Effects of connected vehicle-based variable speed limit under different foggy conditions based on simulated driving

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ABSTRACT

In response to developing and/or diminishing foggy conditions, the variable speed limit application in a connected vehicle environment (CV-VSL) can estimate and deliver recommended travel speeds to individual drivers, which can help to reduce crashes when visibility conditions change. This study aims to quantify the effectiveness of the CV-VSL application by exploring drivers' reactions to warnings (e.g., recommended travel speeds). In order to analyze the effectiveness of the CV-VSL application, a connected vehicle testing platform was established based on a driving simulator, and characteristics of the drivers' speed adjustments after receiving warnings were analyzed with respect to different levels of visibility (i.e., no fog, slight fog, and heavy fog). This study also examined the effect of warnings on drivers in different impact zones (i.e., clear zone, transition zone, and fog zone). Three indicators were identified: 1) speed at the end of the clear zone, 2) maximum deceleration rate in the transition zone, and 3) average speed reduction in the fog zone. Throughout the experiment, the relationship between speed adjustments and the level of visibility was explored. The results indicated that the CV-VSL application is effective in making drivers reduce travel speeds in all three types of zones. Furthermore, it appeared that the CV-VSL application could help manage travel speeds prior to vehicles entering the transition zone, and influence drivers' braking decisions upon encountering reduced visibility. It was also found that the CV-VSL application was more effective in heavy fog conditions than in light fog conditions. The connected vehicle testing platform based on the driving simulator provided a new method for evaluating the effectiveness of in-vehicle messaging generated by connected vehicle applications.

1. Introduction

Fog is a weather condition that reduces visibility on roads. Visibility is a critical factor in drivers' perceptions of the driving environment, and reduction in visibility due to fog is a major factor influencing drivers' ability to accurately perceive factors crucial to safe driving, such as depth of field and speed. Crashes are always possible in foggy conditions because of drivers' failure to maintain safe following distances under adverse weather conditions (World Health Organization, 2018). Fog likely played a role in 20,159 police-reported fatal crashes that occurred in China in 2016 (The Ministry of Public Security Traffic Management Bureau, 2017).

Several recent attempts have been made to reduce the number of traffic crashes in foggy conditions through countermeasures such as fog detection and warning systems, low visibility driving safety campaigns, and driver training; some studies have attempted to address the issue of

fog and its impact on highway safety with connected vehicle technologies. Connected vehicle technologies can create a safe, interoperable, ad hoc wireless communications network, which allows vehicles to talk to one another, to transportation infrastructure (e.g., traffic signals, and traffic management centers) and to pedestrians, cyclists, and passengers in a cooperative manner. Connected vehicle applications can help improve drivers' situation awareness and enhance the safety and efficiency of operating vehicles (McGurrin et al., 2012). In 2016, the National Highway Traffic Safety Administration (NHTSA) estimated that V2V- and V2I-related safety applications could address or eliminate up to 80 percent of non-impaired crashes (NHTSA, 2016). Meanwhile, several studies have employed connected vehicle technologies to address the issue of highway safety in foggy conditions (Richard et al., 2017). Wu et al. (2018a,b) proposed a modeling framework to depict drivers' speed adjustment in risk perception and acceleration/deceleration maneuvering when receiving real-time warning massages.

However, research addressing how to identify and evaluate the information a driver may want or need in a manner that is safe and usable is relatively sparse. The challenges are summarized as follows: 1) the interaction between the connected vehicle system and drivers is not yet well understood; 2) there is lack of an effective testing platform and an evaluation framework for connected vehicle in-vehicle messaging. Therefore, in order to evaluate the effectiveness of connected vehicle applications, an effective connected vehicle testing platform should be structured and changes in driver behavior due to in-vehicle messaging generated by connected vehicle applications should be evaluated. This research puts forward corresponding hypotheses for evaluating the effectiveness of a connected vehicle-based variable speed limit (CV-VSL) application in foggy conditions as follows:

1. The CV-VSL application can help change drivers' behavior by providing timely alerts and warnings.
2. The effectiveness of the CV-VSL application differs according to varying levels of visibility in different foggy conditions.
3. A connected vehicle testing platform can be constructed based on a driving simulator and a human-machine interface (HMI). This platform can help verify the effectiveness of the CV-VSL application in terms of driving safety and drivers' compliance.

The remainder of this paper is organized as follows: Related research studies are reviewed first; then the connected vehicle testing platform and experimental design and data collection are discussed, followed by experimental results, discussions, concluding remarks, and future research directions.

2. Literature review

The primary change in drivers' behavior corresponds to speed regulation. As a consequence, this has been studied extensively and described in the literature, and various connected vehicle applications have been introduced to improve drivers' compliance with speed regulation (Khondaker and Kattan, 2015). Notably, variable speed limit (VSL) or speed harmonization is a speed management strategy that enables dynamic changes of speed limits in response to prevailing traffic, incidents, and/or weather conditions. A CV-VSL application utilizes traffic speed, volume detection, and road weather information to determine the appropriate speed at which drivers should be traveling, and deliver customized alerts and warnings to each individual driver via his/her vehicle's human machine interface (HMI). The CV-VSL application is intended to provide the following benefits:

1. Enhance traffic safety: VSL can help reduce speed differences among vehicles traveling in the same lane and/or adjacent lanes. This reduction in speed differences harmonizes drivers' behavior and discourages lane changing behavior, thereby decreases the probability of collisions (Abdel-Aty et al., 2006).
2. Delay the onset of congestion: When traffic volume is close to capacity, any disruption in the traffic stream can lead to traffic breakdown. VSL can help maintain uniform speeds and decreased headways, and thus traffic flows more smoothly and efficiently (Hegyi, 2004).
3. Reduce environmental impacts: Improving traffic flow is often associated with decreased fuel consumption, decreased noise and decreased emissions (Zegeye et al., 2010).

However, literature has shown mixed results on the effects of CV-VSL applications on mobility and safety. Lee et al. (2006) demonstrated that a real-time CV-VSL application could reduce crash risk, but at the expense of higher travel times. On the other hand, Abdel-Aty et al. (2007) indicated that the CV-VSL application provide a significant reduction in crash probability only for non-congested conditions. Li et al (2014) developed a variable speed limit strategy to reduce secondary

collision risks during inclement weathers. Park and Yadlapati (2003), Lavansiri (2003), Lin et al. (2004) and Lyles et al. (2004) showed the effectiveness of some VSL applications in the work zone about reducing travel time and improving throughput. In a recent study, Talebpour et al. (2013) studied the impact of early shockwave detection on breakdown formation and safety using speed harmonization as a control strategy in a connected vehicle environment. Connected vehicle technologies allow vehicles and transportation infrastructure to share high-resolution information not only from aggregated traffic, but also between individual vehicles on the road. With such connectivity, the CV-VSL application can transmit traffic control information to individual drivers through wireless communication and onboard units (OBUs). However, the effectiveness of VSL applications is not systematically evaluated in a connected vehicle environment. Evaluating the effectiveness of CV-VSL applications before implementation is critical. This research study simulated a CV-VSL application based on a driving simulator platform and an HMI, and then evaluated its effectiveness based on the change in speed harmonization in a connected vehicle environment.

