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Evaluation of cooperative systems on driver behavior in heavy fog condition based on a driving simulator

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ABSTRACT

This paper studies the effectiveness of fog warning systems on driving performance and traffic safety in heavy fog condition. A comparison study was conducted for four scenarios in heavy fog condition. First, a series of indexes corresponding to driving speed adjustments and surrogate measures of safety was obtained to explore the impacts that fog warning systems have on driving behavior and traffic safety when approaching a fog area. This study divided the analyzed road into three different zones (clear zone, transition zone, and fog zone) according to visibility levels. Then, multivariate analysis of variance (MANOVA) was conducted, and the effects of drivers' individual characteristics on driving behavior were also investigated. Moreover, the linear mixed model with random effects was estimated to consider the contributing factors of the drivers' speed adjustment behaviors. In addition, the standard deviation of speed, TET (time exposed time-to-collision), and TIT (time integrated time-to-collision) were selected to evaluate the longitudinal safety. To obtain the driving data, an empirical driving simulator platform was established based on a real-world road in Beijing. Thirty-five drivers were recruited to participate in the driving experiment. The results showed that the cooperative vehicle-infrastructure warning systems could be beneficial to better driving behavior and safer traffic operations. The results revealed that the warning systems could be beneficial to speed reduction before entering a fog area. In addition, the On-Board Unit (OBU) had a significant impact on individual speed adjustment. Moreover, the results showed that scenarios with fog warning systems improve safety significantly over the no warning system scenario. The study results could also facilitate the selection of a proper information release format in the context of connected vehicles.

1. Introduction

Fog is formed by the condensation of a large amount of water vapor in the near-surface air. A foggy area on a road will reduce a driver's visibility. The visible distance is an important indicator for the driver to judge the needed operation. The visibility reduction caused by heavy fog is the main factor affecting the efficiency of traffic operations and traffic crashes. According to the annual traffic statistics of road traffic crashes issued by the Ministry of Public Security of China from 2004 to 2014, 10% of the total number of crashes during adverse weather conditions (rain, fog, snow, strong wind, etc.) occurred under foggy conditions. The number of crashes ranked second, and the crashes caused by heavy fog were the most serious (Ding et al., 2010). For example, a fog-related crash with a 60-vehicle pileup occurred on the Shenhai Freeway in the Yancheng Development Zone on June 5, 2013. This crash caused 11 deaths and more than 30 injuries, five of which were serious (Yang, 2014). Therefore, it is necessary to solve the traffic safety problems in a fog area. A fog zone warning system that provides alerts about the fog location and appropriate speed limit helps driver to adjust speed before entering the fog zone. With the development of connected vehicles, drivers can obtain fog warning information through vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications. However, there have been few studies on the effect of these fog warning systems on driving behavior and traffic safety. Therefore, studies evaluating the effect of warning systems on driving behavior and traffic safety under foggy conditions need further investigation.

The impact of visibility reduction on driving behavior (car-following, lane-changing, and speed adjustments) is an important basis for

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studying the design of fog traffic management systems and safety early warning strategies (Brooks et al., 2011; Broughton et al., 2007; Hassan and Abdel-Aty, 2011). Among them, speed reduction is the most typical adjustment to reduce the risk of crashes when approaching a foggy area (Hamdar et al., 2016; Qin and Hamdar, 2013; Wu et al., 2017). Moreover, the results of previous stdudies showed that speed and headway decreased significantly, and the standard deviation of speed and headway increased under reduced visibility condition (Peng et al., 2017). Furthermore, the collection of driving behavior data under bad weather conditions is mainly obtained by driving simulation experiments. For example, Yue et al. (2018) have utilized a driving simulator to analyze the effect of the forward collision warning (FCW) system on driver behavior under foggy condition. It is found that FCW system could reduce near-crash events by 35% under foggy condition. Yan et al. (2008) verified the relative effectiveness of driving simulators in studying traffic safety by comparing the similarities between driving behaviors in the driving simulator and the field data. Saffarian et al. (2012) studied the speed control behavior of drivers with different social attributes and in different visibility fog areas through driving simulation experiments. Mueller and Trick (2012) used driving simulation technology to analyze the average speed of different experienced drivers before and after entering a fog area. The average speed of the professional drivers and novice drivers in a heavy fog area is basically the same. Nevertheless, in the clear area ahead of the fog area, the average driver speed of the professional drivers is higher than that of the novice drivers. Trick et al. (2009) obtained the speed data of drivers of different ages in foggy conditions using driving simulator studies. The results showed that the experienced drivers reduced the speed in the fog area, while novice drivers rarely reduced the speed and the driving risk was high. Although the driver will make speed adjustment maneuvers when approaching a low-visibility fog area, studies have shown that the stopping distance is insufficient (Li et al., 2014; Peng et al., 2017), especially when you are in a dangerous situation (i.e., the car suddenly decelerates or an accident occurs in front of the driver).

