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Effects of foggy conditions on drivers' speed control behaviors at different risk levels

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ABSTRACT

Driving in foggy weather is a potentially dangerous activity that has been investigated using various approaches. However, most of the previous research has focused on the driver's response in a particular situation under foggy conditions and lacks a systematic analysis of driving performance, especially speed-related behaviors. This paper presents a hierarchical driving performance assessment method to investigate the effects of foggy conditions on drivers' speed control behaviors. With this method, driving behaviors were tested in three simulated driving scenarios classified into three risk levels: basic speed control while driving along road segments at a low risk level, dynamic speed adjustment in car-following situations at a medium risk level, and emergent speed responses to precrash situations at a high risk level. The driving simulation experiment results indicated that the drivers intended to reduce their speeds in order to lower the driving risk in foggy conditions at all three risk levels. However, due to the limited visibility in fog, the drivers could not observe and respond to impending changes in road geometries in a timely way, which resulted in higher operating speeds than in clear weather conditions. At the medium risk level, the drivers' dynamic speed adjustment behavior was degraded in the fog, with both acceleration and deceleration rates lower than in the clear conditions; therefore, more rear-end collisions happened in the foggy conditions than in the clear conditions. At the high risk level, the experiment results showed that drivers' speed compensation in foggy conditions does not sufficiently reduce their crash-involvement risk, but it can effectively lower the crash severity, as indicated by a significantly lower collision speed.

1. Introduction

Adverse weather conditions have significant impacts on visibility distance, driving behavior, vehicle performance, pavement conditions, travel demand, traffic flow characteristics, and traffic safety. According to statistics from 2010, 26.12% of the traffic accidents on highways in China happened in adverse weather, such as rain, snow and fog and 31.7% of the direct economic losses from accidents were caused in such weather (The Ministry of Public Security Traffic Administration, 2010). The effects of different weather conditions on traffic operation and safety have been paid much attention in the field of transportation research (Cools et al., 2008; Hassan and Barker, 1999; Keay and Simmonds, 2005).

Among the adverse weather conditions, fog is the most hazardous weather and the one that drivers most fear (Musk, 1991). Driving in fog can be risky for drivers of all abilities. From a visual perspective, fog can result in a reduction not only in visibility but also in the visual field. Visibility is critical to the task of driving. Low visibility can significantly reduce travel speeds and roadway capacity by up to 12% (US Department of Transportation, 2009). Compared to crashes under clear visibility conditions, fog-related crashes tend to result in more severe injuries and to be more likely to involve multiple vehicles (Abdel-Aty et al., 2011). Research on roadways in the UK (Moore and Cooper, 1972) reported that, despite a 20% decrease in the amount of traffic in heavy fog, there was a 16% increase in crashes causing personal injuries (Codling, 1971).

A number of previous studies have focused on how driving behaviors change due to foggy conditions (Hassan and Abdel-Aty, 2011; Ni et al., 2010; Brooks et al., 2011; Van Der hulst et al., 1998; Shrivastava et al., 2005). Broughton et al. (2007) and Kang et al. (2008) found that drivers had decreased car-following performance (failure to maintain following distance) under simulated

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foggy conditions. Klinjnhout (1991) reported that drivers would not slow down to a safe speed in fog if the environment misled them. In fog, the driver's brain translates vagueness as being far distant, and thus the driver will feel as though he/she is driving more slowly than normal. Some studies have investigated the effect of the human factor on driving behaviors in simulated fog. Ni et al. (2012) examined age-related differences in collision detection performance when the clarity of the driving scene was reduced by simulated fog. The results showed that under reduced visibility older drivers may have an increased crash risk due to a decreased ability to detect impending collision events. Mueller and Trick (2012) investigated the influence of driving experience on behavioral compensations for fog. It was found that experienced drivers drove faster than novice drivers under clear conditions but at the same speed as them under foggy conditions, indicating that the experienced drivers reduced their speed more than the novice drivers in decreased visibility. Besides this, compared to the experienced drivers, the novice drivers had higher hazard response times, greater speed and steering variability, and were more likely to be involved in collisions. Among all the adjustments to driving behavior corresponding to foggy conditions, changing speed is the most typical. Speed is a major contributing factor in many of the pile-up crashes that occur in foggy conditions (Edwards, 1998) and it is also an aspect of driving that can be altered in challenging situations to reduce the risk of collision.

Although quite a few previous studies have paid attention to drivers' speeds in foggy conditions, most have only focused on a particular driving scenario and there is a lack of systematic analysis of different speed-related situations graded according to risk level. Actually, drivers demonstrate different abilities when encountering situations of increasing difficulty and complexity. The situations that the drivers encounter and their response behaviors can be categorized into different risk levels according to the complexity of the driving environment and the probability of the driver being involved in a traffic accident. Safe driving performance involves the successful negotiation of different levels of risk. If a driving intervention factor, e.g. fog, is involved in the driving process, it may change driving behavior to different extents at different levels of risk.

In this paper, a hierarchical driving performance assessment concept, as shown in Fig. 1, is adopted to evaluate the effects of foggy conditions on drivers' speed control at different risk levels using a high-fidelity driving simulator. In this method, driving behavior is classified into three levels, namely basic speed control at a low crash risk level, dynamic speed adjustment in complex traffic environments at a medium risk level, and an emergent speed response to a precrash situation at a high risk level. Broadly, the low risk level corresponds to simple driving scenarios that only require basic vehicle control maneuvers according to the roadway alignment, such as speed control, braking, steering, staying in lane, and other vehicle control behaviors. The medium risk level corresponds to scenarios involving moderate risk and complex skills, such as car-following, overtaking, route choice in unfamiliar road networks, and the decision to stop or go when a traffic light changes to yellow or red, etc. Drivers in such scenarios need to make critical decisions that rely on the continuously successful negotiation of dynamic traffic situations and road features. For example, in the car-following scenario, drivers need to adjust their vehicle speed according to the status of the vehicle in front, and if the front vehicle makes a sudden deceleration but the driver in the following vehicle does not respond in time, a rear-end crash may occur. The high risk level corresponds to emergent traffic situations in which an immediate crash risk is present and drivers have to take emergency response actions to avoid the potential crash successfully. This involves such aspects as the drivers' awareness, response, acceleration, braking, and steering in the face of a traffic accident such as an angle collision, side-impact, jostling, or frontal crash. The proposed concept emphasizes that any intervention introduced into the driving process, such as fog, may influence driving speed performances systematically at all of the above risk levels. Thus, speed-related behaviors under different foggy conditions were investigated in this study, and controllable, repeatable, and safe driving simulation experiments with three levels of driving risk were designed and realized using a high-fidelity driving simulator.

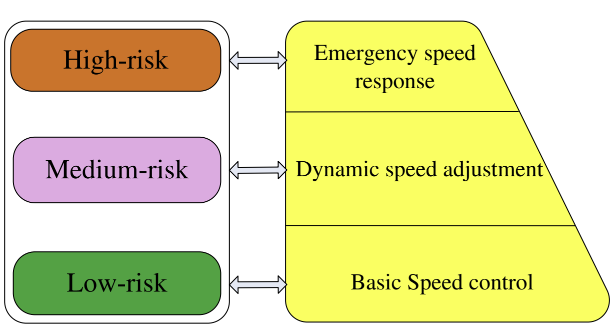


Fig. 1. Hierarchical diving behavior assessment concept.