Previous studies have investigated the effects of different fog levels on crash severity. However, the literature about the impact of connected vehicle applications in different fog levels is quite limited. Louw et al. (2015) and Louw et al. (2017) developed a screen manipulation technique, which used a fog-like display to vary the degree of visual information available to drivers via two types of information dissemination mechanisms: in-vehicle displays and dynamic message signs on the road. Williams et al. (2015) examined drivers' responses to different color configurations, brightness levels, and flashing beacons of a fog warning system during day and night under foggy conditions. The results indicated that the black-on-white, white-on-black, and amber-on-black color combinations had longer detection and legibility distances. In this research, the effectiveness of the CV-VSL application in varying fog visibility was compared. To summarize, although several previous studies have examined the effects of the CV-VSL application on drivers' speed adjustment maneuvers in foggy conditions, most of them have only focused on several particular driving scenarios and have only analyzed drivers' speed adjustment when they were already in foggy conditions. Safety benefits of the CV-VSL have been evaluated in the previous studies many of which indicated that the CV-VSL could effectively help reduce rear-end crash risks. Fildes et al. (2015) proposed to evaluate the effectiveness of low speed autonomous emergency braking (AEB) technology in current model passenger vehicles based on real-world crash experience. The findings showed that a 38 percent overall reduction in rear-end crashes for vehicles fitted with AEB compared to a control sample of similar vehicles. There was no statistical evidence of any difference in effect between urban (≤ 60 km/h) and rural (> 60 km/h) speed zones. Areas requiring further research were identified and widespread fitment through the vehicle fleet was recommended. However, there was a lack of studies on the safety effectiveness of the CV-VSL on rear-end crashes under fog conditions. Therefore, Wu et al. (2018a,b) conducted a driving simulator study to evaluate the effectiveness of the Head-up Display warning system and the audio warning system on drivers' crash avoidance performance when the leading vehicle made an emergency stop under fog conditions. Drivers' throttle release time, brake transition time, perception response time, brake reaction time, minimum modified time-to-collision, and maximum brake pedal pressure were assessed in the analysis. Therefore, different from previous studies, Wu et al. (2018a,b) conducted a driving simulator study to evaluate the effectiveness of the Head-up Display warning system and the audio warning system on drivers' crash avoidance performance when the leading vehicle made an emergency stop under fog conditions. Drivers' throttle release time, brake transition time, perception response time, brake reaction time, minimum modified time-to-collision, and maximum brake pedal pressure were assessed for in the analysis which investigated the effects of static warning systems (beacons and variable message signs) and crash

Fig. 1. Connected vehicle testing platform.

warning systems on rear-end crash avoidance on drivers' behaviors in fog, and the effects of several CV-VSL application settings under different conditions should be systematically analyzed based on a reliable connected vehicle testing platform.

Driving simulators are useful research tools for analyzing driving behavior under different conditions. Simulator-based research provides insights into driver response and ability in a range of different conditions which are otherwise impossible using on-road assessments (Brooks et al., 2010). Clearly, a driving simulator has multiple advantages for creating the connected vehicle testing platform: a) flexible experiment conditions, b) ability to simulate adverse weather and driving scenarios that are often unsafe and impossible to perform in real-life situations, c) economical research method, d) convenient method for collecting data on participants' behavior in a wide variety of situations, and e) convenient way to objectively measure driving performance (Lee et al., 2008). What is more, the simulator's data interface can be expanded, so that researchers can integrate the simulator-based platform in accordance with the multifunction interface of the simulator. In this platform, the data exchange between a driving simulator and an external user terminal through the User Datagram Protocol (UDP) interface was conducted in real-time, and messages could be relayed in real-time to drivers through the HMI (Ding et al., 2013). With these advantages, driving simulators have become increasingly popular research tools for analyzing the effects of connected vehicle applications on driving behavior (Shechtman et al., 2009). However, an effective testing platform and an evaluation framework in a connected vehicle environment is still lacking, making it difficult to evaluate connected vehicle applications based on a driving simulator.

Generally, the objective of this research was to evaluate the effectiveness of the CV-VSL application in foggy conditions by exploring drivers' reactions to warning messages. An effective connected vehicle application testing platform was established, and the drivers' speed adjustments after receiving warning messages were analyzed with respect to different levels of fog visibility. The findings of this research can be used to support decision-making for implementing the CV-VSL application, and the connected vehicle testing platform based on a simulator provides a new method for evaluating the effectiveness of connected vehicles in adverse weather and roadway conditions.

3. Methodology

3.1. Connected vehicle testing platform

In this research, the connected vehicle platform was designed based on driving simulator technology. This platform consisted of three devices: a driving simulator, a central database, and a user terminal. Normally, the simulator recorded the vehicle operating data (e.g., braking force, acceleration, speed, lateral placement, lane number and turning angle of steering wheel) at a rate of 30 times per second. It had multiple Application Programming Interface (API) functions and an open UDP interface. Driving scenarios were developed by using the API to add weather, signs and other connected vehicle system elements, and the data exchange between driving simulation and external user terminal through the UDP interface. The connected vehicle application testing platform included three parts (see Fig. 1).

Part 1 involved data collecting and transfer. Connected vehicle safety applications use the data collected from surrounding equipped connected vehicles and roadside units, including vehicle speed, vehicle location, weather conditions, and road conditions. In this research, the required scenarios were developed and the required data were collected through the API of the driving simulator. The UDP interface was used for data exchange between the driving simulator and the external central database. Data were transmitted in real time and real-time feedback was sent to the central database at a rate of 30 times per second. Finally, data from the central database were transmitted wirelessly to the on-board display (e.g. mobile phone, PAD, and etc.,) in real time at a rate of 5 times per second.

Part 2 involved the message production. The data in the central database is complete and complex, and the main task of this part was to define the rule for extracting useful data and generating warning messages. The data from the central database were selected to create the required warning messages, and the warning messages were sent to the on board display when nearing the range of the adverse conditions. The V2V message showed information about nearby vehicles' position and speed in the warning range, which was within 200 m of the vehicles (Xu et al., 2012). Similarly, as the V2I message was produced, the required data was selected from the database and the message was sent to the on-board display.