There has been plenty of studies based on real data and driving simulators to gain a better understanding on how driver errors could occur and to find effective ways that can improve driving safety and driver performance under various circumstances (Hamdar et al., 2016; Qin et al., 2019; Qin and Hamdar, 2015; Yan et al., 2018). Using a driving simulator to simulate foggy weather and focus on driving behavior and driving safety started to gain more attention in the research community. In particular, Wu et al. (2018a) analyzed the influence of dynamic message signs (DMSs) on driver's brake pedal behavior through driving simulation data. The research results show that the DMS helps the driver adjust the speed and has a significant influence on the driver's braking behavior during the first portion of driving the experimental road. Wu et al. (2018b) used the driving simulator to evaluate vehicle-based communication technology. The results showed that early warning systems in foggy conditions can reduce the driver's reaction time and the probability of rear-end crashes. Along with that, an algorithm for the assessment of rear-end collision risk under foggy conditions was also developed based on real-time data (Wu et al., 2018c). Meanwhile, a micro-level approach was used to evaluate the effectiveness of the connected vehicle technologies in fog condition using microsimulation software VISSIM (Rahman and Abdel-Aty, 2018). Although previous studies have begun to focus on the impact of different fog warning systems on driver behavior, most of the research has focused on specific driving scenarios and fog areas (single warning systems or only considering fog concentrations).

A great deal of attention has been given to the development of cooperative driving of both connected vehicles and autonomous vehicles (Aliedani and Loke, 2018; Andersen et al., 2017; Baber et al., 2005; Chang et al., 2019; Mousavi et al., 2015; Walch et al., 2016; Zhou et al., 2017). Based on an on-road experiment, a general theoretical support for safe decision-making of automated driving systems have been proposed regarding different driving situations (Yan et al., 2017). However, this study did not consider how weather conditions would affect the choice of driving mode for a driving automation system. There is still a lack of systematic analysis of the effects of different types of warning systems on driving behavior. Moreover, how fog warning systems could improve driving safety through shared weather information with cooperative systems remains unclear. This study aims to evaluate the influence of different fog warning systems on speed adjustment behavior and traffic safety in fog based on driving experiment in a driving simulator.

2. Methods

2.1. Subjects

According to Central Limit Theorem, if the sums of random variables are normally distributed, a large sample size obtained from those variables also fits a normal distribution. In addition, a sample size not less than 30 is a commonly applied rule and is often used in driving simulator experiments (Cai et al., 2018; Maddala and Lahiri, 1992; Wu et al., 2016; Zhao et al., 2018). For example, Farah and Koutsopoulos (2014) used 35 test drivers to study the effect of cooperative infrastructure-to-vehicle systems on driver behavior. Saffarian et al. (2012) used 27 test drivers to study the car-following behavior in foggy conditions. A study focusing on the overall impact of the in-vehicle intersection crossing information display system (i.e., in-vehicle CICAS-SSA) on rural intersection crossing performance and age-related effects was performed with 32 participants (16 older drivers and 16 younger drivers) (Becic et al., 2018). A study evaluating the effects of cruise control and adaptive cruise control on driving behavior was performed with 31 participants (Schleicher and Gelau, 2011). Accordingly, a total of 40 participants were recruited in this study, however, only 35 participants' data were valid and analyzed in this study.

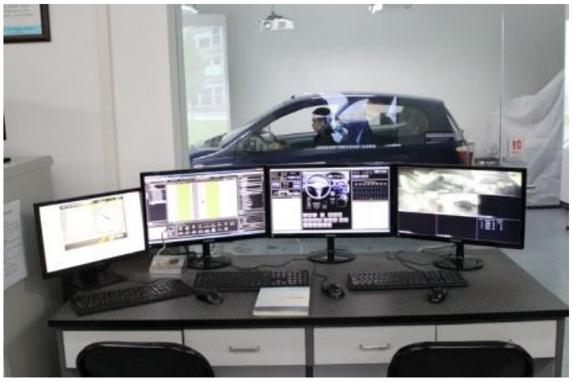
Based on the distribution of ages and driving experience of licensed drivers in China (Mps, 2017), participants in this study were distributed into two age groups and two driving experience groups as detailed in Table 1. The experienced drivers with professional driving skills (driving experience > 10 years, average of 15 years driving experience) were recruited from a driving service company in Beijing. The non professional drivers (driving experience < 10 years, average of five years driving experience) were staff and students recruited from the university. All participants had no crashes in the past 10 years and no more than 12 demerit points for speeding in the past three years. The entire experiment lasted for about one hour for each participant, including filling out the questionanires and trying out test drive before the actual experiment. All the drivers agreed and signed an informed consent form before participating in the study, and they were paid RMB 800 after completing the experiment.

