 m distance was considered as sufficient to allow a driver to decelerate from the posted speed limit to a recommended VSL or accelerate from a recommended VSL to the posted speed limit (Lee and Abdel-Aty, 2008; Yang et al., 2019*)*. Therefore, this research selected the spot speed data at CV TIMs locations and 200 m downstream of each CV TIM location to analyze the effects of CV TIMs on participants' speed adaptation behavior. The percentage of speed changes (% Change), t-Values, p-Values, and significance for the speeds at each location between the two scenarios are listed in Table 3.

It was found that for the work zone experiment, there was no significant difference between the average speed under baseline and CV scenarios. The only significant difference occurred in the vicinity of the third CV TIM (i.e., 3900 m downstream of the starting point), which was within the fog area and warned participants a work zone will be presented one mile ahead. This indicates that participants generally drove more conservatively when driving in an active work zone, particularly, under low visibility conditions.

In comparison, significant differences were found for the slippery road surface experiment and the road closure experiment. These two experiments mainly aimed at testing the effects of CV TIMs under winter adverse weather conditions. The general trend is that the speeds under CV scenarios are significantly lower than the baseline scenarios, indicating that participants generally posed a more conservative driving behavior and better complied with the CV TIMs.

In terms of the variations of speed between baseline and CV scenarios, the ANOVA test results reveal that for all the three driving simulator experiments, the variation of speed under CV scenario was significantly lower than the baseline scenario (particularly for Experiments 2 and 3), as presented in Table 4. This indicates that CV TIMs affected participants' driving behavior and resulted in lower speeds (Experiments 2 and 3) and variances of speed (all the three experiments). These speed harmonization effects are recognized as potential safety benefits of CV TIMs in terms of reducing crash risks under adverse weather conditions. Since under adverse weather conditions, the visibility and road friction is usually lower than under normal weather condition; therefore, driving at a lower speed will allow drivers to have more reaction time to an unexpected event and avoid abrupt speed changes.

For the work zone driving simulator experiment (i.e., Experiment #2), a virtual proximity sensor was added to the subject vehicle to simulate Wyoming CV Pilot's FCW application. Therefore, this research employed Time-to-Collision (TTC) and Modified Deceleration Rate to Avoid a Crash (MDRAC) as two additional SMoSs to assess the crash risks experienced in the work zone driving simulator experiment under both Baseline and CV scenarios.

TTC is defined mathematically as follows:

$$TTC = \begin{cases} \dfrac{D_{1-2}}{V_2 - V_1}, & if\ V_2 > V_1 \\ \infty, & Otherwise \end{cases} \tag{1}$$

Where D_{1-2} represents the distance gap between the risk to crash vehicle (leading) and the following vehicle, V_1 and V_2 are the speeds of vehicles involved. TTC values of less than 1.5 s are recorded as risky situations.

MDRAC takes account the perception-reaction time (PRT) where a critical situation is depicted when the following vehicle just adapts its speed to that of the leading vehicle, which is expressed as follows (Wang and Stamatiadis, 2014; Kang et al., 2015):

$$MDRAC = \begin{cases} \dfrac{V_2 - V_1}{2(TTC - R)}, & if\ TTC > R \\ \infty, & Otherwise \end{cases} \tag{2}$$

Where V_1 and V_2 represent the speeds of the leading and following vehicles, respectively, R means the PRT, which is defaulted as 1.5 s. DRAC values greater than the threshold is considered as potentially risky driving situations.

The descriptive statistics of the two SMoSs for baseline and CV scenarios are presented in Table 5 below. In general, it was found that the baseline scenario has lower values of TTC and larger MDRAC values. The means TTC and MDRAC for the baseline scenario are 0.77 s and 4.36 m/s^2, respectively. In comparison, for the CV scenario, these values are 1.08 s and 3.52 m/s^2 for TTC and MDRAC, respectively.