Part 3 involved the message display. The on-board display received

the message from the central database. The weather, road and traffic conditions, and surrounding vehicles' speed and location were received by the driver's vehicle in real time. The corresponding message displayed in the on-board display with a change of symbol and a verbal warning.

This study chose the CV-VSL system in foggy conditions as a case study based on the connected vehicle testing platform. The results revealed that the majority of drivers agreed with the validity of this platform. The validity of this platform has been determined in our previous research (Shechtman et al., 2009).

3.1.1. Apparatus

The fixed-base driving simulator located in the Key Laboratory of Traffic Engineering of Beijing University of Technology consists of a real car, computers, video and audio equipment (see Fig. 2). The road scenario was projected onto three big screens, providing a 130-degree field of view. The screen resolution of the driving simulator was 1920 × 1080. Moreover, the on-board display was designed based on the HUAWEI PAD M3. The screen resolution of the pad was 1920 × 1080, and the size was 215.5 mm × 124.2 mm × 7.3 mm. The operation system was Android 6.0.

A driving simulator experiment was conducted in this study; accordingly, as with any driving simulator study, there are certain limitations inherent to this approach. The driving behavior may not match the normal driving behavior because the participants know that they are being observed. The data validity has consistently been found to impact the experiment (Mayhew et al., 2011). Therefore, to decrease the gap between the reality and the simulation, scenarios were designed to represent real segments of highway whenever possible to improve the validities of the scenarios. Moreover, to address the problem in which the participant exhibits a lack of risk while driving in the simulator, the subjects were encouraged to drive realistically by allowing them to become familiarized with the drive, increasing the lengths of the scenarios, and providing verbal instructions. In a previous study (Ding et al., 2013), the speed, accelerator and other operator validation were tested with a control scenario for a quick before-after comparison, and the questionnaires were used for validation. To date, more than 300 drivers in driving experiments have been utilized to evaluate the validity of this driving simulator through questionnaires. The evaluation items included characteristics such as the realistic feel of the accelerator and brakes and their speed perception. The results of the questionnaire ratings revealed that the majority of drivers agreed with the validity of this driving simulator. However, the relative validation of the CV-VSL application was not performed with a control scenario for a quick before-after comparison because the CV-VSL has not been implemented in the real world. Moreover, the driving effects found in simulators tend to be greater than those found in natural experimental settings (Blana and Golias, 2002). However, those effects do follow the same trends in both types of experiments (i.e., simulated and natural), thereby providing a good relative validity. Hence, given the ability of the current study to control the scenario design, the majority of the limitations on our method were minimized. Additionally, considering the need to collect performance measures of drivers' responses under potentially hazardous situations without putting participants at risk, the existing limitations are acceptable.

3.1.2. Human-machine interface (HMI) design

The CV-VSL application utilizes traffic speed volume detection and road weather information systems to determine the appropriate driving speeds, given current traffic and road conditions. Given the function of the CV-VSL application, HMI design requirements of the on-board display are as follows:

1 The operating status of surrounding vehicles;
2 The operation suggestion based on speed and variable speed limit;
3 The weather conditions and emergency of the road;
4 The state of the vehicle.

By meeting the above requirements, this paper designed the HMI based on the Tesla and domestic interface style. Four types of information about status of surrounding vehicles and weather conditions were indicated by voice and symbol on the HMI (see Fig. 3).

The HMI graphic displays included the following four groups:

Group 1 showed the distance between a vehicle and its lead vehicle. When the lead vehicle was 200 m away, Group 1 showed the "Distance from the lead vehicle: > 200 m"; when the lead vehicle was within 200 m, Group 1 showed the real distance between the vehicle and its lead vehicle;

Group 2 showed the speed warning to the drivers; "Speed" showed the current speed of the vehicle, and "Speed limit" showed the current speed limit of the road. The speed limit was 120 km/h in a no fog or light fog situation, and 60 km/h in a heavy fog situation (China Standardization Administration, 2012). A continuous voice warning (you are speeding, please slow down) alerted drivers of danger whenever the driver's speed exceeded the speed limit;

Group 3 showed imminent dangerous vehicle surroundings. The red exclamation mark appeared with a continuous warning to alert drivers of an imminent collision whenever time to collision (TTC) with the lead vehicle was below a 2-second threshold (Jin and Orosz, 2014). The fog symbol appeared with a voice warning (you are approaching the fog area) when the vehicle neared the 2-kilometer range of the fog. The voice warning was played once every 500 m, and the fog symbol was continuous.

Group 4 showed the traffic situation surrounding a vehicle. The arrow symbol was solid green when the distance between a vehicle and its surrounding vehicles was over 200 m, flashing yellow when the distance was less than the 200 m, and flashing red whenever the TTC was below a 2-second threshold. Fig. 3b showed the different color of the symbol; Fig. 3b(I–III) showed the situation with the lead vehicle. Fig. 3b(IV−VI) showed the situation with right (right-front/right-rear)
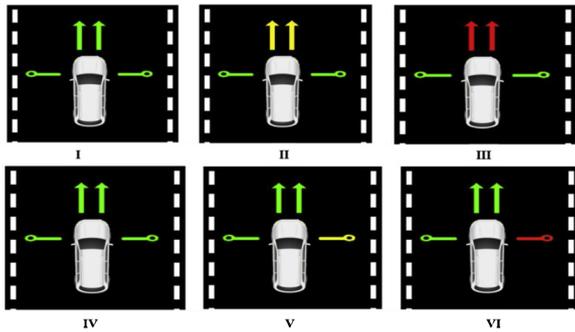

Fig. 2. Connected vehicle testing platform based on driving simulation.
(a) Groups of the HMI.
(b) Different colors of symbols in different situations.
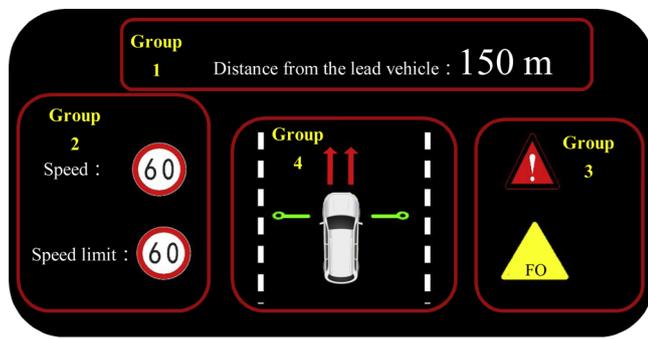
(a) Groups of the HMI

(b) Different colors of symbols in different situations

Fig. 3. Graphic displays of HMI.
(a) The layout of the experimental road.
(b) The three fog scenarios.

vehicles or left (left-front/left-rear) vehicles, but different between right-front (left-front) and right-rear (left-rear) was not be provided. In this paper, the main topic is the effect of the CV-VSL in foggy condition, and the speed is the main control variable. It's important to inform the driver that the nearest vehicle is in front of him/her or at the rear when he/she changes lane, but the lane-change is not the focus of this paper, therefore, the driver was not given warnings about the nearest vehicle, but on different lanes.