2.2. Apparatus

A fixed-based driving simulator in the Key Laboratory of Traffic Engineering at Beijing University of Technology (BJUT) (see Fig. 1a) was used to conduct the driving experiment. The virtual scenarios were projected onto three large screens, providing a 130° horizontal viewing range. In this paper, the interoperability between the On-Board Unit

Table 1
Subjects' overall demographic characteristics.

Gender	Age groups		Driving experience groups	
	age < 45	age ≥ 45	Novice (driving experience < 10 years)	Experienced (driving experience > 10 years)
Male	11	12	4	19
Female	11	1	11	1



a) The driving simulator platform at BJUT

b) The Experimental driving simulator with OBU interface

Fig. 1. Driving simulator.
a) The driving simulator platform at BJUT.
b) The Experimental driving simulator with OBU interface.

(OBU) and the driving simulator was designed to simulate the connected vehicle environment, allowing drivers to cooperatively cope with changing visibility conditions in the experiment. Throughout this study, the simulator vehicle driven by subjects will be called as subject vehicle, and vehicle immediately ahead of the subject vehicle in the artificial environment is called as a lead vehicle. The functions of the OBU starts to record the speed and distance of the lead vehicle when the distance between the subject vehicle and the lead vehicle is less than 250 m. Furthermore, the lead vehicle was programmed to follow a certain speed profile and a car-following model (the intelligent driver model, IDM) is selected to regulate the driving behavior of other vehicles in the scenario of the driving simulator. The acceleration ($\dot{v}_{IDM}$) is expressed as follows (Talebpour and Mahmassani, 2016):

$$\dot{v}_{IDM}(t + t_a) = \max\left\{b_m, a_m\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*}{s}\right)^2\right]\right\} \tag{1}$$

$$s^* = s_0 + \max\left[0, vT + \frac{v\Delta v}{2\sqrt{a_m b}}\right] \tag{2}$$

where, t_a = the perception-reaction time, b_m = the maximum deceleration, a_m = the maximum acceleration, v = the speed of the following vehicle, v_0 = the desired speed, δ = the acceleration exponent, s = the gap distance between two vehicles, s_0 = the minimum gap distance at standstill, T = the safe time headway, and b = the desired deceleration.

The parameters of the IDM are presented in Table 2.

The OBU also has an acoustic unit in different warning modes about the speed limit of and the distance to the fog zone. The text warning messages were presented through the human machine interface of the OBU at the lower left side of the middle screen, which would not obstruct the drivers' view (see Fig. 1b). All experimental data were collected at a frequency of 20 Hz.

Table 2
Model parameters for the car-following model of IDM (Talebpour and Mahmassani, 2016).

IDM parameters	Lead Vehicle
t_a	1 s
b_m	2 m/s^2
a_m	4 m/s^2
v_0	33.33 m/s
δ	4
s_0	2 m
T	1 s
b	2 m/s^2

2.3. Scenarios

The experimental road was created according to the Xingyan Freeway which is located northwest of Beijing (see Fig. 2). The entire road in the experiment was a 5 km four-lane divided freeway with two lanes in each direction, and the width of each lane is 3.75 m. The traffic flow condition (density and speed) was kept constant during each experiment. In addition, three different zones along the test drive were considered, which were described as following:

1) Clear zone (2.5 km);
2) Transition zone (0.5 km); and
3) Fog zone (2 km).

To explore how a driver comprehends the message from these fog warning systems and perceives the environment when approaching a fog area, this study designed the experiment referred to a previous experimental design (Wu et al., 2018a). The scenarios were arranged using mixed factorial designs with four types of warnings, which were presented as following:

1) No warning: participants will not receive any warning about the coming fog condition;
2) OBU warning only: the warning message – Heavy fog 2 km ahead and the speed limit is 60 km/h, be careful! – will be displayed through OBU;
3) DMS warning only: the warning message – Heavy fog 2 km ahead, please be careful in Chinese – will be displayed through on-road DMS; and
4) OBU&DMS warnings: the warning message about the heavy fog will be displayed through both the OBU and the on-road DMS.

