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Effects of crash warning systems on rear-end crash avoidance behavior under fog conditions

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ABSTRACT

Reduced visibility conditions increase both the probability of rear-end crash occurrences and their severity. Crash warning systems that employ data from connected vehicles have potential to improve vehicle safety by assisting drivers to be aware of the imminent situations ahead in advance and then taking timely crash avoidance action(s). This study provides a driving simulator study to evaluate the effectiveness of the Head-up Display warning system and the audio warning system on drivers' crash avoidance performance when the leading vehicle makes an emergency stop under fog conditions. Drivers' throttle release time, brake transition time, perception response time, brake reaction time, minimum modified time-to-collision, and maximum brake pedal pressure are assessed for the analysis. According to the results, the crash warning system can help decrease drivers' reaction time and reduce the probability of rear-end crashes. In addition, the effects of fog level and drivers' characteristics including gender and age are also investigated in this study. The findings of this study are helpful to car manufacturers in designing rear-end crash warning systems that enhance the effectiveness of the system's application under fog conditions.

1. Introduction

Fog is an inclement weather with reduced visibility and has a significant impact on driver behavior, traffic flow characteristic, and traffic safety. Compared to the crashes under clear conditions, fog-related crashes are prone to be more severe and involve multiple vehicles (Abdel-Aty et al., 2011; Naik et al., 2016). According to fatal crash statistics from the National Highway Transportation Safety Administration (NHSTA), fog contributed as a major factor to 7070 fatal crashes that have occurred in the United States from 2000 to 2015. In 2008, a fog-related crash with 70-vehicle pileup happened in Florida, causing five deaths and many injuries (Hassan and Abdel-Aty, 2011).

In the previous studies, a number of studies have investigated the change of driver behavior under fog conditions. Broughton et al. (2007) observed reduced headway distance under fog conditions. It was suggested that drivers may reduce their headway distances to seek visible cues in fog. Based on the real-time traffic data and airport weather data, Wu et al. (2017) analyzed the traffic flow pattern and found that both volume and speed under fog conditions dropped significantly. By proposing a Crash Risk Increase Indicator (CRII), the authors confirmed that crash risks could increase under fog conditions. Mueller and Trick (2012) compared experienced and novice drivers' behavioral compensation in fog. The authors suggested that changing speed is the most typical change among all the driving behavioral adjustments corresponding to fog. The study also showed that experienced drivers would reduce their speeds

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more than novice drivers. Wu et al. (2018a) investigated the impacts of static fog warning systems (beacons and variable message signs) on drivers' speed adjustments for fog conditions using a driving simulator study. The authors found that the warning system could significantly affect drivers' speed adjustments before they drove into the fog area, but could not sufficiently change drivers' final speed after entering into the fog area.

Since some drivers tend to reduce their headway distance during fog, they may not be able to have enough response time to react to imminent events even if they had reduced their speeds, which results in an increase of the rear-end crash risk (Shi and Tan, 2013). A driving simulator study conducted by Yan et al. (2014) further confirmed that drivers' speed compensation in fog conditions could not sufficiently reduce the rear-end crash risk at the medium and high crash risk levels. Meanwhile, although some drivers would keep longer headway distances, rear-end crashes may still happen since they may not be able to see the braking lights of the front vehicle (Wu et al., 2018b).