This HMI can help drivers predict the driving potential hazards based on the status of surrounding vehicles and weather conditions. However, this HMI tends to provide too much information, which may result in drivers' poor performance under safety critical situations. Notably, non-free flow may influence drivers' operation, therefore, traffic was free flow in this research. However, free-flow traffic is not very ideal to measure drivers' distraction when the HMI shows two much information, for example, changes in Groups 1 and 4 were not apparent. The effectiveness of Groups 1 and 4 will be analyzed in future research.

3.2. Experimental design and data collection

Experiments were conducted to determine the relationship between warning messages and speed adjustment. Then the effectiveness of the CV-VSL application in foggy conditions was evaluated based on the connected vehicle testing platform.

3.2.1. Participants

A total of 43 healthy participants (age: M = 35 years, SD = 11.88), including 28 males and 15 females, were recruited from universities and social organizations to participate in the experiment. The participants were required to have at least 20/20 (normal or corrected, self-reported) vision and no hearing problems (self-reported). All participants provided informed written consent and demographic data (see Table 1) before joining the experiment. To clarify, the homogeneous sample of subjects was selected in order to minimize any bias

Table 1
Descriptive Statistics.

Variables	Mean (SD) Statistics or Percentages	
	Male Participants	Female Participants
Age (years)	37.5 (13.1)	25 (12.97)
Age of license (years)	16 (10.2)	13 (9.3)
Average driving mileage (per year/ km)	18,524 (3548.22)	9,584 (5514.21)
Percentage of rural road driving	34%	22.75%
Percentage of urban road driving	58.24%	72.55%
Percentage of freeway driving	7.76%	4.7%

attributable to sample heterogeneity. This study calculated the required sample size, based on the expected variance, target confidence level, and margin of error. The method of measuring the sample size is shown in Eq. (1).

$$N = Z^2 * \sigma^2 / E^2 \tag{1}$$

As written in Eq. (1), the required sample number (N) was calculated by the standard normal distribution (Z); the standard deviation (σ) and the maximum error (E). Typically, a significance level of 10 percent was chosen to reflect a 90 percent confidence level regarding the unknown parameter. In this research, the Z was 1.25 and the σ was 0.5; the E was 10 percent (Chow et al., 2017). The required sample size in this research was 40. Therefore, the sample size of this research is in line with the requirement.

3.2.2. Simulated scenarios

The experimental road in this study was based on the northbound sections on the Xingyan freeway (a freeway with a total width of 18.8 m (lane width = 3.75 m, median (green belt) width = 0.8 m and shoulder width = 1.50 m) in the north of Beijing. The selected sections were located in a relatively foggy area. The Xingyan freeway is a four-lane freeway with a 120 km/h speed limit, while in a heavy fog the speed limit is 60 km/h. For each road section, the total length was about 6 km, consisting of three zones: (1) a clear zone (3.5 kms), (2) a transition zone (0.5 kms), and (3) a fog zone (2 km) (Fig. 4a). There were two types of scenarios with and without the CV-VSL application. The clear zone was to ensure that the driver had entered into the normal driving situation and had adequate time to respond to warnings; the distance (1.5 km) before the warning was to ensure drivers could reach the normal speed. The CV-VSL application warning appeared when the vehicle neared the 2 km range of the fog. There were 5 warning points in the clear zone, each at an interval of 500 m. The transition zone was designed with gradually reduced visibility to avoid a sudden visibility change, and the visibility changes to the fog zone's level when the drivers arrive at the fog zone. It was assumed that drivers could get used to the reduced visibility with the 0.5 km distance. In addition, drivers were expected to drive in the fog zone for a 2- kilometer distance. As shown in Fig. 4b, three different fog level scenarios were used in this research: no fog, light fog (visibility = 725 m), and heavy fog (visibility = 125 m) (China Standardization Administration, 2012).

In total, 6 scenarios were designed based on 2 variables, which included visibility levels (3 levels) and whether the CV-VSL application was present (2 × 3). And this simulation scenario is a full factorial design. Each participant was assigned to 6 different scenarios with a full sample experimental design. The traffic setting was based on recorded traffic data that was collected on a similar freeway segment in Beijing. Since fog usually forms during the early morning hours, the traffic volumes during this period were not congested, which was consistent with previous studies showing that traffic volume decreases under fog conditions. Therefore, this study chose the free-flow traffic with an average headway of 36 s, and the average speed of other vehicles is 100 km/h if there is no fog and 55 km/h under foggy conditions.

(a) The layout of the experimental road

No Fog   Light Fog (625m)   Heavy Fog (125m)
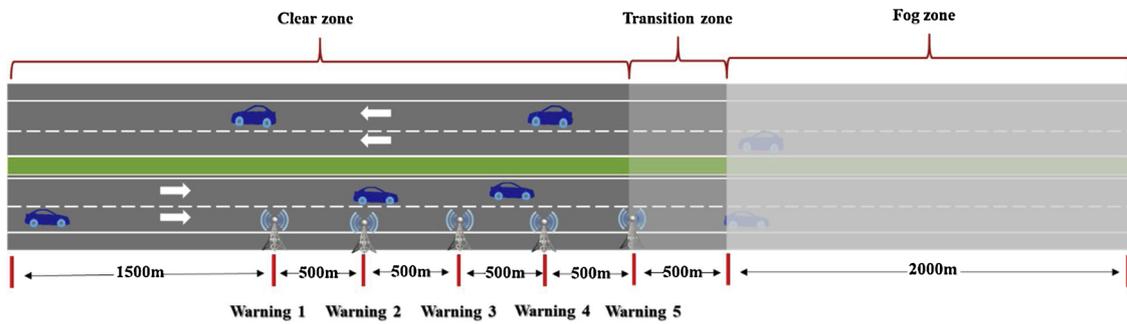
(b) The three fog scenarios

Fig. 4. Layout of the experimental road and three fog scenarios.

Note: NW- no fog with VSL; NWN- no fog without VSL; SW- slight fog with VSL; SWO- slight fog without fog; HW- heavy fog with VSL; HWO- heavy fog without VSL.

3.2.3. Experimental procedure

The experiment included four stages.