2. Methodology

2.1. Subjects

The experiment was a 3 (foggy conditions) × 2 (genders) × 2 (professions) within-subject repeated measures design. A profession and gender balance was considered in case the drivers' characteristics should affect their driving behaviors. A total of 41 paid participants were recruited for this research: 19 professional drivers (11 male, 8 female) and 22 non-professional drivers (11 male, 11 female). The professional drivers selected for the experiment were full-time taxi drivers with an average mileage of 74.1 thousand kilometers per year and an average self-reported accident record of 6 per million kilometer. The non-professional drivers used their vehicles for the purpose of daily travel only. Their average mileage was 16.1 thousand kilometers per year, with an average self-reported accident record of 13 per million kilometer. The average age of the subjects was 33.6, ranging from 20 to 52 years old (S.D. = 9.9). Every participant held a valid driver's license of Beijing (China) and had at least two years of driving experience. The experiment lasted for about 30 min in total and each subject was paid 500 Chinese RMB (about 80 U.S. dollars) for their participation.

2.2. Apparatus

This study used the BJTU (Beijing Jiaotong University) driving simulator for the experiment and data collection, as shown in Fig. 2. Saluäär et al. (2000) proposed a scheme of classification of simulators as low-level, mid-level, and high-level. In the scheme, the low-level simulators are PC-based driving simulators. The mid-level simulators generally consist of a mockup automobile and projection screens connected with a personal computer for data collection and research. The high-level simulators are more advanced and sophisticated, and they may have a Stewart platform or hexapod for support of movement and orientation of the mounted automobile. According to the simulator classification scheme, the BJTU simulator is one between mid-level and high-level with shaking simulation system and a linear motion base capable of operating with 1 degree of freedom. It is composed of

Fig. 2. BJTU driving simulator cab.

full-size vehicle cabin (Ford Focus) with real operating interface, noise simulation system, digital video replay system, and vehicle dynamic simulation system. The simulated environment is projected at 300° of front/peripheral field view at a resolution of 1400 × 1050 pixels and on left, middle, and right mirrors. The software in the simulator lab is intended for driving scenario design, virtual traffic environment simulation, and virtual road modeling.

2.3. Scenario design

The design of the scenario was based on the classification of risk levels according to the aforementioned driving performance assessment concept. The road network for the driving simulation was composed of different test segments with different risk levels, which included segments testing basic speed control at the low risk level, segments testing dynamic speed adjustment at the medium risk level, and segments testing the emergent speed response to a precrash situation at the high risk level. The whole road network was a closed circular road consisting of two-way two-lane and two-way four-lane segments, and its total length was about 5.6 km (see Fig. 3). Along the test route, a subject would encounter all of the three risk-level scenarios. Each subject was assigned to drive along the test route three times, under no fog, light fog, and heavy fog respectively, as illustrated in Fig. 4. In order to counterbalance the effects of time order, the weather conditions were arranged in a random sequence. In the light fog and heavy fog scenarios, the visibility was 250 m and 50 m respectively.

2.3.1. Low-risk driving scenario design

The low-risk driving scenario was used to investigate the effect of foggy conditions on basic speed control behaviors in road segments with four different road alignments, namely straight, uphill and downhill (15° slope), and S-type continuous curve segments (see Fig. 5). The test road was two-way with two lanes and a lane width of 3.5 m. The speed limits were 80 km/h on the straight segment, 50 km/h on the uphill and downhill segments, and 30 km/h on the S-type curve segment. A free vehicle flow situation was arranged on the road to avoid interactions between the simulator and other vehicles.

2.3.2. Medium-risk driving scenario design

The medium-risk driving scenario (see Fig. 6) was designed to test the driver's speed adjustment behavior during a car-following situation in a high density of vehicle flow. This test was arranged on a straight two-way segment with four lanes and a speed limit of 80 km/h. Two platoons of vehicles stopped in the two driving lanes going in the simulator's direction, waiting for it to join the road, and then the vehicles would start, accelerate or decelerate once the proximity sensors were triggered. To ensure that the subjects' car-following behaviors could be observed, the highway design did not allow drivers to pass the leading vehicles in either the opposing- or same-direction lanes. During the car-following process, once the leading vehicle's speed had reached 30 km/h (from 0), the subjects' driving behaviors would be tested in two sequential stages:

- Stage 1 – accelerating car-following stage, during which the leading vehicle would accelerate at 1 m/s^2 from 30 km/h to 65 km/h, and then keep a constant speed of 65 km/h.
- Stage 2 – decelerating car-following stage, during which the leading vehicle would decelerate at 5 m/s^2 from 65 km/h to 10 km/h.

2.3.3. High-risk driving scenario design

The high-risk driving scenario was designed to investigate the subjects' speed change processes when reacting to a potential collision between the simulator and a pedestrian, as illustrated in Fig. 7. In the scenario, a roadside pedestrian suddenly ran across the road in front of the driving simulator at a speed of 15 km/h and the distance between the pedestrian's starting point and the conflict point (the centerline of the driving lane) was 15 m. The time it took the pedestrian to run from the side of the road to

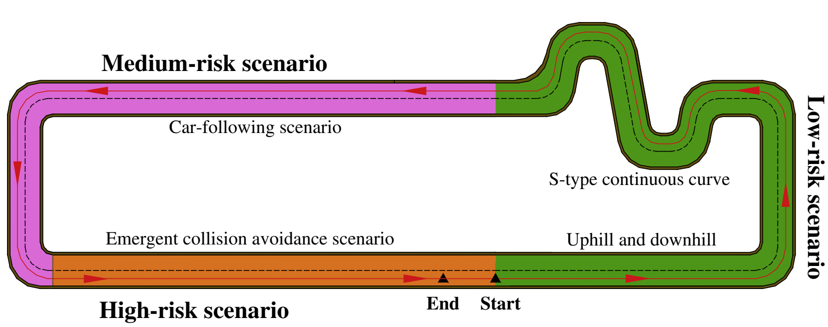
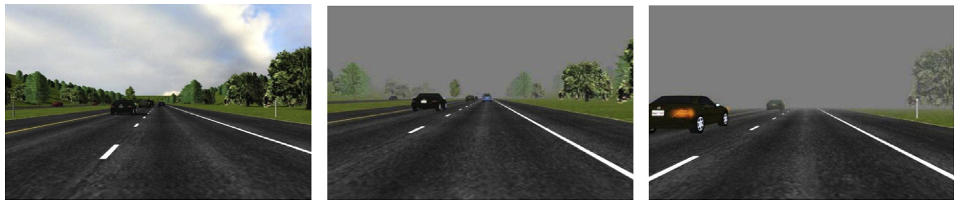
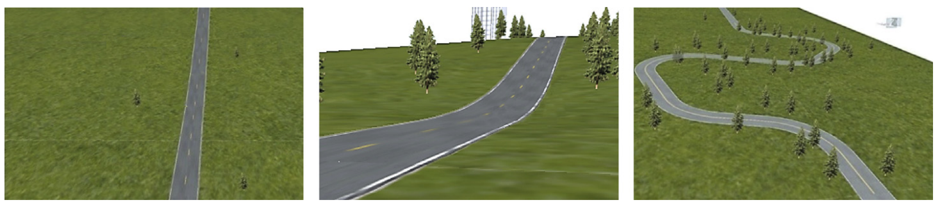


Fig. 3. The experiment road network.



(a) No fog (b) Light fog (c) Heavy fog

Fig. 4. The 3 kinds of weather conditions.



(a) Straight segment (b) Uphill and downhill (c) S-type continuous curve

Fig. 5. Testing roads of the low-risk scenario.

