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The influence of in-vehicle speech warning timing on drivers' collision avoidance performance at signalized intersections

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ABSTRACT

Collision warning systems have been identified as an effective technique for avoiding accidents. In such a system, the delivery time of warning messages is a crucial factor that influences the success of collision avoidance. This study therefore contributes by providing experimental analyses on a range of delivery times of warning messages, which has been overlooked in past studies. Using simulator-based techniques, experimental scenarios are specifically designed for accounting the red-light-running events at intersections and drivers are recruited to test on different settings of warning timings. Several measures including brake reaction time, alarm-to-brake-onset time and deceleration are adopted as reflections of drivers' performances under the collision avoidance process and they are connected to several factors by mixed effect models. According to the results, the collision warning system actually can largely reduce the occurrence of red-light-running collisions, more importantly it reveals the influence of warning timings within the predefined ranges and 4.0 s or 4.5 s may be a proper warning timing for the right-angle collisions accused by red-light-running vehicles in this study. Besides, effects from directional information embedded in warning messages are also investigated in this study. Findings are important to the design of collision warning systems especially in the aspect of warning timings.

1. Introduction

Among all traffic crashes, a large portion of them were occurred at intersections (PIARC, 2008). For instance, the crashes occurred at junctions in Norway account for about 40% (Elvik and Vaa, 2011) of all crashes. In the United States, the intersection or intersection-related crashes account for approximately 27% of all crashes (FHWA, 2011). In fact, intersection areas contain many confliction spots, and intersection-related areas usually have many traffic markings and signs that demand additional mental workload of drivers. These aspects may highly enhance the chance of collisions especially when conflicting vehicles appear. Accident data showed that the most important reason of traffic accidents at intersections was red light violation behavior. For example, in the US, red light running (RLR) contributed to around 260,000 crashes each year of which about 750 were fatal (Retting et al., 1999). Red light running crashes were also found to be more severe than other types of crashes (Yousif et al., 2014). Towards this, the collision warning system (CWS) is developed as an important tactic approach for avoiding crashes. RLR-CWS detects all vehicles approaching an intersection and identifies RLR vehicles based

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on vehicles' real-time positions and speeds with sensors equipped in vehicles and devices at intersections, such as detecting radar. If a RLR vehicle is approaching the intersection, RLR-CWS can timely provide warning information to drivers in order to avoid the potential collision with the RLR vehicle (Atev et al., 2004; King and Refai, 2011). Usually, it posts lights or sound signals to drivers if potential crashes are detected. Such a system will affect driving performances and collision-avoidance abilities of drivers and further affect the success rates of collision avoidance.

RLR-CWS is one of technology-based solutions to enhance drivers' crash response capability in hazardous situations. The collision warning technologies have been widely explored for their application scenarios, such as detecting pedestrian conflicting with vehicles by stereo vision (Llorca et al., 2012), evaluating different types of Cooperative/Chain Collision Avoidance applications in a freeway and an urban road scenarios (García-Costa et al., 2013) and releasing warning to unprotected right-turning vehicles at two-way stop-controlled rural intersections (Dabbour and Easa, 2014). Past studies have illustrated many advantages of CWS in mitigating crashes. For example, Jamson et al. (2008) indicated that all drivers could benefit from the forward collision warning system. Ben-Yaacov et al. (2002) found that collision warning systems could help drivers estimate headway more accurately and consequently to maintain longer and safer headways. Lee et al. (2002) showed that, compared with the no-warning condition, an early rear-end collision avoidance warning system reduced the number of collisions by 80.7% and the collision severity by 96.5%.

In such warning systems, auditory messages are usually used to remind drivers of possible hazardous situations. Liu and Jhuang (2012) showed that auditory message with spatial compatibility could significantly improve drivers' performance in reacting to the divided attention task and making accurate stimulus–response task decisions. Compared to the simple beep sound, speech messages were suggested because they could lead to a significant reduction of perception-reaction time of drivers (Chang et al., 2008).

After receiving a warning message, drivers need certain amount of time for reacting and then performing appropriate actions to avoid the crash. Therefore, the delivery time of warning messages could seriously influence the effectiveness of the warning system (Janssen and Nilsson, 1993; Ho and Spence, 2009; Tang and Yip, 2010). Werneke and Vollrath (2013) found that the early warning signal showed a positive effect in avoiding accidents at intersections. In fact, drivers could avoid most collisions if the warning messages were delivered in advance of the potential accidents with sufficient amount of time. Lee et al. (2002) found that later warning timing was also able to reduce collisions, but it was less effective than the earlier warning timing.

Abe and Richardson (2006) indicated that drivers' trust would be reduced if they had already made a decision to brake prior to an alarm. Under such a condition, drivers were more likely to ignore the system and relied on their individual judgments of impending collisions (National Highway Traffic Safety Administration, 2005). Abe and Richardson (2004) tested three different conditions of warning timing: early timing, middle timing and late timing under a forward collision warning system. The results indicated that early alarm timing would lead to well-prepared responses to an imminent collision than middle and late timing. However, earlier warning timing was more likely to be functioned as a false alarm which in turn leaded to a reduction in future use of the collision warning system (Seller et al., 1998).

Therefore, the delivery time of warning messages is a crucial factor to the design of CWS. With an appropriate setting of warning timings, CWS should be able to provide drivers with in-time, precise and reliable forecasts of impending accidents. In fact, there are limited studies considered this aspect in past, and existing literatures have only examined qualitative influence of warning timings. For example, the influence of in-advance deliver times of warning message was investigated using two comparative categories: early timing and late timing (Werneke and Vollrath, 2013; Abe and Richardson, 2005, 2006), or three categories: early timing, middle timing and late timing (Abe and Richardson, 2004). There still lacks analyses on a range of warning timings, which actually can illustrate more detailed relationships between different warning timings and drivers' performances on collision avoidances. With more defined categorization of warning timings, it is also useful to find a more appropriate range of warning times for further design of collision warning systems.

In addition, directional information is a part of the warning messages, which can inform drivers with the orientation of potential collisions. In detail, the directional information indicates whether the direction of collision is on the drivers' left side or right side. Such information is supposed to reduce drivers' mental workload by narrowing their vision of attentions and therefore might help drivers take timely crash avoidance actions. However, Yan et al. (2014) concluded that a directional warning may delay the mental processing of the warning information and cause insufficient decelerations under a late warning timing (3 s). Thus, the directional information combined with different warning timings could result in various crash avoidance behaviors and performances, which will be inspected in this study.

Towards this end, this study is going to investigate the impacts of warning timings and directional information on collision avoidance performance based on driving simulator experiments, which have demonstrated great potentials for examining the influence of CWS on driving performance (Suetomi et al., 1995; Lee et al., 2002; Yamada, 2002; Becic et al., 2013; Fort et al., 2013; Wu et al., 2014). More specifically, instead of use arbitrarily designed earlier and later warning timings, this study initially discusses a practical range of in-advance delivery time of warning messages (varied from 2.5 s to 5.5 s) for avoiding collisions from RLR vehicles and examines drivers' reactions and the effectiveness of collision avoidance under a set of continuously scatter points within the predefined range of warning timings. In addition, the different in-advance delivery times are also combined with a binary choice of directional information of the warning messages.