In stage 1, participants were given training to become familiar with the HMI. In stage 2, participants were allowed approximately 3–5 min of practice driving before the experiment. The main purpose of the practice was to minimize the effect of unfamiliarity with the driving simulator equipped with the CV-VSL application. In stage 3, each participant was allowed to have a break to ensure that they were not dizzy from using the simulator. In stage 4, each participant was assigned to drive in scenarios 1-6. Six scenarios were randomly sorted for participants to increase the degree of randomness. Each participant was given a 7-minute break between two consecutive simulation runs to maintain certain psychophysical conditions and to minimize any effects of fatigue. The total duration of experiment is about 3 h, and the experiment was divided into two sections. Two experiment sections were conducted three days apart to prevent drivers becoming familiar with simulator scenarios. During each experiment section, drivers took a break every 40 min.

3.2.4. Data processing and Indicator

During the experiment, the position of warning 1 (see Fig. 4) was also the initial data collection point, and the data collection continued until it reached the end of the fog zone. A total of 258 (43 participants × 6 scenarios) trials were conducted and 11 trials were dropped because the participants had motion sickness during the experiment. The number of remaining trials was 247. After the experiment, six scenarios including explanatory variables related to the participants' behavior were collected and are shown in Table 2. Specifically, the effectiveness of the CV-VSL application in this research can be divided into four groups as mentioned above.

The role of Group 2 was to prevent drivers from speeding and warn them when speeding, so as to improve driving safety. Therefore, the speed reduction proportion compared with the speed limit (Proportion$_{limit}$) and the frequency of speeding violations that a driver committed ($N_{speeding}$) was used as an explanatory indicator for the effectiveness of Group 2.

The role of Group 3 was to warn drivers gradually to adjust their speed when approaching the fog. Actually, the warning effect is different in the different zone, so drivers' speed adjustment was hierarchical and correlations existed among the three speed adjustment indexes, including the speed (V_{end}) at the end of the clear zone, the maximum deceleration rate in the transition zone (a_{max}), and the speed reduction proportion in the fog zone compared with the clear zone (Proportion$_{fog}$) (Wu et al., 2018a,b). In detail, the visibility was not reduced when drivers were driving in the clear zone. Thus, the speed adjustment was not affected by the fog levels but the drivers' perception of the upcoming risk based on the warning messages. The V_{end} can reflect a driver's final speed adjustment, indicating how the driver prepares for the downstream fog conditions. When driving in the transition zone, drivers should adjust their speed dynamically in response to the warning message and reduced visibility. When drivers entered the transition zone with gradually reduced visibility, most drivers reduced their speed. Hence, the a_{max} was adopted as an index of drivers' aggressiveness in the transition zone. In the fog zone, the visibility does not change and the speed should become stable after drivers adjust their speed in the clear zone and transition zone. Considering the fact that drivers may have different speed preferences corresponding to the reduced visibility and warning system, the Proportion$_{fog}$ is employed to evaluate the final changes. The proportion of average speed change is calculated using Eqs. (2) and (3):

$$Proportion_{limit} = \frac{V_{limit} - V}{V_{limit}} \tag{2}$$

$$Proportion_{fog} = \frac{V_{clear} - V_{fog}}{V_{clear}} \tag{3}$$

Table 2
Descriptive Statistics of Dependent Variables.

Group	Indicator	Description	Unit	Mean	Standard deviation
2	$Proportion_{limit}$	The positive average speed reduction proportion compared with the limit speed	%	0.12	0.09
	$N_{speeding}$	The frequency of speeding violations that a driver committed	Count	87	
3	V_{end}	The speed of entering transfer zone	Km/h	96	10
	a_{max}	The maximum deceleration rate in the transition zone	m/s^2	−2.29	1.69
	$Proportion_{fog}$	The average speed reduction proportion in the fog zone compared with clear zone	%	0.17	0.16
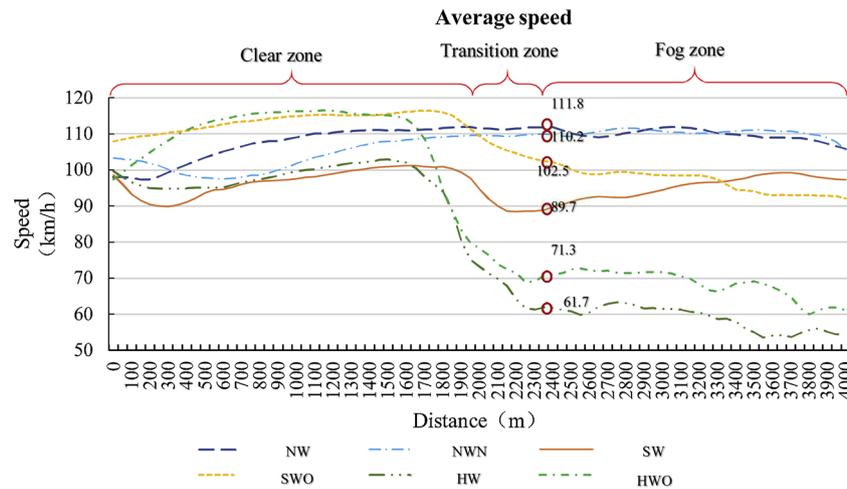
Fig. 5. Average speed under different scenarios.

where V_{limit} is the speed limit of the road, V_{fog} is the average speed in the fog zone and V_{clear} is the average speed in the clear zone. It should be noted that sometimes drivers may increase or maintain their speed in the fog zone. In that case, the $Proportion_{limit}$ and $Proportion_{fog}$ can be a negative or zero value.

4. Results

Fig. 5 displays the average speed in the three zones under different visibility conditions with and without the CV-VSL application. It is clearly shown that the average speed is more consistently reduced from the clear zone to the fog zone with the CV-VSL application, indicating that participants would adjust their speed according to the gradual warning instructions. In addition, the speed with the CV-VSL application in the fog zone was lower than without the CV-VSL application. It was further revealed that participants lowered their speed in the fog zone when the fog was denser. Notably, the speed of the vehicle approaching the start of a fog zone impacts the safety immediately; consequently, several studies have investigated the safety based on the approaching speed (Strawderman et al., 2013). The approaching speed with the CV-VSL application was lower than without the CV-VSL application. It shows that the CV-VSL application can warn drivers to choose safety approaching speed. Two scenarios that are in green with a strong reduction of speed as drivers moved from the clear zone to the transition zone, which shows that participants lowered their speed in the fog zone when the fog was denser. This trend is significant in the heavy fog situation. Then, drivers entered the deceleration state earlier with the CV-VSL compared with no warning (P = 0.045). They entered the fog area at a lower speed with the CV-VSL compared with no warning (P = 0.05). This conclusion illustrates the effectiveness of the CV-VSL application and the influence of fog once again.

