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Effects of real-time warning systems on driving under fog conditions using an empirically supported speed choice modeling framework

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ABSTRACT

Fog warning systems can convey warning messages to drivers and help to reduce crashes that may occur due to the sudden occurrence of low visibility conditions. This study aims to assess the effectiveness of real-time fog warning systems by quantifying and characterizing drivers' speed adjustments under different roadway types, traffic conditions, and fog levels. In order to explore how a driver perceives the fog warning systems (i.e., beacon and dynamic message signs (DMS)) when approaching a fog area, this paper divides the roads into three zones (i.e., clear zone, transition zone, fog zone) according to visibility levels and suggests a hierarchical assessment concept to explore the driver's speed adjustment maneuvers. For the three different zones, different indexes are computed corresponding to drivers' speed adjustments. Two linear regression models with random effects and one hurdle beta regression model are estimated for the indexes. In addition, the three models were modified by allowing the parameters to vary across the participants to account for the unobserved heterogeneity. To validate the proposed analysis framework, an empirical driving simulator study was conducted based on two real-world roads in a fog prone area in Florida. The results revealed that the proposed modeling framework is able to reflect drivers' speed adjustment in risk perception and acceleration/deceleration maneuvering when receiving real-time warning massages. The results suggested that installing a beacon could be beneficial to speed reduction before entering the fog area. Meanwhile, DMS may affect drivers' brake reaction at the beginning section of reduced visibility. However, no effects of warning systems for drivers' final speed choice in the fog can be observed. It is suggested that proper warning systems should be considered for different conditions since they have different effects. It is expected that more efficient technology can be developed to enhance traffic safety under fog conditions with a better understanding of the drivers' speed adjustments revealed in this study.

1. Introduction

Fog is a weather condition that reduces visibility of the driving scene. Visibility is a critical factor for drivers to perceive roadway information and reduction in visibility due to fog or other factors is a major traffic operation and safety concern. According to the National Highway Transportation Safety Administration's (NHSTA) Fatality Analysis Reporting System (FARS), fog/smoke contributed as a major factor in 3729 fatal crashes that occurred in the United States between 2000 and 2007. Usually, fog is present

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during the late night and early morning which can increase severe injuries and the possibility of multiple vehicles involved crashes (Al-Ghamdi, 2007). For example, a fog crash with 70-vehicle pileup happened on I-4 in Polk County in January 2008. This crash caused five deaths and many injuries (Hassan and Abdel-Aty, 2011). Efforts to enhance the safety under fog conditions are necessary. The fog warning system serves as an important intelligent transportation system to inform drivers and help them get ready for the upcoming fog. However, little effort has been made to quantify their effects on drivers' speed adjustments. Hence, more detailed analyses are required to describe the speed adjustments within different fog warning systems under different fog conditions.

1.1. Driving behavior under fog conditions

The reduced visibility has a significant impact on driving behavior, which needs to be understood to design appropriate mitigation strategies. Various studies have been conducted to explore the drivers' adjustments corresponding to fog such as drivers' speed control, headway maintenance, and lane keeping (Broughton et al., 2007; Ni et al., 2010; Brooks et al., 2011; Hassan and Abdel-Aty, 2011; Hamdar et al., 2016). There have been a number of studies that have focused mainly on car following behavior (Broughton et al., 2007; Kang et al., 2008; Van Der Hulst et al., 1998). However, in most cases, fog would be present in the early morning when the traffic flow is relatively low and the headway distance would be longer. In that case, drivers would be more likely to be under free-flow condition. Then, instead of car-following behaviors, changing speed is the most typical factor (Hamdar et al., 2016). It was revealed that drivers would like to reduce their speed in order to lower the risk in fog conditions (Van der Hulst et al., 1998; Yan et al., 2014; Hamdar et al., 2016; Wu et al., 2017a). Different drivers may have different adjustment of speed under different fog conditions. Mueller and Trick (2012) found that experienced drivers drove faster than novice drivers under clear conditions while at the same speed if they drove under fog conditions, indicating that the experienced drivers reduced their speed more than novice drivers in reduced visibility situations. Based on the real-time traffic data and airport weather data, Wu et al. (2017b) analyzed the traffic flow pattern. It was found that both volume and speed under fog conditions dropped significantly. By proposing a crash risk increase indicator, the authors confirmed the increase of crash risk under fog conditions based on different traffic measures. Trick et al. (2009) examined the age-related differences in speed reduction when driving in fog. The results showed that older drivers reduced their speed substantially while young drivers were less likely to reduce their speed in fog and prone to have more collisions. Yan et al. (2014) conducted a driving simulator experiment and found that the drivers' speed control ability varied at different risk levels. By conducting experiments with three risk levels, different speed control behaviors were observed: basic speed control at a low risk level, dynamic speed adjustment at a medium risk level, and emergent speed responses to pre-crash situation at a high risk level. Although drivers are likely to reduce speed during low visibility conditions, the reduction of speed is found to be insufficient for them to stop within the visibility distance (Sumner et al., 1977), especially when they meet a dangerous situation (Yan et al., 2014).

1.2. Fog warning system

It is necessary to detect any reduction in visibility and develop efficient ways to convey warnings to help drivers get prepared to adjust their speed when they proceed to fog. A typical fog warning system usually includes Dynamic Message Signs (DMSs) or static signs with flashing beacons to convey information to drivers. The signs are typically located before the area where fog is likely to form frequently and would deliver warning messages when the fog is present. Several research efforts have been made to evaluate the effects of fog warning systems on drivers' decisions. Boyle and Mannering (2004) conducted a driving simulator experiment to analyze drivers' speed adjustments under four different advisory-information conditions. The findings of the study suggested that while the warning messages are significant in reducing speeds in the low-visibility area, drivers tended to increase speed in the downstream when such adverse conditions didn't exist. Al-Ghamdi (2007) and MacCarley et al. (2006) found that the fog warning system was significant in reducing the mean speed in fog while it was ineffective in reducing the speed variability. Hassan and Abdel-Aty (2011) conducted self-reported questionnaire survey to explore factors contributing to drivers' compliance and drivers' satisfaction with the fog warning systems. The study concluded drivers' satisfaction with the warning system was the most significant factor that positively affected drivers' compliance with the warning systems. Also, it was revealed that roadway type affected drivers' compliance to the instructions of warning systems under moderate and heavy fog conditions. Williams et al. (2015) examined the effects of different color configuration, brightness levels, and flashing beacons on a DMS on drivers during the day and night under fog conditions. The results indicated that the DMS with black-on-white, white-on-black, and amber-on-black color combinations had longer detection and legibility distances. Meanwhile, the DMSs with high brightness and red-on-black color configurations would make the drivers feel the urgency.

Although several previous studies have paid attention to the effects of warning systems on drivers' speed adjustment maneuvers in the fog condition, most of them have only focused on several particular driving scenarios and only analyzed drivers' speed adjustment when they were already in the fog. There is a lack of systematic analysis of the effects of different fog warning system settings under different conditions. Also, after receiving the fog warning messages, drivers may already adjust their speed before entering the fog area. Actually, drivers should gradually adjust their speed during the process of driving into and out the fog area with the warning system instructions.

1.3. Objective of this study

In this study, a hierarchical driving performance assessment method is proposed to evaluate the effect of the real-time fog warning system on drivers' speed adjustments under different conditions. Then, an empirical experiment study with a driving simulator is