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Effects of lead time of verbal collision warning messages on driving behavior in connected vehicle settings

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ABSTRACT

Introduction: Under the connected vehicle environment, vehicles will be able to exchange traffic information with roadway infrastructure and other vehicles. With such information, collision warning systems (CWSs) will be able to warn drivers with potentially hazardous situations within or out of sight and reduce collision accidents. The lead time of warning messages is a crucial factor in determining the effectiveness of CWSs in the prevention of traffic accidents. Accordingly, it is necessary to understand the effects of lead time on driving behaviors and explore the optimal lead time in various collision scenarios. *Methods:* The present driving simulator experiment studied the effects of controlled lead time at 16 levels (predetermined time headway from the subject vehicle to the collision location when the warning message broadcasted to a driver) on driving behaviors in various collision scenarios. *Results:* Maximum effectiveness of warning messages was achieved when the controlled lead time was within the range of 5 s to 8 s. Specifically, the controlled lead time ranging from 4 s to 8 s led to the optimal safety benefit; and the controlled lead time ranging from 5 s to 8 s led to more gradual braking and shorter reaction time. Furthermore, a trapezoidal distribution of warning effectiveness was found by building a statistic model using curve estimation considering lead time, lifetime driving experience, and driving speed. *Conclusions:* The results indicated that the controlled lead time significantly affected driver performance. *Practical applications:* The findings have implications for the design of collision warning systems.

1. Introduction

Globally, deaths and injuries resulting from road traffic accidents are a major and growing public health problem. Statistically, 1.2 million people each year are known to die in road accidents worldwide, and as many as 50 million are injured (Peden et al., 2004). In 2012, 5.6 million crashes occurred in the United States, resulting in 30,800 lives lost and approximately one and a half million injuries. Almost 4 million crashes involved property damage only and it is reasonable to assume that there were many more collisions of less severity that went unreported (Highway Traffic Safety Administration, 2014).

With recent technological developments in wireless communication, mobile computing, and remote sensing, connected vehicles (CVs) be able to communicate speed and location data to roadway infrastructure and with other vehicles, and drivers can learn about the traffic situation within or out of sight (Lee & Park, 2012; Papadimitratos et al., 2009). With these traffic information, collision warning systems (CWSs) (Chang et al., 2009; Gray, 2011; Hirst & Graham, 1997; Hoffman, Lee, & Hayes, 2003; Isermann, Mannale, & Schmitt, 2012; Kannan, Thangavelu, & Kalivaradhan, 2010; Lee et al., 2002; Misener, 2010; Neale et al., 2007; Sengupta et al., 2007; Taleb, Benslimane, & Ben Letaief, 2010; Wada et al., 2010) in connected vehicles are able to provide drivers with more accurate and specific traffic information, alert the driver of a potential collision within or out of sight, and promote a braking or steering response to avoid the collision or minimize the damage due to a collision.

Lead time plays an important role in determining the effectiveness of warning messages. Lead time was defined as the time headway from the subject vehicle to the potential collision location calculated by the collision warning system at the time the warning occurred. Existing studies suggested that early warning with longer lead time provides drivers with sufficient time to respond appropriately (Abe & Richardson, 2004, 2005, 2006; McGehee et al., 1998a, 1998b; Michon, 1993; Parasuraman, Hancock, & Olofinboba, 1997; Seiler, Song, & Hedrick, 1998; Tang & Yip, 2010). Early warning also has the potential to reduce variation in braking reaction time, resulting in a more gradual and stable response. However, a warning provided too early without visual feedback may be treated as a false alarm or nuisance alarm, fail to assist the driver, and instead,

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generate an inappropriate braking response. This may lead a driver to no longer trust, and, therefore, ignore such warnings, thereupon impairing their effectiveness. By contrast, late warning with shorter lead time caused fewer trust issues (John Lee & Moray, 1992; Muir, 1994; Muir & Moray, 1996) and may not likely be ignored or forgotten. However, it leaves drivers only a short time to interpret the hazardous situation and find the appropriate response. The late warning may even disrupt an ongoing braking process. Thus, the probability of collision would be increased. A triangular distribution of general in-vehicle message usefulness has been proposed (Sohn et al., 2008). The distribution indicated that the usefulness of the warning message is impaired if the warning is displayed too early or too late. Accordingly, there should be an optimal range of lead time between early and late warnings, considering the tradeoff between sufficient time to respond and trust.

There are experiments providing important insights into the effects of alert timing in emergent rear-end collision events (e.g., the lead time was shorter than 2.5 s) (Abe & Richardson, 2004, 2005, 2006; Lee et al., 2002; McGehee et al., 1998a, 1998b) and emergent and non-emergent right-angle red-light running events at intersections (e.g., the lead time was between 2.5 s and 5.5 s) (Yan, Zhang, & Ma, 2015), but other common collision scenarios remain to be studied. In the study involving red-light running events, still, the authors did not control the visual cue so that drivers might be able to perceive and respond to the impending collisions in ahead of the delivery of warning messages. Therefore, the effects of lead time may be confounded by the visual cues in those studies. A possible means of bridging this gap is to design common collision scenarios in which the driver can only rely on the warning messages to learn about and respond to the upcoming collision. Moreover, a wider range of lead times, including extreme short and long lead times, should also be investigated to study driver response in both emergent and non-emergent scenarios. This can provide a comprehensive picture of how lead time affects driving performance and thus improve the effectiveness of CWSs.