Table 3 summarizes mean and standard deviation (SD) of several indicators with respect to the effectiveness of the different scenarios for the two groups. For instance, in the fog zone with the CV-VSL application, the $Proportion_{limit}$ for heavy fog increased 0.24 (67 percent)

compared with the absence of a warning, and the $N_{speeding}$ decreased 19 (58 percent) compared with the absence of a warning. The most important changes in the indicators were found to be associated with the $Proportion_{fog}$; the $Proportion_{fog}$ for heavy fog increased 0.6 (20 percent) compared with the absence of a warning. The results show that the CV-VSL application could improve driving alertness (e.g., high $Proportion_{limit}$) and safety awareness (e.g., less frequency of speeding). In this study, one-way ANOVA is used to analyze single factor analysis. The test results are provided in Table 3.

Figs. 6–8 show the difference between two groups in different fog levels. A one-way ANOVA model was employed to calculate whether the observed differences in growth were statistically significant. For all experiments, a P-value < 0.05 was considered significant. The analysis included three aspects corresponding to the three zones.

4.1. The effectiveness of the CV-VSL application in the clear zone

Fig. 6 shows the comparison results for the variables $Proportion_{limit}$ and V_{end} in the clear zone. When it comes to the effectiveness of group 2 ($Proportion_{limit}$), presence of the CV-VSL application was significant at a confidence level of 99 percent in both light (F(1,0.008) = 23.02, P = 0.000 < 0.01) and heavy fog (F(1,0.156) = 6.88, P = 0.001 < 0.01) conditions. The $Proportion_{limit}$ was higher with the CV-VSL application warning in both light and heavy fog conditions, and the $N_{speeding}$ was less with the CV-VSL application warning in all levels of fog (Table 3). These results show that drivers adjusted their speed according to the CV-VSL application warning, indicating that Group 2 showed the effectiveness of the speeding warning in the clear zone. As for the effectiveness of Group 3 (V_{end}), the significance was the same as Group 2 in light (F(1,0.064) = 63.36, P = 0.000 < 0.001) and heavy fog (F(1,0.374) = 31.58, P = 0.000 < 0.01) conditions. The drivers reduced their speed before entering the transition zone if a CV-VSL application warning was present, and the result showed Group 3 was effective at altering speeds in the clear zone.

Furthermore, it was found that the effectiveness of the CV-VSL

Table 3
Mean and Standard Deviation (SD) of the Indicators.

Zone	Fog level	Group	Indicator	With VSL		Without VSL		P-value
				Mean	SD	Mean	SD	
Clear zone	No fog	2	$Proportion_{limit}$	0.12	0.09	0.14	0.07	0.784
			$N_{speeding}$	0		1		0.684
	Light fog	2	$Proportion_{limit}$	0.2	0.09	0.06	0.06	0.003[**]
			$N_{speeding}$	0		6		0.068
		3	V_{end}	85	17	106	14	0.009[**]
	Heavy fog	2	$Proportion_{limit}$	0.20	0.11	0.11	0.06	0.007[**]
			$N_{speeding}$	0		1		0.078
		3	V_{end}	62	7	78	16	0.006[**]
Transition zone	No fog	2	$Proportion_{limit}$	0.09	0.08	0.08	0.06	0.652
			$N_{speeding}$	0		5		0.775
	Light fog	2	$Proportion_{limit}$	0.18	0.12	0.05	0.09	0.004[**]
			$N_{speeding}$	0		8		0.748
		3	a_{max}	−0.81	0.86	−0.76	0.87	0.065
	Heavy fog	2	$Proportion_{limit}$	0.41	0.12	0.37	0.12	0.042[*]
			$N_{speeding}$	0		0		0.221
		3	a_{max}	−0.45	0.52	−0.39	0.26	0.033[*]
Fog zone	No fog	2	$Proportion_{limit}$	0.12	0.10	0.11	0.08	0.067
			$N_{speeding}$	4		8		0.254
	Light fog	2	$Proportion_{limit}$	0.01	0.04	0.001	0.01	0.005[**]
			$N_{speeding}$	0		7		0.089
		3	$Proportion_{fog}$	0.09	0.04	0.01	0.02	0.058
	Heavy fog	2	$Proportion_{limit}$	0.35	0.13	0.11	0.17	0.006[**]
			$N_{speeding}$	14		33		0.889
		3	$Proportion_{fog}$	0.36	0.14	0.30	0.11	0.043[*]

[*] $p < 0.05$.
[**] $p < 0.001$.

application in both light and heavy fog conditions were significant at a confidence level of 99 percent in the $Proportion_{limit}$ and V_{end} in the clear zone. As the visibility decreased, the V_{end} was significantly reduced. The magnitude of reduction was greater in heavy fog with the CV-VSL application; therefore the CV-VSL application appeared more effective in heavy fog conditions than in light fog conditions.

4.2. The effectiveness of the CV-VSL application in the transition zone

Fig. 7 shows the compared results for the variables $Proportion_{limit}$ and a_{max} in the transition zone. When it comes to the effectiveness of Group 2 ($Proportion_{limit}$), similar to the clear zone, the variables showed significance in both light ($F(1,1.126) = 106.15$, $P = 0.000 < 0.01$) and heavy fog ($F(1,0.001) = 5.59$, $P = 0.004 < 0.01$) conditions. Group 2 showed effectiveness of a speeding warning in the transition zone. As for the effectiveness of Group 3 (a_{max}), the presence of the CV-VSL application was significant at a confidence level of 95 percent in

heavy fog conditions ($F(1,1.107) = 3.70$, $P = 0.025 < 0.05$). The results indicated that drivers would decelerate more rapidly in the transition zone if they drove with the CV-VSL warning; the results showed Group 3 was effective at altering speed in the transition zone. When the authors compared the effectiveness of the CV-VSL application in the different foggy conditions, it was found that the effectiveness of the CV-VSL application in both light and heavy fog conditions was significant at a confidence level of 99 percent in the $Proportion_{limit}$ and a_{max} in the transition zone. Otherwise, as the visibility decreased, the Standard deviation of a_{max} was significantly reduced. The magnitude of reduction was greater in heavy fog with the CV-VSL application; therefore the CV-VSL application appeared more effective in heavy fog conditions than in light fog conditions.