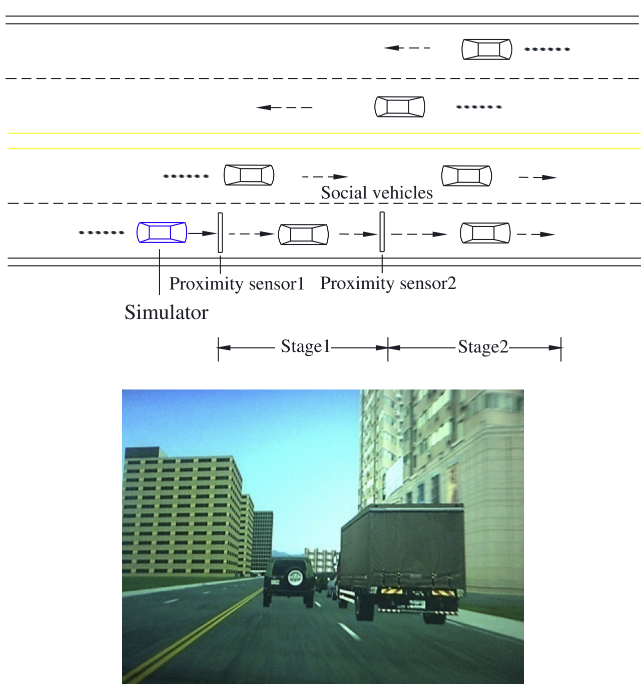


Fig. 6. The medium-risk driving scenario.

the conflict point was 3.5 s. The emergent event was triggered through the TTC (time to collision) sensor in this scenario. The TTC is one of the most widely used safety indicators and a surrogate measure of crash risk, especially in collision avoidance studies using a driving simulator (Bella and Russo, 2011; Gelau et al., 2011; Leung and Starmer, 2005). In this study, TTC is defined as the time required for two vehicles to collide if they continue at their present speeds along their presumed paths. The TTC sensor in this experiment was used to trigger the pedestrian's movement once the time from the simulator to the conflict point reached 3.5 s. Then, if the subject kept to a steady speed as they approached the conflict point, a collision would happen at the conflict point between the simulator and the pedestrian. The speed limit on this road segment was 80 km/h.

2.4. Experiment procedure

Upon arrival, each subject was briefed on the requirements of the experiment and all read and signed an informed consent form (per IRB). The subjects were then advised to drive and behave as they normally would and to adhere to traffic laws as they would in real-life situations. The subjects were also notified that they could quit the experiment at any time in case of motion sickness or any kind of discomfort. The subjects would still obtain at least half of the payment for their participation even if they did not complete the experiment. Prior to the formal experiment, the subjects were trained for at least 10 min to familiarize them with the operation of the driving simulator. In this practice session, the subjects exercised selected maneuvers including straight driving, acceleration, deceleration, left/right turn, and other basic driving behaviors. Next, the subjects performed the formal experiments with the three weather conditions (clear, light fog, and heavy fog) occurring in a random sequence so as to eliminate the effect of the order. For security and liability reasons, each subject was escorted to the simulator cabin to commence the experiment, and rested for at least 5 min between the three rounds of tests.

3. Experiment results

During the experiment, simulator data were sampled at 10 Hz. The original experiment dataset included the real-time information about the simulator, the assigned ambient vehicles, and the pedestrian. The key speed-related variables were extracted according to the analysis of the experiment data. The following analysis of the results focuses on investigating the effects of the fog conditions on the drivers' speed control under the three different levels of risk. The dependent variables include the average speed on the road segment in the low-risk scenario; acceleration, deceleration, and average speed during the car-following process in the medium-risk scenario; and the interval speed in terms of distance to the conflict point during the collision avoidance process and the collision speed if a collision occurred in the high-risk scenario. The dependent variables are analyzed using a 3 (fog) $\times$ 2 (gender) $\times$ 2 (profession) analysis of variance. The hypothesis testing in the following analysis is based on a 0.05 significance level.

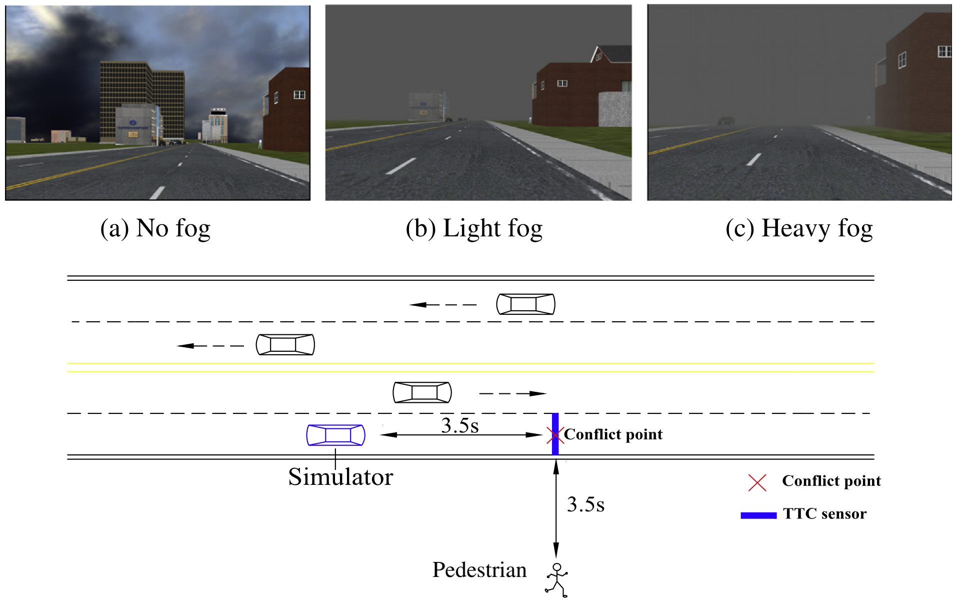


Fig. 7. The high-risk driving scenario.

3.1. Basic speed control behavior at the low risk level

The basic statistical descriptions of the average speeds for the four alignments are listed in Table 1, and the MANOVA (Multivariate Analysis of Variance) results of the differences between factors are shown in Table 2. It is found that both fog and profession significantly influence the drivers' basic speed performance on different types of highway segments, while no gender effects nor interaction effects among the factors are observed in any of the situations.

In the straight segment, the driving speed is significantly affected by the presence of fog ($F = 49.250$, $p < 0.01$): the speed is highest when there is no fog ($M = 68.10$ km/h, S.D. = 10.62 km/h) and there is no obvious difference between the speeds in light fog ($M = 45.43$ km/h, S.D. = 12.81 km/h) and heavy fog ($M = 45.84$ km/h, S.D. = 11.99 km/h) (see Fig. 8a).

Both the presence of fog and the profession of the driver have significant effects on the average speed when travelling uphill and downhill, as shown in Table 2. Drivers tend to have the highest speeds in light fog, both uphill ($M = 53.40$ km/h, S.D. = 15.64 km/h) and downhill ($M = 59.90$ km/h, S.D. = 13.23 km/h), and the lowest speeds in heavy fog, at 35.05 km/h uphill (S.D. = 10.48 km/h) and 51.92 km/h downhill (S.D. = 11.40 km/h) (see Fig. 8b and c). Besides this, the non-professional drivers have higher speeds both uphill ($M = 48.96$ km/h, S.D. = 16.06 km/h) and downhill ($M = 59.69$ km/h, S.D. = 12.15 km/h) compared to the professional drivers' uphill ($M = 42.39$ km/h, S.D. = 13.09 km/h) and downhill ($M = 51.15$ km/h, S.D. = 9.78 km/h) speeds.