The same road geometry and layout were used for four different experiment situations in which the level of fog severity remains constant throughout the heavy fog zone. Within each experiment, a driver will encounter one of those four warning messages about the fog condition when approaching the heavy fog zone. According to the 'Grade of fog forecast' (GB/T 27964 – 2011, China), the visibility of heavy fog condition is less than 500 m and more than 200 m. In this study a visibility distance of 300 m was selected and the speed limit was 60 km/h under heavy fog conditions. A similar method was used to calibrate the fog visibility in the artificial environment (Brooks et al., 2011). Specifically, the visibility calibration procedure was presented as following:

1) In this experiment, seven drivers with normal vision were selected to participate in the calibration of the visibility distance of the fog condition.
2) On a road without any curve, a red vehicle is parked, the distance between the red vehicle and the subject vehicle was set to 300 m.
3) The visibility parameters are adjusted so that the participants can just see the outline of the red vehicle. Consequently, the values of this set of visibility parameter were recorded, representing a

Fig. 2. The study area.

condition in which the visibility distance is 300 m.

4) The average value of the parameter values obtained by the seven participants was taken as the parameter value to set the visibility of 300 m in the formal experiment.

Moreover, the visibility of the fog is increasing in the transition zone when approaching the heavy fog zone. The visibility at the end of the transition zone is 300 m. Using a 'setflag' function of the simulator, the visibilities of the 0.5 km transition areas (500 – 400 meters, 400 – 300 meters, 300 – 200 meters, 200 – 100 meters, 100-0 m) before entering the heavy fog zone are set to 3000 m, 2000 m, 1000 m, 800 m, and 500 m, respectively. Therefore, the fog level was increasing in the transition zone during the transition zone.

Regarding the positions of these freeway DMSs, they were placed according to the Chinese freeway design policy such that these gantries were visible to drivers in each experimental scenario. Fig. 3b illustrates the DMS scenario when drivers in the clear zone and was approaching the heavy fog zone. In the no warning and OBU only scenarios, a visual message (Welcome to Xingyan Freeway in Chinese) was displayed to drivers on the DMS board.

The sound of the OBU was delivered 2 km away before entering the heavy fog zone. The voice was spoken to the drivers: heavy fog will appear at 2 km ahead and the speed limit is 60 km/h, be careful! Meanwhile, the text content was displayed: heavy fog zone will appear at 2 km ahead, the speed limit is 60 km/h. The content is updated every 500 m before entering the fog area. After entering the fog area, the Chinese voice message of the OBU – you have entered the fog area, the speed limit is 60 km/h, and pay attention to safety driving was delivered to the driver. The text content – you have entered the fog area, speed limit 60 km/h in Chinese was displayed to drivers. In addition, the speed limit warning will always be updated. When the driver speeding, there will be a voice prompt and the overspeed warning sign will flash on the screen of the OBU. Before entering the fog area, the limit of the OBU is set to 120 km/h; after entering the fog zone, the speed limit is set to 60 km/h.

Fig. 3. Simulation scenarios.
a) Heavy fog.
b) Freeway DMS with an advisory message.

2.4. Procedures

Upon their arrival, drivers were first required to fill out a

Table 3
Ratings of subjective evaluation of the driving simulator.

	Steering wheel	Accelerator	Brake	Clutch	Gear	Speed perception
Mean	8.2	8.5	7.9	8.2	7.8	8.1
SD	1.10	1.20	1.50	1.25	1.20	1.40

questionnaire before the experiment to collect the demographic information (such as age, gender, driving experience,career, and so on). Next, a 10-minute simulator training session was provided to help the participants familiarize with the control of simulator and the fog warning systems. In order to ensure that all drivers understand these fog warning systems (BSU, DMS, and both BSU & DMS) but to avoid priming and experimental bias, we only introduced the function of the fog warning systems which was more like a product description. Moreover, we also designed the questions to verify that all of the drivers understand the messages of the fog warning systems. However, we did not interfere with the driver's use of the system.

After then training session, the validation of the simulator has been conducted through another questionnaire. The secondard questionnaire evaluated the realistic feelings of drivers' about the accelerator, brake, speed perception, and so forth. Table 3 (1-not real at all to 10-very real) shows the rating results. In fact, the validation of driving speed of this driving simulator has been tested through experiments in a real driving environment before conducting driving training in our driving simulator (Wu et al., 2018). Thus, based on the validation results of driving simulator and recognizing its advantage in driving behavior tests (for example, controlling influence factors, reconstructing driving scenes, and designing traffic incidents), this driving simulator appears to be a valuable research tool for driver behavior studies. Then, drivers will be assigned to four driving scenarios in a random sequence. Meanwhile, drivers were required to take an approximately 5-minute break between each scenario.

