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An Integrated Microsimulation Approach for Safety Performance Assessment of the Wyoming Connected Vehicle Pilot Deployment Program

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ABSTRACT

The 402-mile of Interstate 80 in Wyoming was selected by the U.S. Department of Transportation to develop, test, and deploy a suite of Connected Vehicle (CV) applications (WYDOT CV Pilot). It is expected that after full deployment of CV technology, the pilot will improve safety and mobility under adverse weather conditions by creating new ways to communicate road and travel information to both drivers and fleet managers. In this regard, this research employed an integrated microsimulation modeling approach to assess the safety performance of the WYDOT CV Pilot. A 23-mile representative I-80 corridor was selected for developing the microsimulation models. Traffic flow and driving behavior data under winter snowy weather condition were collected to calibrate the baseline microsimulation model. A driving simulator experiment was conducted to quantitatively investigate the impacts of CV technology on driving behavior; accordingly, the driving behavior data under CV environment were employed to properly update the calibrated CV microsimulation models. The safety effectiveness of the WYDOT CV Pilot were assessed for various demand levels and CV penetration rates. It was concluded that WYDOT CV applications increased drivers' situation awareness under adverse weather conditions, and thus reduced the crash risk. The reductions in conflicts displayed a decreasing trend with the increase of CV penetration rates, but the reduction was not significant when CV penetration was lower than 10 percent. The maximum reduction in conflicts was 85 percent when all trucks were equipped with CV technology.

1. Introduction

The Interstate 80 (I-80) in Wyoming is a major freight corridor connecting the east and west in the U.S. Being affected by the Wyoming's adverse winter weather events such as low visibility and icy road surface from blizzard conditions, there have been remarkable traffic crash records along I-80 in Wyoming, which resulted in fatalities, extended closures, and significant economic loss (WYDOT, 2020). According to the U.S. Department of Transportation (USDOT), more than 1,600 crashes were recorded on I-80 from October 2015 to September 2016 (USDOT, 2017). Weather related crashes on I-80 during 2012 was around 475 crashes. Also, in 2016, truck related crashes were about 8% of total crashes in Wyoming (Gaweesh et al., 2019). To improve traffic safety of the 402-mile I-80 corridor in Wyoming, the USDOT selected the Wyoming Department of Transportation (WYDOT) to deploy a Connected Vehicle (CV) Pilot Program along the corridor (WYDOT CV Pilot) (USDOT, 2017). The WYDOT CV Pilot focuses on the needs of commercial vehicle operators on I-80 in Wyoming, and developed several CV applications that utilize vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) Dedicated Short-Range Communication (DSRC) technologies to support a flexible range of services from advisories including roadside alerts, parking notifications and dynamic travel guidance (Gopalakrishna et al., 2016). Systems and applications developed within the WYDOT CV Piot will enable CV drivers to have improved awareness of potential hazards and of situations they cannot see; consequently, improve traffic operation and safety on the corridor during periods of adverse weather and when work zones are present.

Though CV technology has the potential to develop proactive safety solutions in a timely manner, previous research also pointed out that to achieve such benefit, the market penetration rate of CV should be large enough (Papadoulis et al., 2019), to ensure that sufficient data will be collected. Nevertheless, at an early deployment stage, it has been a global problem that CVs only contribute to a small fraction of a transportation system. In this regard, the traditional safety performance evaluation methodologies are usually challenged by the relatively few

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numbers of CVs that can receive information from the infrastructure or other CVs (Kitchener et al., 2018). Mainly, statistical analysis performed utilizing historical data is the core of the traditional approaches. Moreover, since a traffic collision or conflict is a small-probability event in a real-world setting, traditional empirical data analysis approach requires a relatively long period to collect ample sample for data analysis. Enough data to evaluate the system performance in the after implementation period are not available, which hinders the use of traditional safety performance evaluation methodologies (Yang, 2012). In addition, penetration rates are considered among the key factors affecting the benefits obtained from the CV system as well as it affects its safety evaluation. In order to adopt the traditional methodologies in the evaluation process, a significant proportion of vehicles on the roadways should be CVs (Abdel-Aty et al., 2018; Rahman and Abdel-Aty, 2018; Papadoulis et al., 2019; Rahman et al., 2019; Theriot et al., 2017). At this stage, CV penetration rate on I-80 in Wyoming is still low, which also would delay the ability to use traditional evaluation processes (WYDOT, 2018). In addition, variability of weather events in Wyoming presents extra challenges to the analysis of Pre- and Post-system performance data. Ideally, the performance assessment should compare data during similar weather events, which is not always possible. With these concerns, alternative methodologies are required to investigate the safety effectiveness of this newly introduced technology.

Experiencing several factors that impede the immediate use of traditional performance evaluation approaches for WYDOT CV Pilot, this paper proposes using the microsimulation modeling approach to assess the performance of CV systems. Microsimulation modeling has been proven as a cost-efficient method in assessing both mobility and safety performances of CV systems (Smith and Razo, 2016; Gueriau et al., 2016). In comparison with the traditional approaches that require a large sample size of traffic performance data under CV environment, a well calibrated microsimulation model has the ability to quickly and accurately test various CV strategies and directly output the system performance with very low marginal cost. Another advantage of microsimulation approach is the ability to extrapolate various levels of CV technology penetration rates. Microsimulation modeling employs Surrogate Measures of Safety (SMoS) to assess the number, type, severity, and locations of simulated conflicts. Also, complex geometry and environmental conditions associated with roadway safety performance during hazardous driving conditions can be quantified (Hou et al., 2019).

Since a microsimulation model can control for confounding factors that may affect system performance, this provides a more credible environment for the comparison of system performance between Pre- and Post-deployment periods. More importantly, microsimulation modeling allows for conducting large number of simulations run to test system performance under various CV penetration rates as well as weather scenarios and demand levels. Nevertheless, integrating the variability of weather conditions in microscopic simulation has not been fully exploited. In current practice, there is still not enough knowledge regarding calibrating driver behavior accurately in various weather conditions (Khavas et al., 2017; Hammit et al., 2018; Hammit et al., 2019), particularly the impacts of CV on driver behavior under adverse weather conditions (Gueriau et al., 2016; Songchitruksa et al., 2016). Therefore, this paper proposes using the driver behavior data collected from a driving simulator experiment to calibrate microsimulation models under adverse weather in a CV environment; eventually, assess the safety performance of the WYDOT CV Pilot.