When driving along the S-type curve, the drivers have higher speeds in both light fog ($M = 23.82$ km/h, S.D. = 5.80 km/h) and heavy fog ($M = 22.89$ km/h, S.D. = 5.60 km/h) than when there is no fog ($M = 20.30$ km/h, S.D. = 4.81 km/h), with difference being

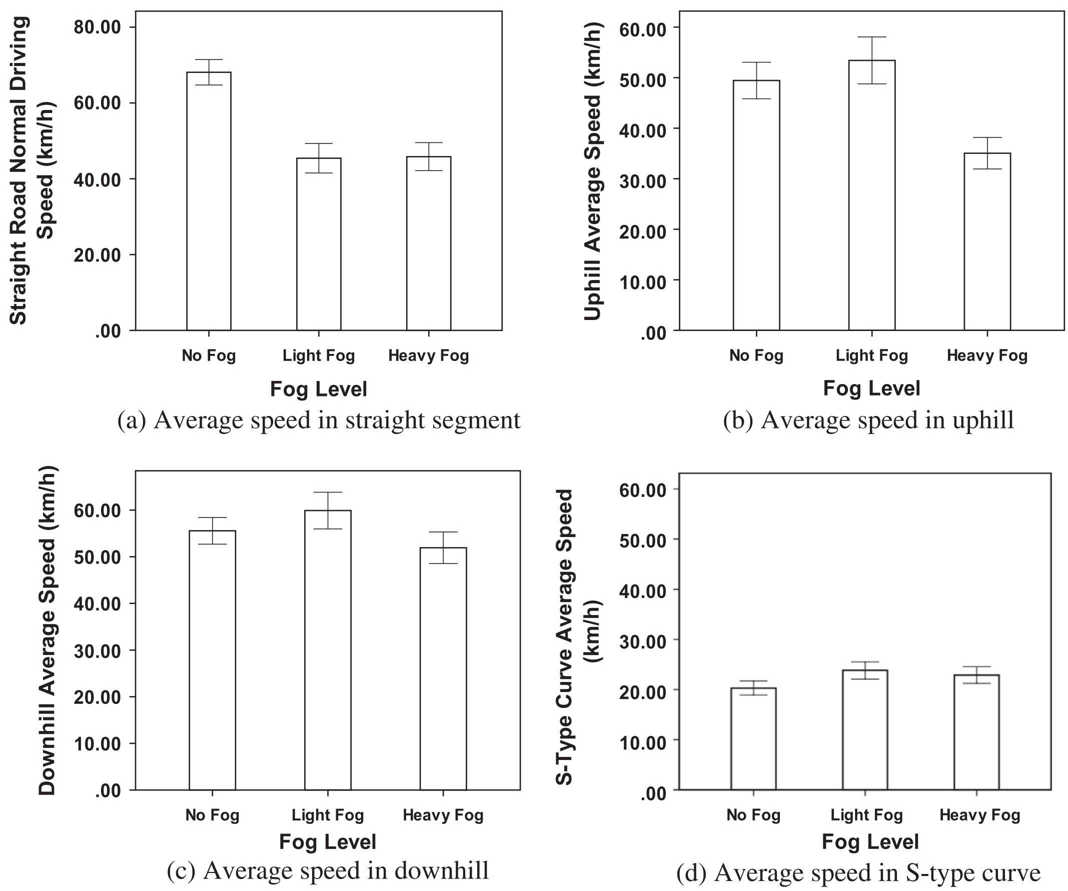
Table 1
Descriptive statistical results for average driving speed in four types of road segments.

Factors	Parameter	Straight segment average speed (km/h)	Uphill average speed (km/h)	Downhill average speed (km/h)	S type curve average speed (km/h)
Fog level					
No fog ($N = 41$)	Mean	68.10	49.42	55.55	20.30
	S.D.	10.62	12.17	9.62	4.81
Light fog ($N = 41$)	Mean	45.43	53.40	59.90	23.82
	S.D.	12.81	15.64	13.23	5.80
Heavy fog ($N = 41$)	Mean	45.84	35.05	51.92	22.89
	S.D.	11.99	10.48	11.40	5.60
Gender					
Male ($N = 66$)	Mean	54.42	46.00	54.61	22.32
	S.D.	14.25	14.73	11.36	5.70
Female ($N = 57$)	Mean	50.96	45.89	57.33	22.35
	S.D.	17.36	15.67	12.47	5.47
Profession					
Professional ($N = 57$)	Mean	53.65	42.39	51.15	20.33
	S.D.	15.68	13.09	9.78	3.38
Non-professional ($N = 66$)	Mean	52.22	48.96	59.69	24.02
	S.D.	15.95	16.06	12.15	6.47
Total					
$N = (123)$	Mean	52.83	45.96	55.79	22.34
	S.D.	15.79	15.09	11.88	5.58

Table 2
Multivariate analysis of variance for average speed in four road alignments.

Source	d.f.	*F*-ratio			
		Straight segment average speed	Uphill average speed	Downhill average speed	S type curve average speed
Fog level	2	49.250**	24.861**	5.816**	5.371**
Gender	1	2.384	.105	.962	.123
Profession	1	1.038	9.061**	20.394**	16.732**
Gender × profession	1	.085	.083	.063	.081
Fog Level × gender	2	.358	1.018	1.346	.146
Fog Level × profession	2	1.614	2.117	.843	.886
Mean square error	112	139.853	157.163	115.311	26.851

* Significant at the 0.05 level.
** Significant at the 0.01 level.



(a) Average speed in straight segment
(b) Average speed in uphill
(c) Average speed in downhill
(d) Average speed in S-type curve

Fig. 8. Average speed in four road alignments in three fog conditions.

at a significant level ($F = 5.371$, $p < 0.01$) (see Fig. 8d). Similarly to the case of the uphill and downhill segments, the non-professional drivers have higher speeds ($M = 24.02$ km/h, S.D. = 6.47 km/h) than the professional drivers ($M = 20.33$ km/h, S.D. = 3.38 km/h) on the S-type curve ($F = 16.732$, $p < 0.01$).

3.2. Dynamic speed adjustment behavior at the medium risk level

As mentioned earlier, the car-following situation was divided into two stages in this study: an accelerating stage (stage 1) and a decelerating stage (stage 2). The basic statistical descriptions of the speeds and acceleration rates in the two stages are listed in Table 3. The MANOVA results for the four variables are shown in Table 4. It is found that only fog significantly influences the drivers' dynamic speed adjustment behavior in the car-following situation, while no significant effects of profession, gender or interaction among the factors are observed in either stage.

In the accelerating stage, the drivers' acceleration rate is largest when there is no fog ($M = 0.392$ m/s^2, S.D. = 0.132 m/s^2), followed by light fog ($M = 0.233$ m/s^2, S.D. = 0.096 m/s^2) and finally heavy fog ($M = 0.191$ m/s^2, S.D. = 0.136 m/s^2) ($F = 46.665$, $p < 0.01$). The average speed shows a similar pattern, of 51.04 km/h (S.D. = 4.92 km/h), 43.77 km/h (S.D. = 3.85 km/h), and 41.91 km/h (S.D. = 4.17 km/h) respectively in no fog, light fog and heavy fog ($F = 52.744$, $p < 0.01$), as shown in Fig. 9a and b.

In the decelerating stage, the drivers' deceleration rate and average speed show trends consistent with those in the accelerating stage, as shown in Fig. 9c and d. Both decrease as the fog density increases: in no fog, light fog and heavy fog, the deceleration rate is −1.879 m/s^2 (S.D. = 1.497 m/s^2), −1.348 m/s^2 (S.D. = 1.113 m/s^2), and −1.167 m/s^2 (S.D. = 1.240 m/s^2) ($F = 3.317$, $p < 0.05$) respectively, and the average speed is 38.50 km/h (S.D. = 5.82 km/h), 27.29 km/h (S.D. = 13.33 km/h), and 26.93 km/h (S.D. = 11.10 km/h) ($F = 17.711$, $p < 0.01$) respectively.