4.3. The effectiveness of the CV-VSL application in the fog zone

Fig. 8 shows the compared results for variables $Proportion_{limit}$ and

The mean of indicators in the clear zone
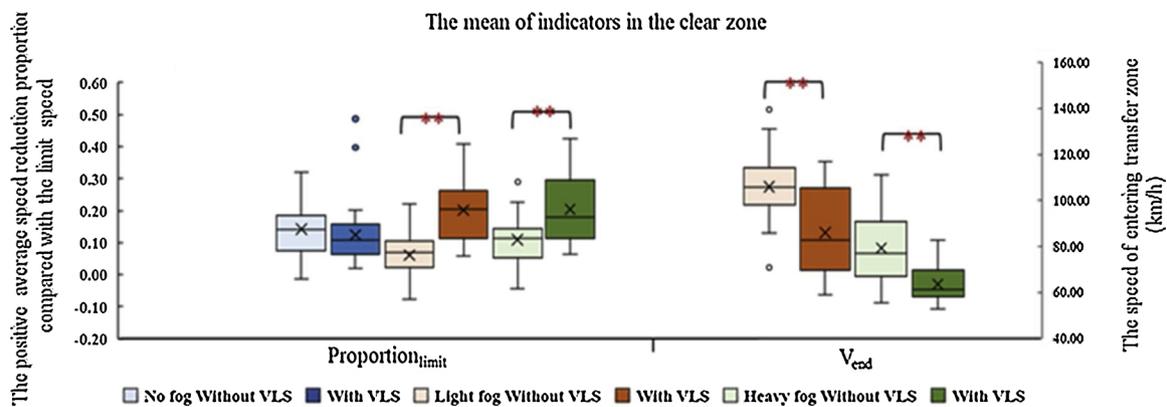
* Significant at the 95% confidence level; ** Significant at the 99% confidence level.

Fig. 6. Mean of indicators in the clear zone.

The mean of indicators in the transition zone

* Significant at the 95% confidence level; ** Significant at the 99% confidence level.
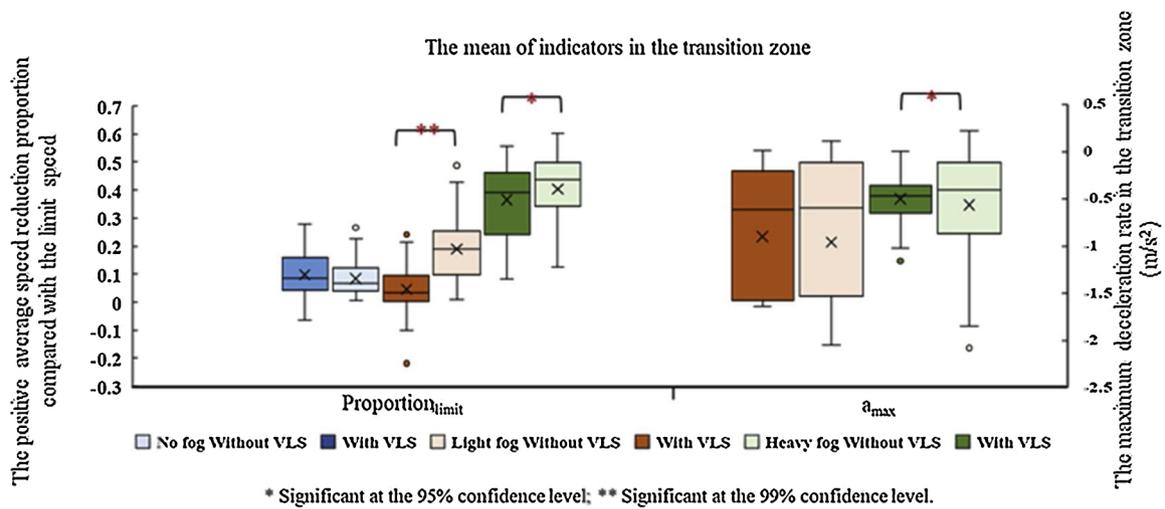
Fig. 7. Mean of indicators in the transition zone.

Proportion$_{fog}$ in the fog zone. Still, in Group 2, the variables were significant in both light ($F(1,0.128) = 4.76$, $P = 0.009 < 0.01$) and heavy fog ($F(1,23.5) = 74.02$, $P = 0.000 < 0.01$) conditions. Group 2 also showed the effectiveness in speeding warnings in the fog zone. When it comes to the effectiveness of Group 3, similar to the transition, the variables were significant in heavy fog conditions. The Proportion$_{fog}$ was higher with the CV-VSL application warning in heavy fog conditions, revealing that drivers were more likely to reduce their speed when a warning is present with heavy fog, and the results showed that Group 3 was effective at reducing speed in the fog zone. The presence of the CV-VSL application was significant at a confidence level of 95 percent in heavy fog conditions ($F(1,2.407) = 5.70$, $P = 0.045 < 0.05$). Moreover, similar to the clear and transition zones, it was found that the effectiveness of the CV-VSL application in both light and heavy fog conditions were significant at a confidence level of 99 percent in the Proportion$_{limit}$ and Proportion$_{fog}$ in the fog zone. The CV-VSL application in heavy fog conditions was more effective than in light fog conditions.

5. Discussion and conclusions

Driving in foggy conditions is a potentially dangerous activity, especially when fog appears suddenly. The CV-VSL application can deliver warning messages to individual drivers and help them improve their decisions in conditions of reduced visibility. Studies have been conducted to evaluate the effectiveness of the CV-VSL application. However, most have only focused on particular driving scenarios and have only analyzed drivers' speed adjustment when they were already in foggy conditions. The effects of several CV-VSL application settings under different conditions should be systematically analyzed, based on a reliable connected vehicle testing platform. Therefore, this research is intended to evaluate the effectiveness of the CV-VSL application in foggy conditions by exploring drivers' reactions to several groups of warning devices.