The remainder of this paper is organized as follows: Section 2 presents a review of state-of-the-art regarding using microsimulation modeling for performance evaluation of CV systems. Section 3 overviews the proposed microsimulation modeling framework. Section 4 summarizes the proposed integrated data collection approach. Section 5 documents the development and calibration of microsimulation models and safety performance assessment results. Finally, preliminary findings of this research and insights into future works are presented in Section 6.

2. Literature review

2.1. Microsimulation for CV safety performance assessment

In reality, the safety benefits of CV technology were mostly stemmed from the changes of driving behavior to real-time CV warnings (Talebpour et al., 2016). At present, being limited by the low number of CVs in a real-world setting, microsimulation methods have been commonly used to assess the impact of CV technology on traffic safety. The most used methods for safety performance assessment have been the Surrogate Measure of Safety (SMoS) based methods (Wang et al., 2018).

The Surrogate Safety Assessment Model (SSAM) were first introduced by Gettman and Head (2003); then, several studies were conducted to validate the simulation traffic conflicts and concluded that there was a reasonable goodness-of-fit between the simulated and the observed conflicts (Huang et al., 2013; Essa and Sayed, 2015, 2020). Also, a study by Zheng et al. (2019) found a high correlation between simulated conflicts and field conflicts. Their extreme value approach indicated that simulated conflicts have high potential to predict crashes if models are calibrated well. To date there has been several studies that adopted SSAM and SMoS-based methods for traffic safety assessment in a CV environment.

For SSAM-based study, Olia et al. (2013) quantified the potential safety benefits of deploying a CV system through microscopic traffic simulation modelling. PARAMICS was used to model CVs, construction zones, and incidents associated with work zones. Simulation results demonstrated that CV system improved network safety. The percentage of CVs within the network was the most significant factor to increase network safety. This was mainly because CV system improved drivers' awareness of the road conditions. Another reason was a portion of CV drivers detoured to alternative routes, which reduced the exposure to construction zones. Paikari et al. (2014) evaluated the safety and mobility benefits of two V2V and V2I CV applications on freeways: advisory speed and re-routing guidance. Their study tested fifteen scenarios differentiated by the CV percentage penetration (0%, 10%, 20%, 30%, and 40%), and demand loading (60%, 80%, and 100%). It was found that CV technology can enhance traffic safety on freeways, if the percentage of CVs is significant, i.e., 30–40%, and when it is accompanied by advisory speed limits transmitted via VMSs not only upstream but also downstream of the incident location. Fyfe and Sayed (2017) combined VISSIM and SSAM with the application of the Cumulative Travel Time (CTT) algorithm to evaluate the safety under CV environment. The study showed a 40% reduction of rear-end conflict frequency at a signalized intersection with the application of CV. Papadoulis et al. (2019) developed a decision-making CAV control algorithm in VISSIM and employed SSAM to evaluate the safety performance of the developed algorithm. Simulation results showed that CAVs brought in considerable safety benefits; the simulated traffic conflicts reduced up to 47% when CAV penetration rate was 25%, and reduction of conflicts reached up to 94% when CAV penetration rate was 100%. Similarly, Virdi et al. (2019) investigated the safety performance of CAVs at various types of intersections using SSAM. It was concluded that CAVs at low penetration rates resulted in an increase in conflicts at signalized intersections but a decrease at priority-controlled intersections; at high penetrations, CAVs indicated a global reduction in conflicts at all the intersection types.

2.2. Surrogate measures of safety

In terms of SMoS-based research, Genders and Raviza (2016) evaluated the potential safety benefits of deploying a CV system on a traffic network in the presence of a work zone. The modeled CV system in the study uses V2V communication to share information about work zone links and link travel times. Vehicles which receive work zone information will also modify their driving behavior by increasing awareness and decreasing aggressiveness. Improved time-to-collision was used as a SMoS to assess the safety of the network. Various market penetrations of CVs were utilized along with three different behavior models to account for the uncertainty in driver response to CV information. The results showed that network safety was strongly correlated with the behavioral model used; conservative models yielded conservative changes in network safety. The results also showed that market penetrations of CVs under 40% contributed to a safer traffic network, while market penetrations above 40% decreased network safety. The decrease in safety when rerouting more than 40% of traffic on a work zone could be explained by the fact that more traffic diverted to other alternate routes resulting in more exposure to higher traffic volumes and increased crash risks. Abdulsattar et al. (2018) presented an agent-based modeling and simulation framework to evaluate the safety performance impacts of CV technologies in work zone under various CV market penetration rates and traffic demand levels. Time-to-Collision (TTC) and Time Exposed Time-to-Collision (TET) were used as SMoS for safety evaluation, and concluded that the higher the traffic flow rate, the higher CV market penetration level is needed to show safety performance improvement at work zones. Rahman et al. (2018) employed standard deviations of speed and headway, as well as rear-end crash risk index as SMoSs in a microsimulation environment to assess the safety effectiveness of CV technologies. Simulation results indicated that CV significantly improved traffic safety in fog conditions as market penetration rates of CV increase. Another study made by Rahman et al. (2018) investigated the safety benefits of CVs on congested expressways with a large number of lane-changing and merging maneuvers via microsimulation modeling. Five SMoSs, including standard deviation of speed, time exposed time-to-collision, time integrated time-to-collision, time exposed rear-end crash risk index, and sideswipe crash risk were employed as indicators for safety evaluation. Simulation results showed that CVs significantly improved traffic safety compared to the non-CV scenario.

