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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.

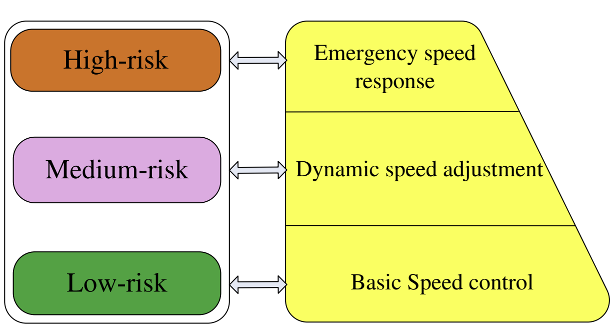

Fig. 1. Hierarchical diving behavior assessment concept.

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