Besides lead time, researchers found that other factors might also influence the effectiveness of warning messages. Patten et al. (2006) concluded that drivers with better training and experience were able to automate driving more effectively compared with those with less driving experience in accordance with theoretical psychological models (the skill–rule–knowledge-based framework) (Rasmussen, 1987). Compared with novice drivers, experienced drivers were found to drive faster and have better performance in adjusting their driving speed appropriately when confronted with a hazard (Mueller & Trick, 2012). Compared with experienced drivers, novice drivers had incomplete inspections of the roadway for potential hazards and were less sensitive to road complexity. When responding to emergencies, the novice drivers' speed reduction was less and their response time was longer (Cavallo & Laurent, 1988; Deery, 2000; Markkula et al., 2012; Mueller & Trick, 2012; Patten et al., 2006; Underwood, 2007; Underwood et al., 2002). Additionally, the instantaneous driving speed when the warning message sounded was found to affect driver response to the upcoming collision. According to the laws of kinematics, in order to avoid a collision or reduce the damage due to a collision, the driver with a higher speed has to brake harder than those with lower speed when confronted with the same headway or distance to the collision location. This may put more pressure on the driver and affect the driver's response process (Brown, Lee, & McGehee, 2001; Hirst & Graham, 1997; Lee et al., 2002).

The overall objective of this research is to investigate the effects of lead time on a driver's response to various collision scenarios with a laboratory driving experiment by controlling the effects of lifetime driving experience and driving speed. Additionally, the triangular distribution of the effectiveness of warning messages proposed by Sohn et al. (2008) will be tested with driving performance. The safety benefits of warning messages and measures of the driver response process (Lee et al., 2002) were calculated and analyzed using the experimental data to explore the optimal lead time.

2. Methods

2.1. Participants

Thirty participants (22 males, 8 females) with ages ranging from 18 to 26 years (Mean = 21.07, SD = 2.53) took part in this study. Their lifetime driving experience ranged from 1250 to 275,000 miles (Mean = 35,732, SD = 60,139). To be more specific, the average time since having obtained a U.S. driver's license was 4.43 years (SD = 2.46) and the mean value of annual mileage was 7833 miles (SD = 6342). All of them had normal or corrected-to-normal vision and reported being free of psychiatric or neurological disorders. None of the drivers had previously participated in any simulator or crash avoidance studies.

2.2. Self-report questionnaire

All participants were asked to complete a questionnaire before engaging in the driving task. The questionnaire was designed to collect participants' demographic information (e.g., age and gender) and driving history (e.g., annual mileage and the year a U.S. driver's license was first issued).

2.3. Apparatus

A STISIM® driving simulator (STISIMDRIVE M100 K, Systems Technology Inc., Hawthorne, CA) was used in the study. The steering wheel was mounted to a desk. It includes a Logitech Momo® steering wheel with force feedback (Logitech Inc., Fremont, CA), a throttle pedal, and a brake pedal. The resting position of the throttle pedal is 38.2° (the angle between the pedal surface and the ground) and the maximal throttle input is 15.2°. For the brake pedal, the resting position is 60.1° and the maximal brake input is 28.6°. The STISIM simulator was installed on a Dell Workstation (Precision 490, Dual-Core Intel Xeon Processor 5130 2 GHz) with a 256 MB PCIe × 16 NVIDIA graphics card, Sound Blaster® X-Fi™ system, and Dell A225 Stereo System. Driving scenarios were presented on a 27-inch LCD with 1920 × 1200 pixel resolution. A speaker in front of the participant provided auditory information in the form of a digitized human female voice with a speech rate of ~150 words/min and loudness level of ~70 dB. Another speaker provided driving sound effects with a loudness level of ~55 dB.

The behavioral measures (time elapsed (s), speed (ft/s), acceleration (ft/s^2), and distance (ft)) from the driving simulator were automatically collected and outputted to another identical Dell Workstation. This computer would calculate the time to collision (TTC) in real time based on the subject vehicle's speed and acceleration at each time point. Once the calculated lead time reached the expected value (controlled lead time), the warning would occur. In addition to objective data quantifying the driver's vehicle control inputs, a video camera was used to record the driver's hands on the steering wheel and foot on the throttle and brake pedals for analysis of driving performance, reaction time, and response to collision events.

2.4. Driving scenarios

The Test Block was a simulated two-lane (in each direction) urban environment with traffic lights, and road signs (e.g., stop signs) involved. There were running vehicles in each direction. Speed limit signs with a constant speed limit of 45 mph were displayed 200 ft in front of the driver. Sixteen different collision scenarios were designed