2.3. CV impacts on secondary crashes

In addition, one of the key purposes of CV technology is to eliminate the occurrence of secondary crashes. With this concern, Yang et al. (2017) investigated the impact of CV on mitigating secondary crash risk through a simulation-based modeling framework that enables V2V communication. A 4-mile highway section was modeled in PARAMICS; a modified time-to-collision was proposed as the SMoS to capture vehicular conflicts as a proxy for secondary crash risk upstream of a primary crash site. Simulation results showed that CVs can be a viable way to reduce the risk of secondary crashes, and the benefits increased with increasing market penetration rates of CVs. Nair et al. (2018) developed an enhanced microsimulation model to quantify the safety benefits of a CV application - Road Hazard Warning. Safety performance was measured by time integrated time-to-collision and number of secondary crashes. Eventually, a linear relationship was drawn between CV market penetration rate and safety improvement.

2.4. Summary of research gap

From the review of state-of-the-art, it was found that although there have been a handful of research that using microsimulation modeling for safety performance evaluation in various CV environments, there is still not sufficient efforts on using microsimulation modeling for performance evaluation of freeway CV systems, particularly rural low-volume mountainous freeways and under adverse weather conditions.

3. Overview of microsimulation modeling framework

The U.S. Federal Highway Administration (FHWA) defines Analysis, Modeling, and Simulation (AMS) as an evaluation process for assessing traffic operations along a corridor (FHWA, 2018a,b). Based on while, researchers could identify key transportation challenges, and explore potential management strategies to be used to improve the operational performance of the corridor. Typically, an AMS framework contains three components (Patire et al., 2016): 1) Analysis, which requires investigation of the traffic and environmental conditions about the corridor, 2) Modeling, which refers to developing and calibrating a model or models to capture the real-world traffic and environmental conditions, and 3) Simulation, which means using the developed model(s) to assess the performance of the corridor, and identify the operational issues as well as potential solutions to these issues. To date, FHWA has launched several AMS testbeds to support the evaluation and deployment of different ITS-based transportation programs such as Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) (Vasudevan and Wunderlich, 2013; Yelchuru and Kamalanathsharma, 2017), and Connected and Automated Vehicle (CAV) Applications (Patire et al., 2016; FHWA, 2017, FHWA, 2018a,b). In light of these guidelines, this paper proposed a microsimulation modeling-based AMS framework for assessing the safety performance of the WYDOT CV Pilot. An overview of the proposed AMS framework is illustrated in Fig. 1.

The proposed AMS framework employs the VISSIM simulation with the Surrogate Safety Assessment Model (SSAM) for safety performance evaluation, as it is known that microsimulation software cannot directly simulate traffic crashes. The SMoSs used for safety evaluation were

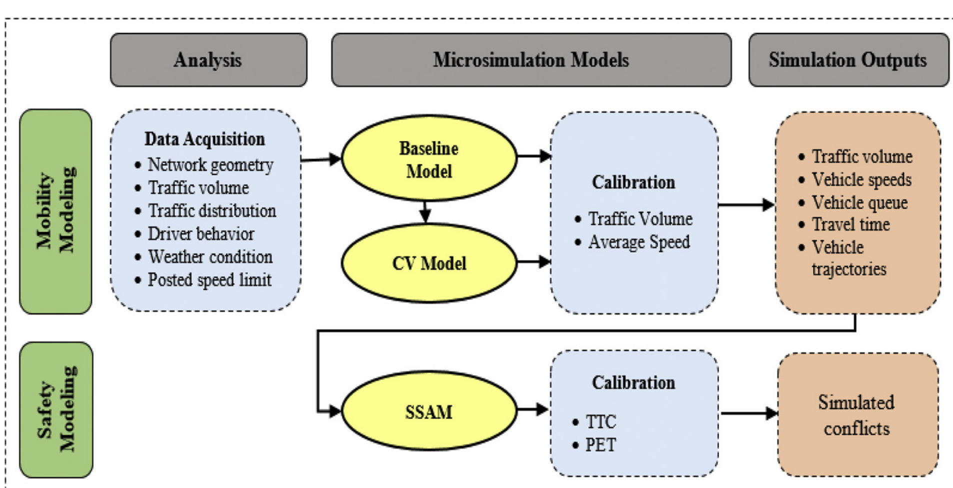

Fig. 1. Overview of the proposed microsimulation modeling framework.

based on traffic conflicts (i.e., crash opportunities determined by safety assessment parameters such as TTC and Post-Encroachment Time (PET)) generated by the VISSIM simulation models. High-resolution traffic flow data were collected from field (baseline scenario) and truck driving simulator experiment (CV scenario) and feed into the developed microsimulation models to more accurately capture the real-world traffic operation condition and driver behavior (Yang and Ahmed, 2020).

4. Data acquisition and processing

Being in the deployment and testing phase of the WYDOT CV Pilot, there is still no available traffic flow in a CV environment collected from the field for microsimulation model calibration. Therefore, this research proposed an integrated data acquisition methodology. For pre-deployment period, traffic flow and speed data were collected by the WYDOT's roadside Wavetronix sensors installed the corridor. For post-deployment period, the micro-level driver behavior data were obtained from a high-fidelity driving simulator at the University of Wyoming Driving Simulator Lab (WyoSafeSim). In current practice, a number of studies have demonstrated that the fidelity of driving simulator data could perfectly replicate the actual speed measurements (Godley et al., 2002; Bella, 2008; Branzi et al., 2017; Hussain et al., 2019), and could be used as an alternative model calibration approach for micro-simulation modeling of CAVs or adverse weather conditions (Zulkefli et al., 2017; Shao et al., 2019; Chen et al., 2019).

4.1. Development of driving simulator testbed

The CV driving simulator testbed was designed as a 5 mile (8 km) two-way four-lane freeway segment with 75 mph speed limit to represent the basic operating conditions of I-80 in Wyoming (Ahmed et al., 2019; Yang et al., 2019). A comprehensive experiment scenario was developed to simulate real-world traffic and weather conditions, and test the impact of CV warnings on driver behavior (Yang et al., 2019). As shown in Fig. 2, the driving simulator experiment scenario started with a clear weather condition with 75 mph posted speed limit; later, participants encountered snowy weather condition. After passing the first curve, the weather condition deteriorated to severe weather. Eventually, an icy road surface was generated prior to the second curve. The participants received CV warnings at the predetermined locations. Specifically, a Snow warning with the regular speed limit of 75 mph appeared on the CV Human-Machine Interface (HMI) at 1,850 mdownstream of the starting point. Then, at 2,600 meters downstream, an advisory speed limit of 65 mph was displayed on the HMI. Before entering the icy road segment (3,200 m downstream), an Icy Surface warning and a 55 mph advisory speed limit were displayed on the HMI to warn the driver to reduce speed while driving on the icy road section; later on, at 3,600 m downstream, a Distress Notification (DN) was displayed on the HMI to notify drivers that there has been an incident ahead on their driving direction. Each participant drove the driving simulator two times; one with the CV HMI turned-off (baseline scenario) and another time with the CV HMI turned-on (CV scenario). Sequence of each participant's scenarios (baseline or CV scenario) was randomly assigned to eliminate participant's learning effect on the accuracy of the experiment results.