Table 3
Descriptive statistical results for average acceleration rates and speeds in stage 1 and stage 2.

Factors	Parameter	Stage 1 Average acceleration (m/s^2)	Stage 1 average speed (km/h)	Stage 2 average deceleration (m/s^2)	Stage 2 average speed (km/h)
Fog level					
No fog (*N* = 41)	Mean	.392	51.04	−1.879	38.50
	S.D.	.132	4.92	1.497	5.82
Light fog (*N* = 41)	Mean	.233	43.77	−1.348	27.29
	S.D.	.096	3.85	1.113	13.33
Heavy fog (*N* = 41)	Mean	.191	41.91	−1.167	26.93
	S.D.	.136	4.17	1.240	11.10
Gender					
Male (*N* = 66)	Mean	.285	46.19	−1.390	32.10
	S.D.	.136	5.93	1.307	11.43
Female (*N* = 57)	Mean	.255	44.77	−1.562	29.35
	S.D.	.135	5.68	1.151	12.17
Profession					
Professional (*N* = 57)	Mean	.261	45.82	−1.265	32.73
	S.D.	.137	5.96	1.112	10.10
Non-professional (*N* = 66)	Mean	.281	45.36	−1.633	29.37
	S.D.	.135	5.78	1.323	12.91
Total					
N = (123)	Mean	.272	45.57	−1.465	30.90
	S.D.	.136	5.85	1.240	11.79

Table 4
Multivariate analysis of variance for average acceleration rates and speeds in stage 1 and stage 2.

Source	d.f.	*F*-ratio			
		Stage 1 average acceleration	Stage 1 average speed	Stage 2 average deceleration	Stage 2 average speed
Fog level	2	46.665**	52.744**	3.317*	17.711**
Gender	1	3.679	3.126	.433	2.417
Profession	1	2.324	.265	2.828	2.117
Gender × profession	1	1.959	.401	.006	3.211
Fog level × gender	2	.477	1.495	1.380	.328
Fog level × profession	2	1.506	.096	.908	1.040
Mean square error	112	.011	18.783	1.459	107.956

* Significant at the 0.05 level.
** Significant at the 0.01 level.

In general, drivers control their speed through acceleration and deceleration to maintain a safe distance (headway) between them and the vehicle in front. The results of this experiment indicate that a driver will reduce the vehicle speed as a compensatory strategy to lower the crash risk during a car-following situation. However, the better is the road visibility, the more sensitive will the driver be to the speed changes of the lead vehicle, and thus the more effectively will the vehicle be controlled.

3.3. Emergency speed response behavior at the high risk level

The drivers' emergent speed response behavior in the precrash scenario directly reflects their collision avoidance ability. Figs. 10 and 11 show the approaching speed and deceleration rate in each 10 m interval within the 80 m before the conflict point in the three weather conditions. Drivers have significantly higher speeds in the clear conditions than they do in the light and heavy fog conditions during the crash avoidance process (see Fig. 10) according to the MANOVA results (see Table 5). As they get closer to the conflict point (at about 10 m distance), the drivers' speeds in light fog fall to nearly the same level as in heavy fog and they are obviously slower than those in the clear conditions. Fig. 11 shows that, after the potential collision with the pedestrian has been perceived, the drivers start to decelerate at about 35 m before the conflict point in the clear conditions, and about 25 and 20 m respectively in the light and heavy fog. This indicates that in clear conditions drivers have a more timely response to emergency events than in foggy conditions.

Also, an interesting phenomenon is found in the deceleration rate curve in the condition of light fog: after the drivers begin to decelerate 25 m before the conflict point, the deceleration is not continuous. Therefore, it can be inferred that, since the driver's visibility in light fog falls between clarity and fuzz, this causes larger variability in the decelerating rate profile. In clear conditions, as soon as the collision risk is eliminated (the pedestrian has crossed the road in front of the simulator), the drivers then reduce their deceleration rates. This trend can be found in Fig. 11, which also explains why the speed near the conflict point is higher when there is no fog than when there is light or heavy fog, as shown in Fig. 10.

According to the results of the experiment, 17 crashes between the simulator and the pedestrian were observed, among which four happened when there was no fog, six in light fog, and the other seven in heavy fog (see Table 6). However, chi-square tests show that there is no significant correlation between any of the factors (fog, gender, or profession) and the occurrence of a crash.

From Fig. 12, we can see that the instantaneous speed when drivers brake (braking speed) obeys the normal distribution generally in the three fog conditions. The speed distribution when there is no fog is concentrated in a relatively high speed range with a mean value of 68.10 km/h (S.D. = 10.62 km/h). For the four crashes that happened when there was no fog, the average braking speed was 74.91 km/h. However, owing to the drivers' attempts to lower

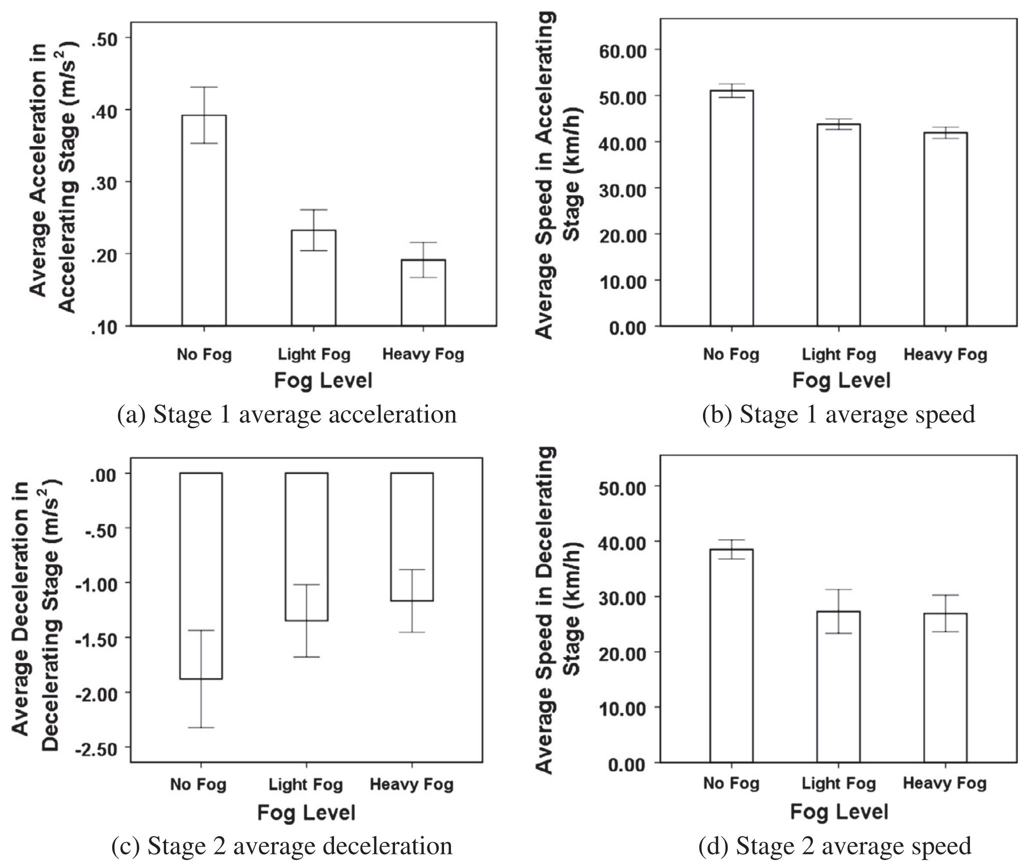


Fig. 9. Average acceleration, deceleration and speed in car-following.