Actually, the analysis of driving behavior in the fog scenario is different with normal situation, because the change of visibility. Before entering the fog area, the driver receives warning information about the change of visibility. With the change of visibility, the driver showed different driving behavior. In the previous studies, the analysis zone was always divided for studying the effectiveness of systems in different situations (Wu et al., 2018a,b). This method also suit for the analysis of this research; this research established an effective connected vehicle system testing platform, and the drivers' speed adjustments after receiving warning messages were analyzed in different zones with different visibility levels (i.e., clear zone, transition zone, and fog zone). The driver behavioral characteristics of each zone are explored clearly. For the three zones, three different safety indexes were used for two groups (with and without the CV-VSL application). As for Group 2, Proportion$_{limit}$ and N$_{speeding}$ were used in all zones. For Group 3, the indicator in the clear zone was V$_{end}$; in the transition zone it was a$_{max}$;
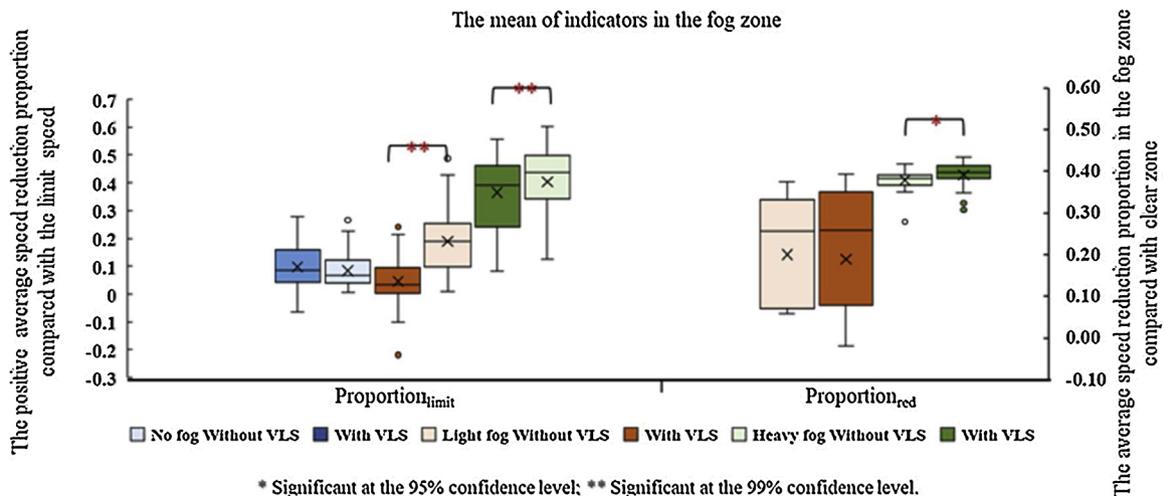
The mean of indicators in the fog zone

* Significant at the 95% confidence level; ** Significant at the 99% confidence level.

Fig. 8. Mean of indicators in the fog zone.

and in the fog zone it was Proportion$_{fog}$; these indicators were evaluated in the analysis. In particular, the V$_{end}$ in the clear zone represented whether drivers prepared for the upcoming fog, the a$_{max}$ in the transition zone indicated the driver's aggressiveness of speed adjustment with gradually reduced visibility, and the Proportion$_{fog}$ denoted a driver's final speed choice for the fog.

The results of the driving simulator experiment are consistent with real-world observations, indicating the reasonableness of the experiment. According to the results, Group 2 showed the effectiveness of speeding warnings in all zones. Moreover, the CV-VSL application could be beneficial for Group 3 in terms of speed reduction before entering the transition zone. It guided drivers' braking decisions at the initial section of reduced visibility. Similarly, it led to a considerable influence on the speed reduction proportion in the heavy fog zone. In addition, the study found that drivers' speed adjustments were also affected by visibility levels. Drivers were more likely to reduce their speeds or brake harder when the fog became heavier. Furthermore, it was found that the effectiveness of the CV-VSL application in both light and heavy fog conditions were significant at a confidence level of 99 percent in Groups 2 and 3. The results showed that the CV-VSL application in heavy fog conditions was more effective than in light fog conditions and reduce the accident risk, this result was same as the study by Soriguera et al. (2013) demonstrated the effectiveness of CV-VSL in reducing crash risk.

In this study, the effectiveness of the CV-VSL application under non-free flow conditions was not evaluated, so the relationship of driving behavior between Groups 1 and 4 was not analyzed. Moreover, this research only considered speed adjustments; other driving safety indicators (e.g., braking force, lateral placement, and turning angle of steering wheel) will be considered in future research.

This study evaluated the effectiveness of the CV-VSL application on drivers' speed adjustments in the different foggy conditions and different foggy zones. The results revealed that the CV-VSL application can help drivers manage their travel speeds before entering fog zones. Considering these results, the following recommendations are made to improve driving safety.

1 Enforcement of connected vehicle testing rules can enhance the development of connected vehicle applications. Specifically, the index system, a strict testing method definition, could improve driving safety in adverse weather conditions. Actually, the index system provided in this research can be used as a reference.
2 With a better understanding of drivers' speed adjustments in response to the CV-VSL application, more appropriate speed warning systems can be designed to enhance traffic safety when fog is present. Research on the effectiveness of the CV-VSL application in this research could be considered in the development of other connected vehicle applications and the design of human-machine interfaces (HMIs).
3 Field testing connected vehicle applications is expensive and limited. The connected vehicle testing platform in this research can be used as a primary research tool for analyzing drivers' reaction to connected vehicle applications under a wide variety of roadway, traffic and weather conditions.

A connected vehicle test platform is important for revealing the applicability and usefulness of connected vehicle applications based on the driving behavior. The main contribution of this research is to build the connected vehicle test platform based on the driving simulator using UDP and API technology. The effect of CV-VSL application was evaluated in the different foggy conditions, and the effectiveness of the application appeared to be different in the clear zone, transition zone, and fog zone.

In this study, the variable speed limit of the fog area refers to the relevant provisions in the actual situation (China Standardization Administration, 2012). When drivers enter the fog zone, the HMI will warn them about the speed limit, and the speed limit is not different between the reality and the simulation. In this study, we can see that the CV-VSL application has the effectiveness of warning the dangers and controlling speed. Because under the CV-VSL environment, the vehicle is expected to know the positions of the surrounding vehicles, therefore, relative smaller gaps are needed under the CV-VSL conditions. In that case, the speed limit under the CV-VSL environment can be different. Therefore, in the future study, we will analyze how different speed limits influence the driving behavior.

Then, in this study, we only analyzed the two situations of the CV-VSL (no warning vs. CV). However, it is necessary to add another level in the warning type variable (i.e. level 1: no warning; level 2: VSL signs; 3: CV). Therefore, in the future research, we will compare the effects between VSL sign and CV based on driving behavior.

In this study, the "frequency of speeding violations" was used as an indicator to test the driver's awareness of speed limit. However, the "duration of speeding violations" also can be used for evaluating the driver's awareness of speeding, and it is a great indicator for evaluating the effect of the HMI. Therefore, in the future study, both the "frequency of speeding violations" and "duration of speeding violations" will be used as indicators for evaluating the effect of the HMI.

In the future research, the effectiveness of several connected vehicle applications can be tested. This platform demonstrated good performance in exploring the effectiveness of connected vehicle applications based on driving behavior. In addition, additional adverse weather conditions (e.g., rain and snow) will be considered in future research. In the future, the connected vehicle testing platforms is a useful tool for analyzing the effectiveness of connected vehicle applications. Crash risks can be lessened by incorporating drivers' characteristics into the warning systems, ultimately improving traffic safety in adverse weather conditions.

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