The participants for the driving simulator experiment were professional snowplow truck drivers from the WYDOT; they are expected to drive connected trucks after the full deployment of CV system in Wyoming. A total of 18 snowplow truck drivers were recruited to participate in the driving simulator experiment; all the participants were male; their age ranged from 21 to 61 years (Mean = 41; S.D. = 11), and driving experience ranged from 0.5 to 35 years (Mean = 12.5; S.D. = 10.4). Among the 18 participants, 6 participants aged between 41 to 45; for age groups 21 to 25, 31 to 35, and 51 to 55, each group has 3 participants. For age groups 36 to 40, 46 to 50, and larger than 60, each group has 1 participant. In terms of years of driving experience, 10 participants have a driving experience of less than 10 years, 5 participants have a driving experience between 10 and 20 years, and 3 participants have a driving experience that is long than 25 years. Prior to the driving simulator experiment, each participant received training on the WYDOT CV Pilot and CV applications and was provided with a 10-minute warm-up driving practice, which aimed to allowing participants get familiar with the operation of the driving simulator. During the experiment, participants were instructed to follow their normal driving habits.

4.2. Data processing

4.2.1. Baseline scenario

As mentioned before, the baseline traffic performance data and weather data were collected and provided by the WYDOT (Kitchener et al., 2018). This research first identified one weekday under snowy weather condition based on the WYDOT's Road Weather Information System (RWIS) sensor data. Then, based on the available dataset, traffic performance data from two speed sensors were selected: Sensor #2146 and #2178. The key traffic performance data extracted were traffic volume counts and spot speed of each vehicle at each speed sensor. Afterwards, detailed traffic volume and composition, percentile speeds and speed-time profile at each sensor location were extracted, as shown in Table 1.

4.2.2. CV scenario

This section presented and analyzed participants' instantaneous speeds at various locations to reveal how drivers changed their speeds to the CV warnings displayed on HMI. The speed data presented in this

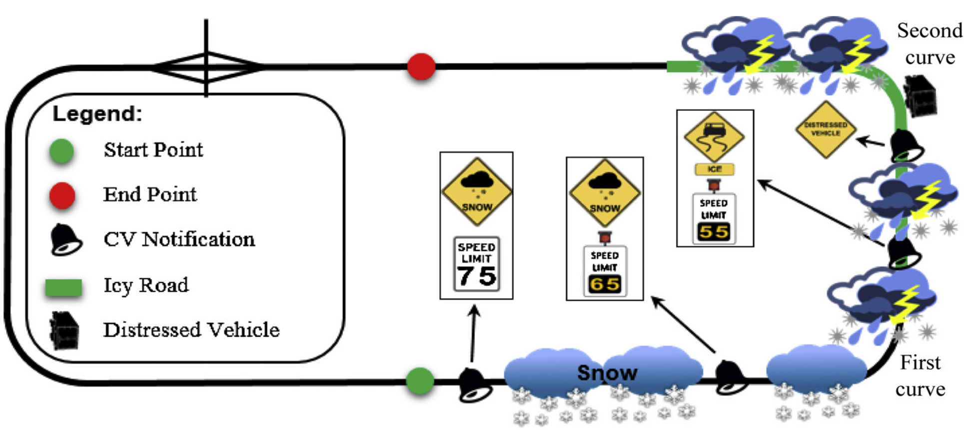

Fig. 2. Illustration of the driving simulator testbed scenario.

Table 1
Summary of traffic flow data under snow weather condition at two speed sensors.

Sensor Location	Speed (mph)	I-80 Eastbound		I-80 Westbound	
		Car	Truck	Car	Truck
Speed Sensor #2146 (Milepost 322.6)	Max	85.2	80.5	86.6	92
	5th %	78.3	77.3	78.6	71.7
	15th %	76.1	73.7	75.2	68
	25th %	73	71.2	71.9	65
	50th %	68	67	66	60
	75th %	62.4	59	60.9	54.4
	85th %	60.7	57.1	58.4	50.4
	95th %	58.3	49.1	50.3	44.1
	Min	53.1	40.4	41.6	19.3
	Avg.	67.9	65.1	65.9	59.3
	S.D.	6.72	8.45	8.45	8.67
	Traffic Volume (veh)	139	93	225	371
Speed Sensor #2178 (Milepost 329.88)	Max	94.4	85	89.2	89.3
	5th %	82.2	78.8	83.3	78.7
	15th %	78.6	75.7	79.5	72.8
	25th %	76.9	74	77	68.5
	50th %	73.2	68.4	70.8	62.1
	75th %	67.8	65.2	66.3	57.5
	85th %	66.3	63.8	63.7	54.3
	95th %	63.2	62.1	58	50.4
	Min	56.5	60.3	47.9	36.2
	Avg.	72.5	69.5	71.1	62.9
	S.D.	6.17	5.35	7.55	8.56
	Traffic Volume (veh)	202	194	137	398

paper were the average and percentile speeds of the 18 participants at location of each CV warning and 200 m upstream and downstream of the CV warning. Since all the participants were provided sufficient warm-up practice to adjust themselves to the operation of driving simulator, and were trained on the concept and function of the Wyoming CV warnings before they participated in the driving simulator experiment, it was assumed that the speed changes were caused by the CV warnings. Simulation results are listed in Table 2. In general, the average speeds in a CV environment are significantly lower than baseline condition at 0.05 significance level. The speed reductions range from 2.5% to 14.7% with an average of 10%. In addition, it was found that variations of speed under CV scenarios are significantly lower than the baseline scenario (F-Value = 12.671, p-Value = 0.002).