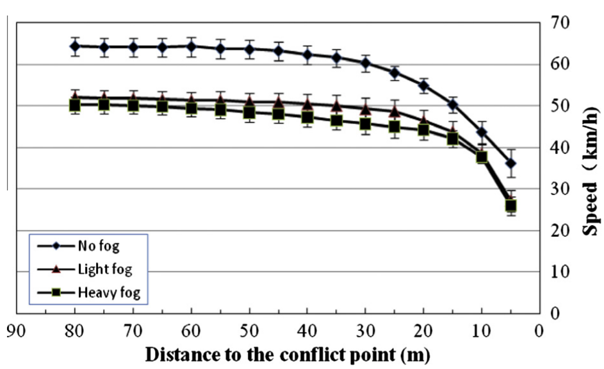


Fig. 10. The relationship between distance to the conflict point and speed.

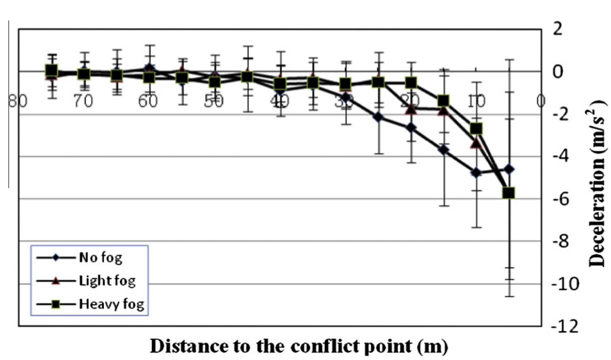


Fig. 11. The relationship between distance to the conflict point and deceleration.

the crash risk through speed reduction, the speed distributions in the light fog (M = 45.32 km/h, S.D. = 13.25 km/h) and heavy fog conditions (M = 45.54 km/h, S.D. = 12.09 km/h) were concentrated in relatively low speed ranges. Accordingly, the collision risks in foggy conditions shift into a low speed level. Therefore, although it can be inferred that the collision risk would increase with an increase of driving speed (Svenson et al., 2012; Aarts and van Schagen, 2006), the collision risk analyses for foggy conditions should be differentiated from that for clear conditions.

Consequently, a binary logistic regression is conducted to model the collision risk based on driving behaviors in foggy conditions. The regression results of the model are shown in Table 7. It shows that three variables are significantly associated with the occurrence of crashes (based on the 0.1 significance level considering the limitations of the collision sample size), namely fog level (light or heavy fog), braking distance (the distance between the simulator and the conflict point when the driver brakes), and the brake response time (the time from the pedestrian starting to cross the road to the driver starting to brake). Additionally, there is an interaction effect between the brake response time and the fog level. The modeling results can be formulated as in Eq. (1).

$$p = \frac{e^{-3.845+4.214\times f-0.096\times d+3.965\times t-2.830\times t\times f}}{1+e^{-3.845+4.214\times f-0.096\times d+3.965\times t-2.830\times t\times f}} \qquad (1)$$

where p represents the possibility of collision between the simulator and the pedestrian, and $0 < p < 1$; f represent the fog conditions, with $f = 0$ meaning light fog and $f = 1$ heavy fog; d represents the braking distance, in m and t represents the brake response time, in s.

In Table 7, the model's correct class rate is 89% and the c-statistic value is 0.822, The correct class rate is often used to examine

Table 5
Multivariate analysis of variance for average speeds before conflict point.

Source	d.f.	*F*-ratio									
		Speed 5 m	Speed 10 m	Speed 15 m	Speed 20 m	Speed 25 m	Speed 30 m	Speed 35 m	Speed 40 m	Speed 45 m	Speed 50 m
Fog level	2	15.555**	7.893**	13.141**	19.901**	25.766**	32.586**	38.236**	39.074**	41.449**	42.330**
Gender	1	0.463	0.035	0.246	0.996	1.967	2.389	2.426	2.174	1.721	1.675
Profession	1	6.897**	1.029	0.474	0.749	0.563	0.794	0.676	0.450	0.280	0.137
Gender × profession	1	2.040	0.030	0.281	0.437	0.190	0.313	0.039	0.003	0.000	0.012
Fog level × gender	2	0.035	0.810	0.340	0.237	0.186	0.212	0.131	0.087	0.019	0.006
Fog level × profession	2	0.781	0.470	0.518	0.758	0.672	0.854	0.972	0.923	0.888	0.652
Mean square error	109	7.328	5.014	4.949	5.428	5.641	5.681	5.154	5.072	4.838	4.768

** Significant at the 0.01 level.

Table 6
Chi-square tests between factors and the occurrence of a crash.

Factors	N	Ratio	Pearson Chi-Square		
			Value	d.f.	Asymp. Sig. (2-side d)
Fog level			.783[a]	2	.676
No fog	4	0.10			
Light fog	6	0.15			
Heavy fog	7	0.17			
Gender			.920[a]	1	.337
Male	11	0.17			
Female	6	0.11			
Profession			.191[a]	1	.662
Professional	8	0.14			
Non-professional	9	0.14			

[a] a represents 0 cells (0.0%) have expected count less than 5.

the performance of a prediction model (Dong et al., 2011). It presents the goodness of fit between the predicted value of model and the actual observed value intuitively. Alternatively, the prediction performance of a predicted model can be evaluated via the *c*-statistic value (equivalent to the area under the Receiver Operating Characteristic curve). The *c*-statistic value is a standard measure of the predictive accuracy of a logistic regression model when outcomes are binary, which ranges from 0.5 (for models with no predictive capability) to 1.0 (for models with perfect predictive power). Generally, the *c*-statistic value over 0.8 indicates that the model has a good prediction performance.

Based on the model, Fig. 13 illustrates the relationship between the possibility of collision occurrence (between the simulator and the pedestrian), the braking distance and the brake response time in light and heavy fog conditions. The figure shows that the collision possibility in both light and heavy fog conditions increases as the brake response time increases and the braking distance decreases. Interestingly, the collision-possibility curve surfaces for light fog and heavy fog cross when the brake response time is about 1.5 s. As there is an interaction effect between the fog conditions and the brake response time on the collision possibility, the drivers can be divided into two types according to the brake response time, which are quick responders whose brake response times are shorter than 1.5 s and slow responders whose brake response time are longer than 1.5 s. For the quick responders, their possibility of collision occurrence is larger in heavy fog than in light fog. A possible explanation for this phenomenon is that because the light fog's visibility is better than heavy fog, it is easier for drivers to identify potential traffic hazards and avoid collisions. On the other hand, for the slow responders, their possibility of collision occurrence in heavy fog is smaller than that in light fog. There are two presumable reasons associated with this phenomenon. Firstly, drivers in heavy fog are generally more cautious due to the drastically reduced visibility and more likely to perform safety-related adaptations (Al-Ghamdi, 2007; Brooks et al., 2011). Therefore, they tend to take more decisive braking action to avoid a collision once a risk has been perceived. Secondly, the operation speed is one of the main contributing factors causing car accidents (Svenson et al., 2012). A higher speed increases the accident risk as it increases the stopping distance and time (Aarts and van Schagen, 2006; Cameron and Elvik, 2010; Nilsson, 2004). For the slow responders in this experiment, their average braking speed in heavy fog (46.84 km/h) was lower than that in light fog (53.40 km/h). Thus, for the drivers who have a slow braking response, a slower driving speed will effectively decrease the crash risk. The above interaction effect is also consistent with the observations of the decelerating rate profile in Fig. 11, in which the decelerating rate in light fog was more variable than that in heavy fog. Therefore, although drivers in light fog have an advantage in visibility, the speed compensation in heavy fog provides a vital effect on collision avoidance.