3. Driving behavior analysis

3.1. Overall analysis

To explore drivers' speed adjustment in heavy fog with various warning formats, the drivers' speed adjustment was divided into three parts, which were analyzed individually. Descriptive statistics were presented to show driving behaviors between various levels of the scenario variables. SPSS was used to test the statistical characteristics of the data. Before the descriptive statistics were analyzed, all data were subjected to the Kolmogorov-Smirnov test, the results indicated that the obtained data follow a normal distribution. Table 4 summarizes the overall statistics of different scenarios. The results showed that the average speed (Avg. Speed) and the standard deviation of speed (speed SD) in the transition zone without the warning systems are higher than those with the systems. However, 88.85 km/h was much higher than the speed limit in a heavy fog zone (60 km/h). This indicated that drivers have no time to slow down when approaching an upcoming fog area. The average speed was higher than in the other scenarios. The results revealed that the cooperative vehicle-infrastructure system could help drivers obtain information in advance. It was observed that drivers with the OBU warning system had a higher speed but did not exceed the speed limit based on the results from the fog zone. The results suggested that fog warning systems could help improve drives' operational efficiency. In particular, the OBU's optimization of individual behavior is more evident.

Fig. 4 illustrates the average speed in three zones with different warning types in heavy fog. The average speed is continuously reduced from the clear zone to the fog zone, and the subjects preferred to slow down when entering the fog zone. Moreover, the subjects would reduce their speed earlier with the warning system installed, which is consistent with the above discussion. In addition, the average speeds at the start of the clear zone are different. The reason for this result might be that the visibility is good enough to see the fog waring from the DMS, and drivers reduce their speed earlier. When the vehicle was installed with the OBU, drivers believed that the OBU will give the warning and won't reduce their speed before the OBU starting to be displayed. Thus, the average speed in the clear zone for DMS only scenario was much lower (about 7–8 km/h) compared to the OBU & DMS scenario.

3.2. Linear mixed model

A series of linear mixed models with random effects were used to estimate the contributing factors to the driver's speed adjustment maneuvers in heavy fog in this study. The linear mixed model is one of the mixed effects models that considers random effects that cannot be controlled in the experiment. Random effect models have been widely applied to account for the repeated observations of all participants in the experiment (Laird and Ware, 1982). Each participant performed four random scenarios, and all 140 (35 participants × 4 experiments) observations were repeated for the three different zones so that each participant had 12 repeated measurements (four observations for the different scenarios and three observations for the different zones). Therefore, the random effects method was applied to modify the relationship between measurements of the repeated observations for each

Table 4
Driving behavior descriptive statistics.

Warning types	Measures		Clear zone			Transition zone	Fog zone	
			0-500 m	500-1000 m	1000-1500 m	1500-2000 m	2000-2500 m	2500-3000 m
No warning	Avg. Speed (km/h)	Mean	**98.88**	**103.33**	**105.28**	**88.85**	53.54	44.81
		SD	3.49	2.42	2.62	**12.26**	7.42	3.91
	Avg. Acceleration (m/s^2)	Mean	0.11	0.05	−0.04	−0.43	−0.20	0.02
		SD	0.14	0.15	0.21	0.68	0.67	0.40
OBU only	Avg. Speed (km/h)	Mean	92.94	96.26	98.33	68.33	**56.15**	**54.71**
		SD	2.30	2.69	2.43	14.64	3.53	2.82
	Avg. Acceleration (m/s^2)	Mean	0.03	0.05	−0.01	−0.45	−0.04	−0.01
		SD	0.16	0.19	0.18	0.84	0.35	0.26
DMS only	Avg. Speed (km/h)	Mean	82.73	83.70	83.47	68.01	60.31	55.21
		SD	3.84	2.85	3.09	7.88	4.73	4.30
	Avg. Acceleration (m/s^2)	Mean	0.06	−0.01	−0.01	−0.22	−0.04	−0.04
		SD	0.23	0.27	0.22	0.60	0.42	0.44
OBU & DMS	Avg. Speed (km/h)	Mean	90.28	89.45	86.43	59.24	52.62	50.91
		SD	2.77	3.25	3.38	8.59	3.26	3.48
	Avg. Acceleration (m/s^2)	Mean	0.03	−0.06	−0.10	−0.25	−0.04	0.01
		SD	0.18	0.24	0.32	0.66	0.28	0.29

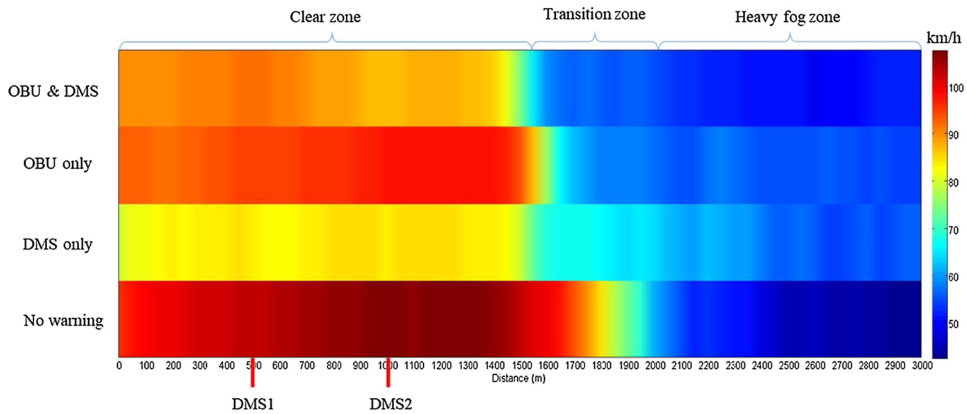


Fig. 4. Average speed (km/h) in heavy fog.

participant approaching the fog zone; the random effects were reflected by adding the μ_i to the linear regression model.