5. Microsimulation modeling

5.1. Development and calibration of VISSIM models

This research developed a VISSIM simulation model for a 23-mile segment of the Cheyenne-Laramie VSL corridor (mileposts 317–340) to determine the suitability of adopting a microscopic simulation approach for providing insights into the safety effectiveness of the WYDOT CV Pilot. The selected corridor represents the most challenging traffic situation along I-80 in Wyoming, such as high altitude, severe weather events, and steep vertical grades. The basic corridor network was uploaded from the standard map data in VISSIM; then, the roadway geometric data, including number of lanes, roadway segment lengths and grades, location of lane additions and drops, etc., have been manually coded in VISSIM Version 11, as shown in Fig. 3.

Since microsimulation models are typically used to analyze traffic volumes and performance rather than detailed physical movements of actual drivers and vehicles, the microsimulation models need to be carefully calibrated to capture the real-world driving behavior (Dong et al., 2015; Smith and Razo, 2016). For the baseline microsimulation model, this research adjusted the microsimulation model's default Wiedemann 99 car-following model and lane-changing parameters based on the traffic flow and speed data collected by the WYDOT's Wavetronix sensors and the SHRP2 Naturalistic Driving Study conducted by the University of Wyoming (Hammit et al., 2019). Two default vehicle types in VISSIM (Car and Truck) were used to define traffic composition. For each vehicle type, detailed vehicle classification and corresponding percentages were obtained from the WYDOT TMC traffic database. A single vehicle category shares the same vehicle performance attributes, which include vehicle lengths maximum speed, acceleration and deceleration capabilities, weight, power, and other mechanical features.

Simulation results were compared against field observed data to check the errors between simulation inputs and outputs. The two commonly used microsimulation model calibration and validation tests (Dong et al., 2015), Geoffrey E. Havers (GEH) statistic test and Mean Absolute Percentage Error (MAPE) statistic test, were employed to verify the errors between simulated and the observed traffic volume and speed profiles, respectively. Results showed that both the GEH test results and the MAPE test results for all the four sensor locations are within an acceptable range. Detailed comparisons between the simulated and field collected traffic volume and 2-min speed profiles are presented in Fig. 4 and Table 3.

In current practice, there are two methodologies for modeling CVs in VISSIM: an internally modeling methodology, which adapts the car following, lane change and vehicle speed parameters to capture the

Table 2
Comparisons of participants' average speeds under baseline and cv scenarios at various locations.

Location (m)	Advisory speed limit (mph)	Baseline scenario		CV scenario		% Change	Significance**
		Speed (mph)	S.D.	Speed (mph)	S.D.		
1650	75	61.8	4.9	63.2	6.1	2.3%	No
1850*	65	62.4	5.1	63.9	6.7	2.4%	No
2050	65	62	5.3	59.2	5.6	−4.5%	No
2400	65	59.9	6.0	57.5	4.6	−4.0%	Yes
2600*	65	59.6	6.8	58.1	4.5	−2.5%	Yes
2800	65	60.3	7.1	57.0	4.6	−5.5%	Yes
3000	65	60.2	7.7	54.5	5.6	−9.5%	Yes
3200*	55	59.7	8.4	54.5	6.0	−8.7%	Yes
3400	55	59.6	8.5	52.0	4.7	−12.8%	Yes
3600*	55	58.7	8.9	50.5	4.0	−14.0%	Yes
3800	55	55.1	9.2	47.0	3.7	−14.7%	Yes

Note: Location means distance from the starting point.
* The location when a CV warning was displayed on the HMI.
** Two-sample t-test, significance level = 0.05.

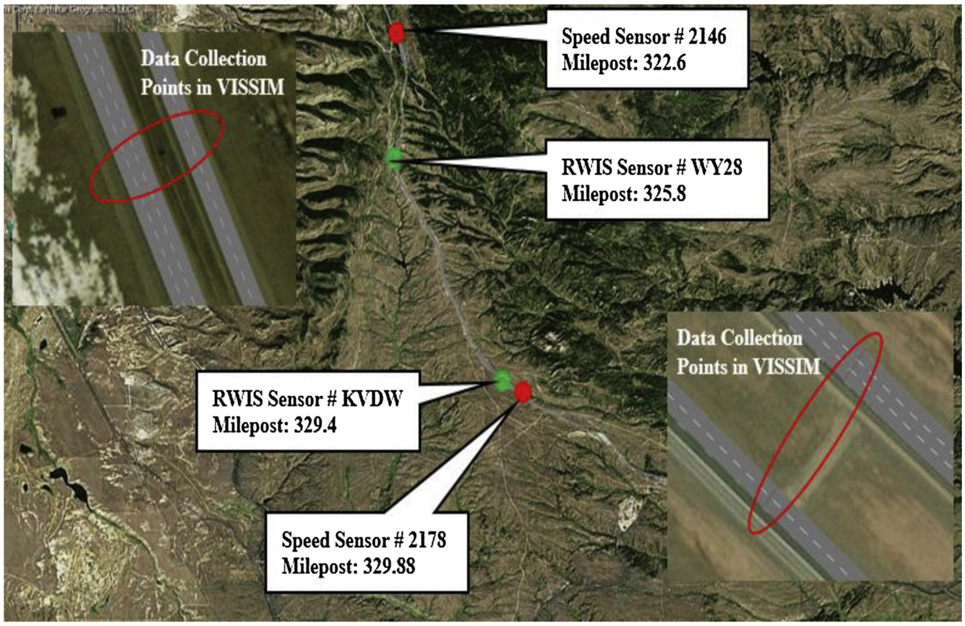

Fig. 3. Location of data collection points for VISSIM model calibration.

behavior of CV drivers; and an externally modeling methodology, which employ's one of VISSIM's interfaces to program CV control algorithms to replace the default driving behavior models (Cisco, 2017; Sukennik, 2018). Generally speaking, internally modeling is a quick and simple method to model some CV-related features within a given network, and is perfect for investigating the influence of different follow-up distances or acceleration oscillations on traffic flow at constant or varying CV penetration rates. In comparison, externally modeling requires extensive programming efforts to define the control logic of the CVs, which mainly aims to investigate complicated interactions between one or more CVs. For instance, VISSIM's Drivermodel.dll Interface could pass the current state of a CV and its surroundings to the Drivermodel.dll, which then computes the reaction of the vehicles from the user defined parameters (Cisco, 2017). In view of the fact that the I-80 in Wyoming is a low volume rural freeway corridor, and considering the primary purpose of the WYDOT CV Pilot is to improve drivers' awareness of hazard driving conditions and maintain a more conservative driving behavior, this research opted for the use of internally modeling approach to assess the performance of WYDOT CV Pilot.