Higher collision speeds usually correspond to more serious crash consequences, which means greater physical damage and personal injury and a higher risk of a fatal accident (Nilsson, 2004; Cameron and Elvik, 2010). The basic statistical descriptions and ANOVA results for the simulator's collision speed are shown in Tables 8 and 9. It is found that only fog significantly influences the collision speed, while no effects are observed from profession, gender or interactions among the factors. The collision speed decreases as the fog density increases ($F = 5.458$, $p < 0.05$): in no fog, light fog, and heavy fog, the collision speed is 14.93 km/h (S.D. = 4.86 km/h), 9.25 km/h (S.D. = 4.12 km/h), and 5.54 km/h (S.D. = 3.56 km/h) respectively. The results indicate that, by reducing speed in adverse weather conditions, drivers can effectively lower the crash severity.

4. Discussions

Previous studies on driving behavior in fog have been carried out using different kinds of driving simulators such as fixed-platform (Mueller and Trick, 2012; Brooks et al., 2011; Broughton et al., 2007), workstation-based (Ni et al., 2010, 2012), and motion-based (MarkVollrath et al., 2011; Van Driel et al., 2007). Although the absolute validity levels of the above simulators may be different from the one used in this study, the experimental results indicate consistent findings regarding driving behavior in fog. Reduced visibility in fog increases the risk of collision to some extent, and most drivers are likely to perform safety-related adaptations, which mainly involve reducing speed in order to give themselves more time to react to hazards (Ni et al., 2010; Broughton et al., 2007). However, speed reductions by drivers are found to be insufficient to compensate for the crash risk (Brooks et al., 2011; Mueller and Trick, 2012). Additionally, from the perspective of relative validity (Blaauw, 1982), most previous studies have concluded that different types of driving simulators can

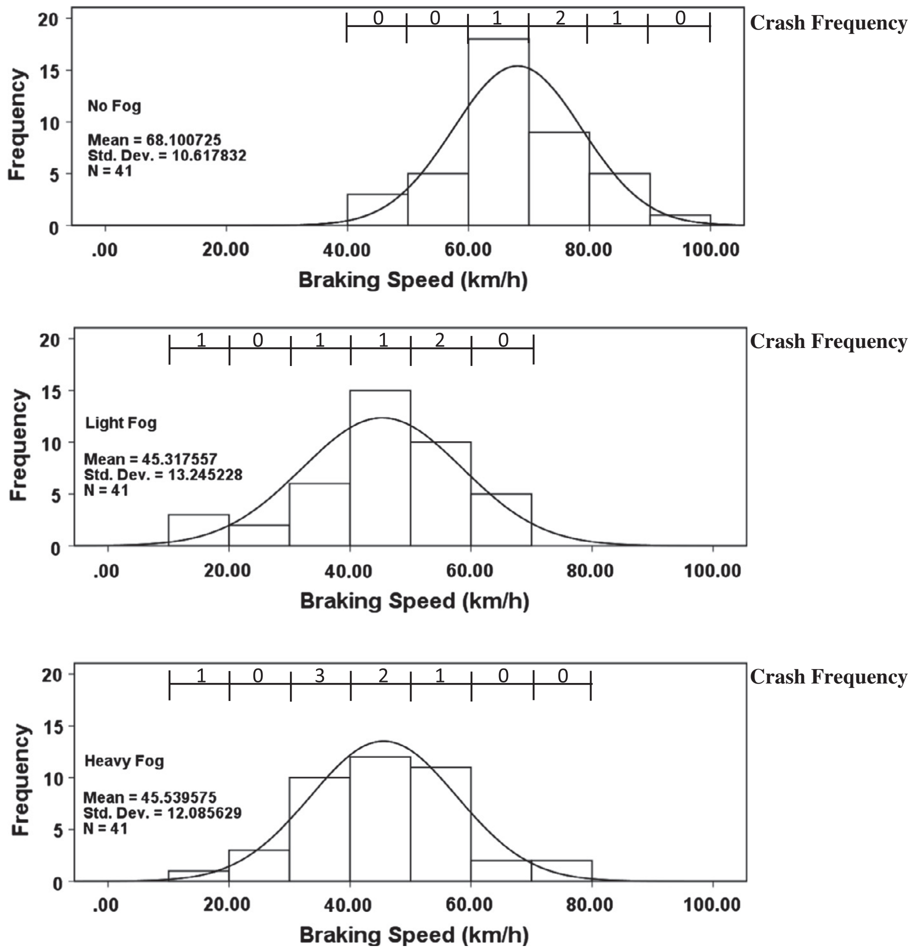


Fig. 12. Braking speed distribution in three fog conditions.

Table 7
Binary logistic regression results between factors and the occurrence of a crash.

Source	*B*	S.E.	Wals	d.f.	Sig.	Exp(*B*)
Fog level (heavy fog)	4.214	2.495	2.853	1	.091	67.605
Braking distance	−.096	.035	7.489	1	.006	.908
Brake response time	3.965	1.294	9.392	1	.002	52.725
Brake response time * fog level (heavy fog)	−2.830	1.492	3.598	1	.058	.059
Constant	−3.845	1.892	4.129	1	.042	.021
Correct class rate			89.0%			
C-statistic value			0.822			

reflect similar trends regarding driving performance to those seen in the real world (Yan et al., 2007; Lee, 2002; Godley et al., 2002; Bella, 2005). Considering that driving simulators allow researchers to assess driving behaviors in dangerous situations that could not be achieved in the real environment, they provide an advantage for systemically examining the effects of fog conditions on driving behaviors at different risk levels.

However, the driving scenarios designed in most previous studies have been limited to a particular crash-involvement risk level, and the experimental results lacked more integrated explanations for driving behavior changes associated with foggy conditions. In this study, we have found that fog has different effects on drivers' speed control behaviors at different risk levels, based on simulation results using different driving scenarios.

In the low-risk scenario, drivers lowered their speeds by around 30% in the straight segment to compensate for the potential risk due to fog, the reduction being almost the same for both light and heavy fog. Previous studies have reported that drivers are not inclined to slow down significantly until the visibility distance is drastically reduced by fog (Klinjnhout, 1991; Brooks et al., 2011). In this study, the 250 m visibility in the light fog scenario caused the subjects to reduce their speeds to the same extent as the 50 m visibility in the heavy fog scenario. However, on the uphill and downhill segments, speed reduction was observed only in heavy fog; the driving speeds in light fog were higher than those in clear conditions. This is because the drivers' sight distance in light fog was influenced somewhat and they could not judge changes in the road alignment in advance and adjust their speed accordingly. In the S-type curve segment, drivers had even higher speeds in the foggy conditions than in the clear conditions.

Overall, these results reflect that, although the drivers realized the potential risk introduced by the fog and intended to reduce

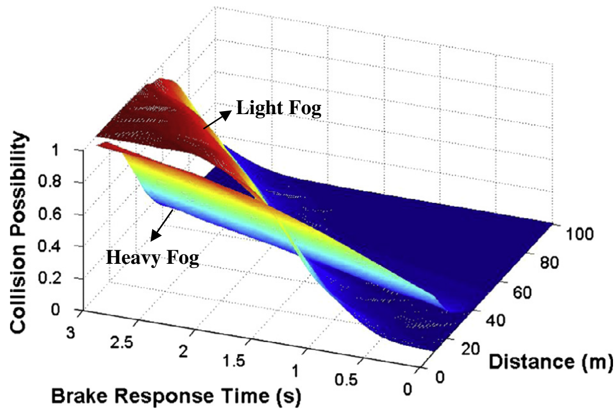


Fig. 13. The relationship between the brake response time, the braking distance and the collision possibility in light and heavy fog conditions.