In this study, the linear mixed model is represented by:

$$y_{ijm} = \alpha_j + \beta_j X_{ijm} + \beta_j X_i + \mu_i + \xi_{ijm} \quad (3)$$

where, y_{ijm} = the response variable (Avg. Speed), i = the participant number from 1 to 35, j = the zone number from zone 1 to zone 3, m = the number of experiments for each participant from 1 to 4, β_j = a fixed vector consisting of the coefficients of the explanatory variables for zone j, X_{ijm} = the explanatory variables for driver behavior data (warning types), X_i = the explanatory variables for driver characteristics (age, gender and driving experience), α_j = the fixed intercept for each zone from 1 to 4, μ_i = the random intercept for each participant i, and ξ_{ijm} = the error terms.

Here, it is assumed that $\mu_i \sim (0, \sigma^2_{\text{int}})$, and that the residual $\xi_{ijm} \sim (0, \sigma^2_{res})$, where σ^2_{int} and σ^2_{res} are the variances of the random intercept and the residual, respectively. The models were established to estimate the effect of the scenario variables (warning systems), and the driver's characteristics on the driver's speed adjustment maneuvers when approaching the heavy fog zone. The backward elimination method was adopted for the variable selection and a set of variables that had a significant effect on the model was selected. Moreover, AIC (Akaike's information criterion), BIC (Schwarz's Bayesian criterion) and the adjusted coefficient of determination (R-squared) variables were used to choose the best model. Better models have a smaller AIC, a smaller BIC and a higher R-squared value. The *t*-test was used to test the significance of these indicators in different scenarios of drivers at the 95% confidence level. The results showed that there was a significant difference in speed between different warning types in heavy fog condition. This indicates that the average speed can be used as a comparison of the warning system performance. The linear mixed model of average speed was established and the results are shown in Table 5. The linear mixed model was estimated considering the interaction terms between warning types and other variables. Only a few interaction variables were found to be significant. The results showed that the effects of the sociodemographic characteristics on average speed were not significant compared with the effect of the warning systems.

3.3. Speed adjustment indexes

Foggy conditions reduce a driver's visibility. To have enough reaction time, drivers usually slow down before entering a fog area. Previous studies recommended the investigation of drivers' speed adjustment behavior when approaching the fog area. Driver's perception of the upcoming risk based on the level of the warning messages determines how they would adjust their speeds. Wu et al. (2018a) used the ending speed of the clear zone (v_{end}) to reflect how drivers were prepared for entering the fog area and used the proportion of average speed reduction in the fog zone compared with the clear zone (P_{redu}) to evaluate the final changes. The P_{red} is calculated in Eq. (2). The minimum acceleration of the transition zone (a_{min}) was usually employed to explore drivers' braking behavior when risky driving conditions occurred (Haque and Washington, 2015; Li et al., 2015; Zhang et al., 2015). In the fog zone, visibility will not change and drivers' speed should become stable. The beginning speed of the fog zone (v_{start}), the proportion of the drivers' speed lower than 60 km/h while entering the fog zone ($Pv_{fog<60}$) and the speed SD of the fog zone were used to evaluate the final speed adjustment in the fog zone. Therefore, data were analyzed for variables that represent the changes, including v_{end}, P_{red}, a_{min}, v_{start} and $Pv_{fog<60}$.

$$P_{redu} = \frac{v_{clear} - v_{fog}}{v_{clear}} \quad (4)$$

where, v_{clear} = the average speed of the clear zone and v_{fog} = the average speed of the fog zone.

Table 5
Average speed model.

Zone		Clear zone	Transition zone	Fog zone
		Estimate (p-value)	Estimate (p-value)	Estimate (p-value)
Intercept		100.495 (.000)		
Warning types	OBU only (vs No warning)	−13.776 (.000)	29.611 (.000)	2.589(.068)
	DMS only (vs No warning)	−5.791 (.002)	9.084 (.001)	6.261 (.000)
	OBU & DMS (vs No warning)	−19.192 (.000)	8.771 (.001)	8.587 (.000)
Gender	Male (vs Female)	–	–	−3.301.587 (.029)
Age	age < 45 (vs age ≥45)	–	–	0.221 (.858)
Driving experience	Experienced (vs Novice)	–	–	2.808 (.072)
Variance of random intercept (μ_i)		1.264 (.000)		
Variance of residual (ξ_{ij})		7.768 (.000)		
Goodness of fit measures		AIC = 3158.843, BIC = 3168.894, and adjusted R-squared = 0.695		

Table 6
Summary of speed adjustment indexes.