For internally modeling of CV, since VISSIM has the capability of

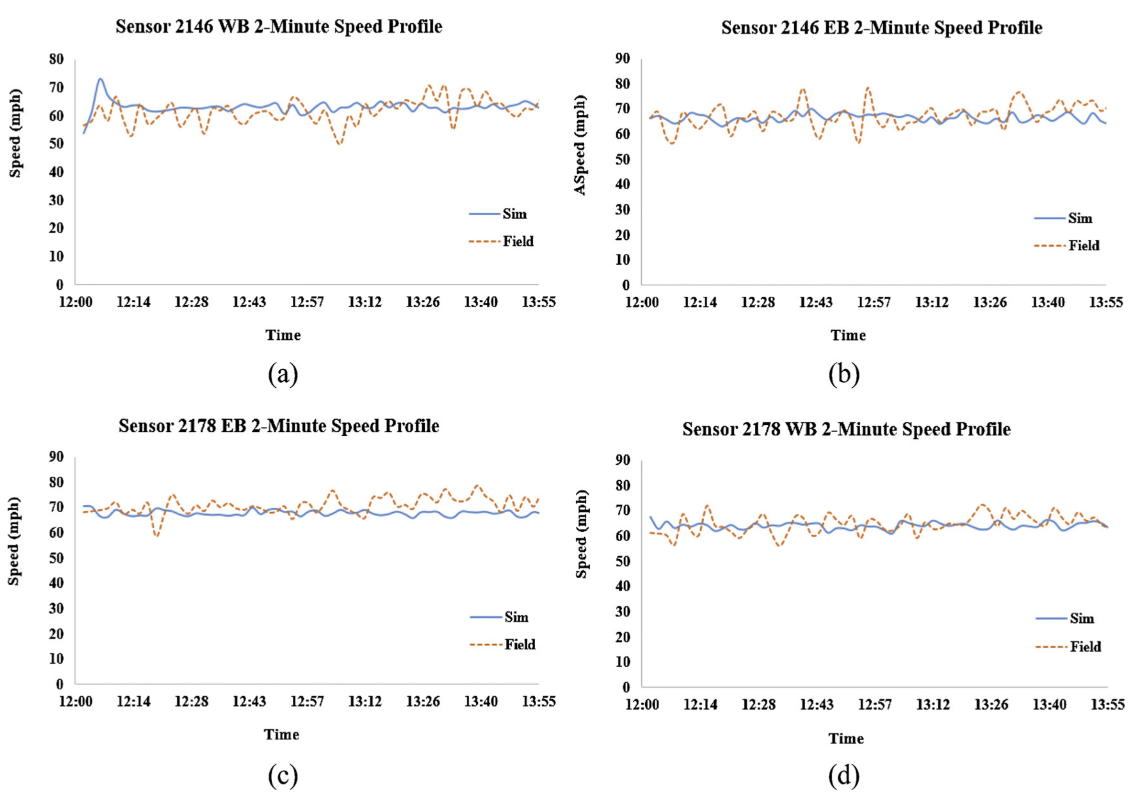

Fig. 4. Comparison of simulated speed profile and field data under snow weather condition.

Table 3
GEH and MAPE statistic test results for baseline scenario.

Sensor Location	GEH statistic test				MAPE statistic test	
	Input volume (Veh. per 2-hr)	Simulated volume (Veh. per 2-hr)	GEH value	Acceptable	MAPE value	Acceptable
Sensor 2146 WB	596	570	1.1	Yes	6.4%	Yes
Sensor 2146 EB	232	249	1.1	Yes	6.2%	Yes
Sensor 2178 EB	396	400	0.2	Yes	5.5%	Yes
Sensor 2178 WB	535	534	0.04	Yes	5.5%	Yes

In addition, by comparing the 2-minte speed profiles between the simulated and field-collected traffic using a two-sample t- test indicated no significant difference in the mean of the simulated speed and field speed. This result is presented in Table 4.

Table 4
Test statistic between simulated speed and field data.

Sensor Location	Test Statistics			
	Mean (mph)	S.D. (mph)	p -Value	Significance*
Sensor 2146WB	65.5	6.9	0.2838	No
Sensor 2146 EB	65.1	6.3	0.4352	No
Sensor 2178 EB	63.1	4.9	0.1619	No
Sensor 2178 WB	61.7	6.8	0.0859	No

Note: * Significance at 0.05 level.

defining vehicle class-specific driving behaviors for each link in the network, different vehicles can behave differently on the same link (Cisco, 2017; Sukennik, 2018; Stanek et al., 2018). This allows the user to simulate CV driving behavior by defining a dedicated CV class and calibrate the default driver behavior parameters based on field collected or tested CV driver behavior data. Since the WYDOT CV Pilot focuses on truck safety, at this stage only commercial trucks, WYDOT snowplow trucks, and the Wyoming Highway Patrol vehicles will be equipped with CV system. Therefore, this research defined three vehicle categories: regular car, non-connected trucks, and connected trucks. According to the user instruction provided by the PTV Group, key methodologies used for internally modeling of Connected and Autonomous Vehicles (CAVs) in VISSIM are described as follows (Cisco, 2017):

- Keep smaller standstill distance (i.e., change CC0 parameter in VISSIM Wiedemann 99 model),
- Keep smaller distances at non-zero speed (i.e., change CC0, CC1, CC2 parameters in VISSIM Wiedemann 99 model),
- Accelerate faster and smoothly from standstill (i.e., change acceleration functions and CC8, CC9 parameters in VISSIM Wiedemann 99 model),
- Follow other vehicles with smaller oscillation distance oscillation (i.e., change CC2 parameter in VISSIM Wiedemann 99 model),
- Perform more co-operative lane change as lane changes could occur at a higher speed co-operatively (i.e., switch cooperative lane change; change maximum speed difference; change maximum collision time),
- Smaller lateral distances to vehicles or objects in the same lane or on adjacent lanes (i.e., change default behavior when overtaking on the same lane),
- Drive as CAV on selected routes and as conventional human controlled vehicles on other routes (i.e., Use different link behavior types and driving behavior for vehicle classes; and/or depending on complexity of CAV behavior).