In recent years, connected-vehicle Crash Warning Systems (CWS) technologies are gaining increasing acceptance in traffic safety, which displays a vista for enhancing traffic safety under fog conditions. Previously, CWS technologies were based on radars or cameras. However, bad weather could reduce the systems' accuracy. Connected vehicles could further improve the performance of CWS by deploying vehicle-to-vehicle (V2V) communications or Vehicle-to-Infrastructure (V2I) communications (Li et al., 2014). The V2V communications can provide the real-time position and speed of the leading vehicle. Thus, the CWS can detect the sudden slow down or stop of the leading vehicle and timely alert the drivers of the following vehicle with an in-vehicle warning message (Benedetto et al., 2015). Many driving simulator studies have conducted to explore the impact of CWS, while drivers' response time, throttle release behaviors, brake pedal behaviors, and TTC could be deployed to evaluate the effectiveness of the warning systems (Scott and Gray, 2008; Wang et al., 2016; Abe and Richardson, 2006; Cai et al., 2014; Fu et al., 2018). It is worth mentioning that TTC is one of the most prevalent measures used to investigate the safety status in driver simulator studies (Strayer et al., 2006; Gelau et al., 2011; De Rosario et al., 2010). Moreover, some studies utilized minimum TTC (MTTC) to evaluate drivers' rear-end crash risks during driving simulator experiments (Aust et al., 2013; Cai et al., 2018; Strand et al., 2014).

In general, the warning type is one of the important attributes of a warning system, which can significantly affect the effectiveness of warning information (Xiang et al., 2016; Zhang et al., 2015). Currently, the warning type can be categorized into three types: visual CWS, tactile CWS, and audio CWS. The visual CWS usually presents warning messages in an instrument cluster or in a Head-up Display (HUD) (Wege et al., 2013). Lind (2007) evaluated the effects of Forward Collision Warning (FCW) and concluded that HUD has the highest detection rate. The audio warning system can be further divided into two types, i.e., nonverbal and verbal information. Nonverbal warning system usually provides a repetitive sound, such as a "bi-bi" beep sound, while verbal warning system delivers information by synthesized voice which imitates human voice (Chang et al., 2009). The nonverbal warning system is usually utilized to alert drivers to brake under emergency situations, especially during high rear-end crash risk situations (Spence and Ho, 2008, Mohebbi et al., 2009). Compared with the audio CWS, the visual CWS could help drivers observe risk faster (Wege et al., 2013). The tactile CWS can direct drivers' attention to a specific direction or location through the localized vibrations of spatial tactile displays (Xiang et al., 2016). Compared with tactile CWS, the visual and audio CWS can provide additional information about the details of the warning events (Haas and Van Erp, 2014). Furthermore, the previous studies also demonstrated that the multimodal CWS which integrated visual and audio CWS could be more effective than visual CWS alone in enhancing drivers' performance.

The safety benefits of CWS have been evaluated in the previous literature and many studies have indicated that the warning systems could effectively help reduce rear-end crash risks (Fildes et al., 2015). However, there is lack of studies on the safety effectiveness of CWS on rear-end crashes under fog conditions. Therefore, different from our previous study (Wu et al., 2018a) which investigated the effects of static warning systems (beacon and variable message signs) on drivers' behaviors in fog, the current study aims to examine the effects of CWS on drivers' rear-end crash avoidance behavior under fog conditions based on a driving simulator experiment. Specifically, the objective of this study is to investigate whether warning systems (visual only vs. visual & audio) have significant effects on drivers' read-end crash avoidance performance, when the leading vehicle makes an emergency stop.

2. Experiment

2.1. Participants

Fifty-four participants were recruited for this study. The average age of the participants was 38.4 years old, ranging from 18 to 75 years old. Each participant held a valid driver license and had at least 1 year of driving experience. The experiment lasted for about 30 min in total for each participant. Institutional Review Board (IRB) approval was obtained before starting the experiments.

2.2. Apparatus

The National Advanced Driving Simulator (NADS MiniSim) was used for this experiment. NADS MiniSim provided a 130° horizontal by a 24° vertical field of view in front of the seated participants with three screens (22.5 in. high and 40.1 in. wide each). Two speakers were installed in the front to mimic the sound of the passenger car as well as deliver the audio warning messages, and a third speaker was mounted below the driver's seat to simulate roadway vibrations. The text warning messages were presented through a HUD interface at the bottom of the middle screen (Fig. 1), which was set up to be transparent and would not obstruct the participants' view. The simulator was equipped with a four-channel video capture system, and collected driving data at a rate of 60 Hz.