The ANOVA test results of TTC and MDRAC for the work zone driving simulator experiment are presented in Table 6. It was concluded that TTC in the baseline scenario was significantly lower than the CV scenario, and MDRAC in the baseline scenario was significantly higher than the CV scenario. These results indicate that for this particular driving simulator experiment, crash risk for driving in a CV environment is lower than driving in the baseline scenario. The safety benefits are mainly because CV TIMs improved drivers' awareness of the driving environment, thus could more timely response to an imminently hazardous situation.

6. Concluding remarks

The primary purpose of the WYDOT CV Pilot is to improve traffic safety on the 402-mile I-80 rural mountainous freeway corridor in Wyoming, particularly under adverse weather conditions. Nevertheless, at an early deployment stage, the market penetration rate of CVs on this corridor is still very low, which limits the applicability of using empirical data for assessing the safety performance of the WYDOT CV Pilot. With this concern, this research developed a driving simulator testbed to quantify the safety effectiveness of the pilot's CV TIMs in terms of harmonizing the speeds on the corridor.

Simulation results indicate that the Wyoming CV TIMs affected driver behavior; based on two-sample *t*-test and Analysis of Variance for the Standard Deviations (ANOVA), it was found that speeds under CV scenarios were generally lower than baseline scenarios, particularly under winter snowy or severe weather conditions. The reductions in speed variations are more significant in comparison with reductions in average speeds. The analysis of variance results revealed that for all the three experiments (i.e., work zone with Forward Collision Warning in fog, slippery road surface and Distress Notification due to snowy weather, and road closure due to accident in severe weather, respectively), the variations of speed under CV scenarios were statistically significantly lower than baseline scenarios. Also, for the work zone driving simulator experiment, this research further compared the crash risks between the baseline and CV scenarios using TTC and MDRAC as additional surrogate measures of safety. It was found that the mean TTC under baseline scenario is approximately 40 % lower than the mean TTC under CV scenario, and the mean MDRAC under baseline scenario is approximately 19.3 % higher than the mean MDRAC under CV scenario, indicating that crash risk is lower in a CV environment than in the baseline scenario. In summary, these findings reveal that CV TIMs have the potential to improve drivers' situational awareness and make better speed adaptation when driving under adverse weather conditions, and thus eliminating or reducing speed variation that may cause traffic collisions. These findings are expected to provide the WYDOT useful insights into the effectiveness of CV TIMs, and thus could assist the WYDOT with developing more efficient transportation management strategies.

Nevertheless, it is necessary to point out that the speed profiles were developed from a driving simulator study, which may not exactly represent the real-world driving conditions. Particularly, since the speed profiles under CV scenarios were generated completely based on CV drivers, indicating that these speed profiles represent a 100 % CV penetration rate condition, which might not be possible in the near future. Therefore, this paper recommends future research to incorporate these changes of driving behavior in a CV environment into microsimulation models to simulate the interactions between vehicles. Based on which, apply TTC, and MDRAC for assessing the safety performance of CV TIMs under various traffic demand levels and CV penetration rates. In addition, the results of this study are based on a limited number of sample with specific sociodemographic (e.g., gender, occupation) and psychological characteristics (e.g., snowplow truck drivers tend to have a conservative driving behavior). This is mainly because at this stage, the primary users of the Wyoming CV system will be snowplow truck and highway maintenance vehicle drivers from WYDOT and commercial truck drivers from the trucking industry. In comparison with general drivers, these professional drivers usually can drive in a more professional manner, which allows for the research team to gain early insights into the effects of Wyoming CV TIMs on speed harmonization. Nevertheless, considering the increasing popularity of CV technology, future works need to recruit a larger number of participants that cover a wider range of demographic features to figure out the confounding variables that affect speed control behavior.

CRediT authorship contribution statement

Guangchuan Yang: Conceptualization, Formal analysis, Investigation, Writing - original draft. **Mohamed Ahmed:** Conceptualization, Project administration, Funding acquisition, Writing - review & editing. **Sherif Gaweesh:** Methodology, Investigation, Writing - review & editing. **Eric Adomah:** Data curation, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aap.2020.105707.

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