Indexes	Warning systems			
	No warning	OBU only	DMS only	OBU & DMS
v_{end} (km/h)	102.48 (SD = 10.51)	94.55 (SD = 12.33)	79.11 (SD = 14.35)	74.35 (SD = 14.90)
a_{min} (m/s^2)	−1.89	−2.35	−1.53	−1.8
P_{redu}	0.52	0.42	0.31	0.41
v_{start} (km/h)	62.59 (SD = 17.03)	56.98 (SD = 6.46)	63.68 (SD = 8.94)	55.61 (SD = 5.23)
$Pv_{fog\,<\,60}$	0.6	**0.91**	0.6	**1**

Table 6 summarizes the results of the speed adjustment indexes of all drivers with different warning systems. The average v_{end} and v_{start} of drivers when driving with the fog warning systems were significantly lower than when driving without the systems. In addition, $Pv_{fog\,<\,60}$ was higher when driving with fog warning systems. The results indicate that the cooperative vehicle- infrastructure system with warning message in advance have positive impacts on driving speed adjustments. The effects were more significant when the OBU was on.

4. Longitudinal safety evaluation

4.1. Surrogate measures of safety

The causes of traffic crashes are complex and are related to human factors, vehicle performance, and weather conditions (Qin et al., 2019; Wang et al., 2006). Previous studies used surrogate measures to evaluate the crash risk, including speed variance, TTC (time-to-collision), and headway SD (Abdel-Aty et al., 2014, 2009; Gettman and Head, 2003; Oh et al., 2006; Rahman et al., 2018; So et al., 2015). According to Rahman and Abdel-Aty (Rahman and Abdel-Aty, 2018), two surrogate measures of safety, derived from TTC and denoted as time exposed time-to-collision (TET) and time integrated time-to-collision (TIT), can be also utilized to evaluate the longitudinal safety of the subject vehicle. In this study, TET and TIT were calculated instead of TTC. Thus, four safety surrogate measures were selected to evaluate the longitudinal safety, including speed SD, headway SD, TET (time exposed time-to-collision), and TIT (time integrated time-to-collision). The indexes TET and TIT are calculated as follows (Rahman and Abdel-Aty, 2018):

$$TET\,(\mathrm{t}) = \sum_{\mathrm{n}=1}^{\mathrm{N}} \delta_t \times \Delta t \delta_t = \begin{cases} 1, & 0 < TTC_{brake}(\mathrm{t}) \le TTC^* \\ 0, & otherwise \end{cases}, \tag{5}$$

$$TET = \sum_{t=1}^{T} TET\,(t) \tag{6}$$

$$TTC_{brake}(t) = \frac{x_{n-1}(t) - x_n(t) - L_{n-1}}{v_n(t)} \tag{7}$$

$$TIT\,(\mathrm{t}) = \sum_{\mathrm{n}=1}^{\mathrm{N}} [\frac{1}{TTC_{brake}(\mathrm{t})} - \frac{1}{TTC^*}]\bullet \Delta t\ 0 < TTC_{brake}(\mathrm{t}) \le TTC^*, \tag{8}$$

$$TIT = \sum_{t=1}^{T} TIT\,(t) \tag{9}$$

where Δt = the data collection frequency, which was 0.05 s in the simulation, N = the total number of vehicles, δ = the switching variable, t = the time ID, T = the simulation period, TTC^* = the threshold of TTC, $TTC_{brake}(t)$ = the TTC at braking, $x_{n-1}(t)$ = the position of the leading car, $x_n(t)$ = the position of the following car, L_{n-1} = the length of the leading car, which was 6 m in this study, and $v_n(t)$ = the speed of the following car.

4.2. Safety performances

Four surrogate measures of safety were considered to evaluate the safety performances of warning systems in each scenario. The TTC threshold was considered as 2 s for the preliminary analysis. Table 7 shows the comparison of safety surrogate measures of safety for subject vehicle in heavy fog zone. It can be seen from Table 7 that there was a significant difference in surrogate measures of safety between different cases. Table 8 illustrates the summary of four surrogate measures of safety, including speed SD, headway SD, TET, and TIT in three scenarios (the vehicle coordinates data of OBU & DMS scenario not collected due to the lack of data acquisition code). The results were consistent with recent studies (Peng et al., 2017; Rahman and Abdel-Aty, 2018). The results revealed that the standard deviation of headway increased in heavy fog conditions compared to clear conditions. Furthermore, compared to the base scenario (No warning), the standard deviation of headway decreased significantly in scenarios other warning systems. It was also found that the headway SD was higher for DMS only than OBU only. The OBU only scenario has the lowest TET and TIT in both zones. Though the DMSs were only equipped in the clear zone, the DMS only scenario had lower speed SD, headway SD, TET, and TIT than the no warning scenario in the fog zone. Thus, the OBU only scenario with real-time warning messages had the lowest level of longitudinal crash risk, while the no warning scenario had the highest level of crash risk.