Table 8
Descriptive statistical results for the collision speed.

Factors	Parameter	Collision speed (km/h)
Fog level		
No fog	Mean	14.93
	S.D.	4.86
Light fog	Mean	9.25
	S.D.	4.12
Heavy fog	Mean	5.54
	S.D.	3.56
Gender		
Male	Mean	8.17
	S.D.	4.70
Female	Mean	10.68
	S.D.	6.50
Profession		
Professional	Mean	8.43
	S.D.	6.56
Non-professional	Mean	9.62
	S.D.	4.31
Total		
	Mean	9.06
	S.D.	5.34

their speeds for compensation, they could not respond to impending changes in the road conditions in advance and decelerate in time when experiencing adverse environments with complex road geometry. This implies that foggy conditions will increase the crash-involvement risk at road alignment transition locations, such as the risk of running off the road. Similarly, Edwards (1999a, 1999b, 2002) found that drivers' mean speed reduced during wet and misty weather but the reduction did not sufficiently compensate for the hazards imposed by the inclement weather.

In this study, the car-following scenario was classified as having a medium risk of crash involvement and was designed to investigate a driver's dynamic speed adjustment behavior in negotiating the leading vehicle's speed changes in a high density of traffic flow. Failure to properly change speed and maintain a safe gap from the leading vehicle during car following may result in an increased risk of a rear-end collision (Oh et al., 2006; Bella and Russo, 2011). In China, rear-end crashes have accounted for over a third of all road traffic accidents in recent years, and in the United States rear-end collisions exceed 1.5 million per year, or approximately 23% of all vehicle crashes. Especially in foggy conditions, the reduced visibility may increase the rear-end crash risk due to a less accurate estimation of the headway distance to the leading vehicle.

Table 9
Analysis of variance for the collision speed.

Source	d.f.	*F*-ratio Collision speed
Fog Level	2	5.458*
Gender	1	.061
Profession	1	.581
Gender × profession	1	.145
Fog level × gender	2	1.246
Fog level × profession	2	4.474
Mean square error	7	10.751

* Significant at the 0.05 level.

A previous driving simulation study found that drivers had more difficulty responding to changes in lead vehicle speed than to changes in headway, and that as the fog density increased, the driver's speed control error when responding to a change in the lead vehicle speed also increased (Kang et al., 2008). Our results further revealed that the drivers' average speeds in the accelerating and decelerating stages in foggy conditions were slower than those when there was no fog. This indicates that the drivers were more cautious when driving in the foggy conditions in a car-following situation, and lowered their speeds to avoid rear-end collisions. However, this speed compensation did not reduce the risk when following cars in fog to the same level as when driving in clear conditions. According to the results, a total of 11 rear-end crashes between the simulator and the leading vehicle were observed in the decelerating stage, among which only one happened when there was no fog, six happened in light fog, and the other four happened in heavy fog. This is because restricted visibility affects drivers' speed control behaviors, including the response time to initiate acceleration or deceleration and the control of the acceleration or deceleration rate when the leading vehicle's speed is changing. In the previous literature, similarly to our results concerning the effect of fog on the rear-end crash risk, it has been reported that more rear-end crashes occur in the dark than in the light, and that the relative risk of fatal rear-end crashes in the dark is twice as large as that in the light (Sullivan and Flannagan, 2003).

At the high risk level, a precrash scenario involving the simulator and a crossing pedestrian was designed to investigate the drivers' emergent speed response behavior in foggy conditions. Usually, in critical traffic situations, crash avoidance actions enable drivers to reduce the likelihood of a crash or at least lower its severity (Harb et al., 2009). Our study indicates that drivers are more reactive to a potential crash and take avoidance actions earlier in clear conditions than in foggy conditions. After perceiving the potential collision with a pedestrian, the drivers took deceleration action 10 m further away from the conflict point in clear conditions than in light fog, and 15 m further away than in heavy fog. This result implies that restricted visibility reduces the required cushion of space that drivers need to make a speed adjustment in response to an emerging hazard. Previous studies have also shown that poor visibility may increase drivers' reaction times, leaving them insufficient time to act upon a critical traffic event (Harb et al., 2007a,b).

It has also been shown that drivers are inclined to have inaccurate expectations about hazards in foggy conditions, which explains to some extent their largely ineffective and delayed identification of hazards while driving (Lerner and Westat, 2001; Pradhan et al., 2009; Vidotto et al., 2011). This explains why more collisions were observed in foggy conditions in this study. According to the results of the experiment, there were three times as many crashes between the simulator and the pedestrian in foggy conditions than clear conditions. However, driving in fog still substantially aroused the drivers' speed-compensation behavior, as the approaching speed and collision speed were both obviously slower in such conditions. This would effectively lower the driving risk and the crash severity in adverse environments.

In addition to the fog's effects, the drivers' characteristics were also found to influence their speed control behavior. For example, in the uphill, downhill and S-type curve segments, the non-professional drivers showed significantly higher speeds than the professional drivers (see Table 2). A similar finding has been reported in the prior literature, with non-professional drivers driving faster than taxi, minibus, and heavy vehicle drivers on highways (Öz et al., 2010). Professional drivers generally have much more experience in terms of driving time and mileage than non-professional drivers. Compared to more experienced drivers, less experienced drivers are more likely to speed (Jonah, 1986, 1990) and have more speed-related collisions (Curry et al., 2011; Liu et al., 2005). Thus, professional drivers' experience leads them to lower their speed to compensate for the potential risks introduced by foggy conditions, while non-professional or less experienced drivers are relatively insensitive to the potential risks.

In previous studies, gender differences have also been found in risky driving behavior (Harré et al., 1996, 2000; Oltedal and Rundmo, 2006). For example, Harré et al. (1996) found that male drivers drove significantly faster in towns, and reported a greater intention to drink and drive than female drivers. However, in this study, no gender effect was found in the drivers' speed control behaviors in foggy conditions, and similarly in Mueller and Trick's (2012) research, gender was concluded to have a non-significant effect on the experiment variables (such as average speed, collision rate, and hazard response time) when the drivers were put in a foggy environment. Thus, it can be inferred that, when driving in fog, the gender differences in terms of risky driving behavior might have been counteracted by the speed compensation behavior.

5. Conclusions

In summary, this driving simulator experiment has illustrated the effects of foggy conditions on drivers' speed control behavior in low-risk, medium-risk and high-risk scenarios. The results indicate that, at different risk levels, although the drivers understood the potential risk introduced by the fog and intended to reduce their speed for compensation, they could not respond in time to impending changes in road geometries, the speed of the leading vehicle when following, or an emerging precrash event. Thus, speed compensation cannot sufficiently reduce the risk of crash involvement for drivers in adverse environments.

The findings also identified that professional drivers were more sensitive to the potential risks and tended to drive at lower speeds in fog compared with the non-professional drivers. These driving simulation experiment results explain how foggy weather conditions increase drivers' crash involvement risk. Therefore, it is not surprising that there are a large number of fog-related traffic crashes, injuries and fatalities reported. Having a thorough understanding of driving behaviors in fog can help traffic engineers and ITS (Intelligent Transportation System) technology designers to search for better safety countermeasures to improve road safety. In further research we will explore other performance-related driving behaviors such as steering, keeping to one's lane, reaction and execution, as influenced by foggy weather conditions, again following this hierarchical driving performance assessment method.

Acknowledgments

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