Nevertheless, it is necessary to point out that driver behavior of CVs might be different from CAVs since CVs are human-driven vehicles while CAVs are assumed to be operated or partially operated by machine. In addition, the guidelines are mostly for urban freeway under normal weather condition, which might not exactly represent the CV driver behavior on low-volume rural freeway and under adverse weather conditions. Therefore, based on these descriptive features of CAV behavior and in accordance with the quantified changes of driving behavior under CV environment (such as a 10 percent reduction in average speed and smaller variations of speeds) obtained from the driving simulator experiment, the CV microsimulation model was developed and re-calibrated by adjusting the desired speed distribution and driving behavior data of the calibrated baseline microsimulation model, as listed in Table 5. In general, this research assumed that connected truck drivers were perceived to be more conservative when driving under snowy weather condition in comparison with non-connected truck drivers, which was based on the driving behavior data collected from a high-fidelity truck simulator, as mentioned earlier.

5.2. Microsimulation scenarios

To better reflect the actual traffic conditions on Wyoming I-80

Table 5
Calibrated Driving Behavior Data for Baseline and CV Scenarios

Driver Behavior Parameter		Regular Car	Non-Connected Truck	Connected Truck
Car Following	CC0 (Standstill Distance) (ft.)	18.2	25.8	30
	CC1 (Headway Time)*	3 - 4	4 - 8	6 - 10
	CC2 (Following Variation)	32.2	37.30	43.70
	CC8 (Standstill Acc.) (ft/s^2)	8.3	4	2
	CC9 (Acc. with 50mph) (ft/s^2)	4	1.5	0.1
	Look ahead distance (ft.)	500	600	800
	Look back distance	300	350	410
	Observed Vehicle (ft.)	1	2	3
Lane Changing	General Behavior	Free Lane Change	Right Lane Rule	Right Lane Rule
	Safety distance reduction factor	0.5	0.6	0.7
	Advanced Merging	No	No	Yes
	Cooperative lane Changing	No	No	Yes
	Maximum deceleration (ft/s^2)	−15	−15	−13

Note: *Headway time followed a normal distribution pattern; regular car and non-connected truck were included in the baseline model; regular car, non-connected truck, and connected truck were included in the CV model.

under winter adverse weather conditions, the microsimulation scenarios were designed based on field collected traffic flow data under snowy weather. For vehicle composition, passenger cars and trucks were determined as 40% and 60% of the total traffic volume, respectively. Three traffic volume scenarios were designed: 200, 400, and 600 vph, which represented low, medium, and high traffic demand levels on this corridor, respectively. In terms of connected truck penetration rate, five levels of connected truck penetration rates in addition to the baseline scenario (0% connected truck) were tested. The penetration rates of connected trucks ranged from 5% (low connected truck penetration) to 60% (full connected truck penetration).

5.3. Safety performance assessment

Since a microsimulation software cannot directly simulate traffic crashes, using Surrogate Measures of Safety (SMoS) derived from data output by traffic simulation models has been proved as an efficient method for safety evaluation (Gettman and Head, 2003; Huang et al., 2013; Essa and Sayed, 2015).

A total of 18 microsimulation modeling scenarios (i.e., 3 traffic demand scenarios multiplied by 6 connected truck penetration rate scenarios) were designed to investigate the safety performance under various demand levels and connected truck penetration rates. For each scenario, 5 simulation runs were performed to eliminate the random errors of microsimulation. Afterwards, the simulated vehicle trajectory files were imported to SSAM for safety performance assessment. Since this research focused on a low-volume rural freeway corridor under adverse weather conditions, it was assumed that CV warnings will improve CV drivers' situational awareness. Among the SMoSs used by SSAM, Time-To-Collision (TTC) was considered as most applicable for assessing the safety performance of the study rural freeway corridor, since vehicles had significantly lower lateral interactions in comparison with driving on urban freeways.

TTC is defined as the time required for two vehicles to collide if they continue at their present speeds on the same path (Rahman et al., 2019), as shown in equation below.

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

Where D_{1-2} represents the gap distance between the leading and the following vehicle, V_1 and V_2 are the speeds of the leading and following vehicles, respectively.

At this stage, there is no field observed TTC threshold values in a CV environment under snowy weather condition. Considering rural freeways have low traffic volume and relatively higher headway distance, this research tested traffic safety performance under various levels of TTC thresholds. The tested TTC thresholds including the default TTC threshold in SSAM (i.e., 1.5 s), which has been widely used by exiting SSAM-based studies (Papadoulis et al., 2019). In addition, previous research pointed out that the characteristics of rural freeways with high speed contribute to the severity of crashes (Elvik, 2013), indicating lower TTC values can still be considered to indicate high crash risk. Therefore, based on the recommendations from previous studies (Bella, 2010) and the driving simulator experiment conducted at the WyoSafeSim that tested drivers' response to CV Forward Collision Warnings (FCW) (Ahmed et al., 2019; Yang et al., 2019), this study adopted three different levels of TTC threshold: high risk (1.5 s), medium risk (3.5 s) and low risk (9 s) to qualitatively compare the simulated conflicts under various traffic demand levels and CV penetration rates.