The above results are mainly based on the same parameter setting of the TTC threshold (2 s). The sensitivity analyses were also conducted for different TTC thresholds: 1 s, 1.5 s, 2.0 s, 2.5 s, and 3.0 s. However, the values of the TTC threshold ranging from 1 to 3 s had almost the same results which are presented in Table 9. However, it was evident that the scenarios with warning systems significantly outperformed no warning systems in heavy fog.

5. Summaries and conclusions

The main goal of this study was to evaluate the effect of warning systems on driving behavior and traffic safety in heavy fog and in the context of connected vehicles. The driving simulation experiment was conducted to validate the proposed analysis framework. The experimental results revealed that warning systems had positive effects on speed adjustment behavior and traffic safety. It was found that the participants would reduce their speed when they were proceeding to a fog zone. Speed adjustment indexes of all scenarios were calculated. The results indicated that the warning systems would help the drivers prepare (speed adjustment) for the upcoming foggy condition. The

Table 7
Comparison of surrogate measures of safety for subject vehicle in heavy fog zone.

Comparisons	Mean difference (P-value)			
	speed SD	headway SD	TET	TIT
No warning vs OBU only	3.69 (< 0.01)	2.19 (< 0.01)	9.44 (< 0.01)	25.40 (< 0.01)
No warning vs DMS only	2.37 (< 0.01)	1.02 (< 0.01)	6.99 (< 0.01)	18.20 (< 0.01)
DMS only vs OBU only	1.03 (< 0.01)	0.59 (< 0.01)	4.72 (< 0.01)	8.39 (< 0.01)

Table 8
Summary statistics of standard deviation of speed, headway SD, *TET,* and *TIT*.

Foggy conditions	Warning types	Clear zone				Fog zone			
		Speed SD (km/h)	Headway SD (s)	TET (s)	TIT (s)	Speed SD (km/h)	Headway SD (s)	TET (s)	TIT (s)
Heavy fog	No warning	10.50	15.35	54.43	50.25	8.59	18.13	109.16	374.79
	OBU only	9.75	**8.68**	**47.83**	**31.62**	**2.60**	**10.03**	**62.37**	**97.23**
	DMS only	5.28	10.32	63.63	79.02	6.62	11.36	84.97	214.93

Table 9
Sensitivity analysis of different values of the TTC threshold.

TTC (s)	Scenarios Measures	Heavy fog					
		Nowarning		OBU only		DMS only	
		Clear zone	Fog zone	Clear zone	Fog zone	Clear zone	Fog zone
1	TET	33.57	106.68	27.06	55.73	46.69	69.47
	TIT	33.09	370.45	19.8	106.54	73.17	178.39
1.5	TET	45.9	107.21	38.02	63.68	52.84	74.56
	TIT	43.41	368.53	27.32	113.47	74.16	201.61
2	TET	54.43	109.16	47.83	62.37	63.63	84.97
	TIT	50.25	374.79	31.62	97.23	79.02	214.93
2.5	TET	57.75	113.56	54.47	61.77	69.85	89.3
	TIT	54.12	385.89	34.91	95.83	80.95	209.04
3	TET	59	116.41	57.11	66	80.44	86.78
	TIT	57.72	393.57	38.64	96.28	83.38	208.23

positive effects were more significant when the OBU was on. Based on the experimental data, MANOVA and the linear mixed model with random effects were estimated. The results suggested that the impacts of warning systems were significant for reducing the speed when approaching a fog area. In addition, it was suggested that, compared with the effects of warning messages, the effects of drivers' individual characteristics were not significant when adjusting the driving speed due to risk perception.

Overall, better driving performance and greater safety benefits could be achieved by providing fog warning information. In connected vehicle environments, drivers could obtain accurate messages through V2V or V2I communication. Equipments that could provide fog warning information could help drivers reduce rear-end crash risks under poor visibility conditions. Future studies can evaluate the effects of different systems and the design of the OBU and human interface on driving behavior considering the sociodemographic characteristics (gender, age, and driving experience). In addition, a microlevel traffic flow analysis can be investigated based on the calibration of the driving behavior parameters.

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