A comparison of the simulated number of conflicts for each scenario is presented in Fig. 5. It is necessary to point out that the majority of the simulated conflicts from SSAM were rear-end conflicts, which is mainly due to the following two factors; 1) Under snowy weather condition, the majority of vehicles choose to drive on the right lane with a relatively lower speed and small number of lane changing maneuvers, and 2) The simulated corridor was a rural freeway corridor with very large space interval between adjacent ramps, and under snowy weather condition, there was almost no on-ramp/off-ramp traffic. These factors resulted in very limited lane-changing maneuvers.

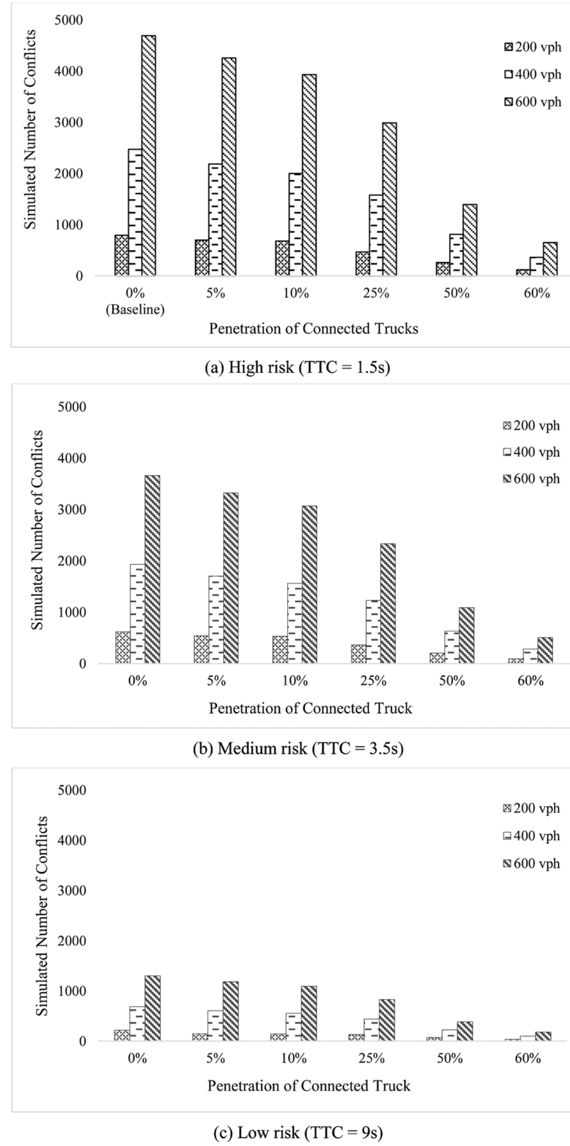

Fig. 5. Sensitivity analysis of different TTC thresholds during winter snow weather condition under various demand levels and connected truck penetration rates.

Simulated results indicated that the number of traffic conflicts increased significantly with the increase of traffic demand and decreased with the increase of connected truck penetration rate. Since the microsimulation models were developed for a 23-mi freeway corridor, thus the simulations resulted in large numbers of conflicts (e.g., up to 4,700 conflicts for baseline scenario under high demand levels). In the high risk scenario, it was found that when the penetration of connected trucks was less than 10%, reduction in number of conflicts was not significant. In comparison, when the penetration of connected trucks was greater than 25%, there were remarkable reductions in conflicts. The reduction reached 85% for fully connected trucks scenarios, indicating that the CV applications developed by the WYDOT CV Pilot have the capability of improving traffic safety of this rural freeway corridor under snowy winter weather condition. Generally, number of conflicts decreased roughly linearly as market penetration of CVs increased in all levels of risk.

6. Conclusions and discussions

With the evolving of vehicle technologies, CVs are being deployed in Wyoming and the nation's transportation systems at a rapid pace. Nevertheless, the actual safety performance of CVs is still not clear, since at this stage the penetration of CVs is still low, and it requires a long time to collect sufficient real-world traffic performance data for performance assessment. In comparison, microsimulation modeling turns to be a cost-efficient alternative to provide the WYDOT a quantitative assessment and early insights of the performance of the WYDOT CV Pilot.

A key methodology innovation of this research is that it quantified the impacts of real-time CV warnings on driver behavior through a driving simulator experiment, which addressed the limitation of lacking real-world traffic performance data in a CV environment. Accordingly, this study developed and calibrated microsimulation models to simulate the operational features of CVs. Various simulation scenarios were designed based on the field collected traffic flow data to represent the actual traffic on Wyoming I-80 under winter adverse weather conditions. Simulation results indicated that CV warnings, by increasing drivers' situation awareness, have the potential to reduce crash risk under adverse weather conditions. The reductions in conflicts showed a decreasing trend with the increase of connected truck penetration rates and reached 85 percent if all the trucks are equipped with CV technology. In addition, it was found that under a lower CV penetration rate, the reductions of conflicts are not significant, which are mainly due to the potential variations of speeds between CVs and non-CV drivers.

Also considering the sensitivity analysis of different TTC, the number of conflicts decreased linearly with the increase of TTC value. This gives an indication of driver response to CV warning and therefore crash risk can be decreased when collision warnings are disseminated early to give drivers enough response time. However, at this stage of the study, there is not enough empirical proof to ascertain the right TTC threshold in a CV environment during snowy conditions on a rural highway.

This research presents some preliminary insights regarding the safety effectiveness of the WYDOT CV Pilot under various traffic demand levels and CV market penetration rates. In addition, the presented AMS framework has the potential to guide similar research activities conducted by other agencies. Nevertheless, it is necessary to point out the driver behavior data obtained from the driving simulator experiment may not exactly represent the real-world traffic operation conditions. Through the sensitivity analysis of different TTC thresholds, this research found that the number of conflicts decreased with the increase of TTC. This indicates that risk of rear-end crash can be decreased when CV collision warnings are disseminated early to give drivers enough response time. However, at this stage of the study, there is no empirical proof to ascertain the appropriate TTC threshold in a CV environment during snowy conditions for rural freeways. Future works should also further investigate the safety benefits of the pilot's CV applications under different weather and traffic events, such as a freeway work zone under low visibility condition, and road closure and rerouting due to traffic crashes.

CRediT authorship contribution statement

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

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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.2020.105714.

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