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Brake reactions of distracted drivers to pedestrian forward collision warning systems

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ABSTRACT

Introduction: Forward Collision Warning (FCW) can be effective in directing driver attention towards a conflict and thereby aid in preventing or mitigating collisions. FCW systems aiming at pedestrian protection have been introduced onto the market, yet an assessment of their safety benefits depends on the accurate modeling of driver reactions when the system is activated. This study contributes by quantifying brake reaction time and brake behavior (deceleration levels and jerk) to compare the effectiveness of an audio-visual warning only, an added haptic brake pulse warning, and an added Head-Up Display in reducing the frequency of collisions with pedestrians. Further, this study provides a detailed data set suited for the design of assessment methods for car-to-pedestrian FCW systems. *Method*: Brake response characteristics were measured for heavily distracted drivers who were subjected to a single FCW event in a high-fidelity driving simulator. The drivers maintained a self-regulated speed of 30 km/h in an urban area, with gaze direction diverted from the forward roadway by a secondary task. *Results*: Collision rates and brake reaction times differed significantly across FCW settings. Brake pulse warnings resulted in the lowest number of collisions and the shortest brake reaction times (mean 0.8 s, SD 0.29 s). Brake jerk and deceleration were independent of warning type. Ninety percent of drivers exceeded a maximum deceleration of 3.6 m/s^2 and a jerk of 5.3 m/s^3. *Conclusions*: Brake pulse warning was the most effective FCW interface for preventing collisions. In addition, this study presents the data required for driver modeling for car-to-pedestrian FCW similar to Euro NCAP's 2015 car-to-car FCW assessment. *Practical applications*: Vehicle manufacturers should consider the introduction of brake pulse warnings to their FCW systems. Euro NCAP could introduce an assessment that quantifies the safety benefits of pedestrian FCW systems and thereby aid the proliferation of effective systems.

1. Introduction

Driver distraction is a major factor in vehicle-to-pedestrian collisions. Approximately one third of fatal pedestrian accidents in Japan are caused by distracted drivers (ITARDA, 2012), a conclusion further supported by recent in-depth analyses of Japanese naturalistic driving data that found that the primary cause of vehicle-to-pedestrian collisions is the diversion of drivers' attention to something other than the pedestrian at risk (Habibovic, Tivesten, Uchida, Bärgman, & Ljung Aust, 2013).

In situations of potential conflict, Forward Collision Warning (FCW) systems may be effective in directing driver attention towards the conflict and thereby help prevent or mitigate a collision. Automated Emergency Braking (AEB) may also prevent or mitigate collisions by braking the car automatically without driver input in certain conditions. FCW and AEB systems designed with the aim of protecting pedestrians have recently been introduced on the car market (Lubbe & Davidsson, 2015).

FCW systems make use of auditory, visual, and haptic Human Machine Interfaces (HMIs) and must balance driver acceptance with effectiveness in terms of allowing time for a driver to brake the vehicle. The earlier and more intrusive the warning, the more effectively a system can prevent collisions. But at the same time, driver acceptance of such systems decreases, and it has been suggested that drivers are then more likely to ignore the system, turn it off, or refrain from having such systems installed (Lubbe & Davidsson, 2015). This claim is empirically supported by an observational study of car owners' active safety settings: Lane Departure Warning, which was more annoying, was found to be switched off more often than FCW, which was less annoying (IIHS, 2016). A FCW system might therefore act as an Imminent Crash Warning with a rather late activation, aiming for immediate driver reaction, or as a Cautionary Crash Warning with early activation, aiming at directing attention and raising risk awareness, or may incorporate both functions in a triggered approach (Campbell, Richard, Brown, & McCallum, 2007; Naujoks, Grattenthaler, & Neukum, 2012).

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Assessment methods for evaluating the safety benefit of pedestrian active safety systems including AEB and FCW are under development by Euro NCAP (Euro NCAP, 2015a, 2015b) and NHTSA (Yanagisawa, Swanson, & Najm, 2014). Much attention has been focused on AEB; the automated nature of these systems requires no driver input and simplifies the development of test and evaluation procedures. The Euro NCAP pedestrian active safety assessment, introduced in 2016, includes AEB and FCW evaluation. Euro NCAP has a part score related to AEB effectiveness and a part score related to HMI evaluation. AEB is scored for its ability to reduce vehicle speed prior to a simulated pedestrian impact in four different test scenarios at driving speeds gradually increasing from 20 to 60 km/h. A maximum of 18 scoring points are assigned to each scenario, depending on the speed reduction resulting from testing. FCW is not tested for its ability to reduce impact speed, but is part of the HMI evaluation. FCW is assigned a score of 1 point if operating above 40 km/h and warning at a Time-To-Collision (TTC) of at least 1.2 s (Euro NCAP, 2015b). Further components of the HMI evaluation are an assessment of the system's ease of deactivation (2 points) and night-time operation (1 point). The overall active safety system score is weighted 5:1 for AEB to HMI. As the FCW activation accounts for one fourth of the HMI score, the balance between AEB and FCW is 20:1. Clearly, the relevance of FCW compared to AEB is low in Euro NCAP's assessment. However, the extent to which this reflects the actual safety benefits of these systems has yet to be analyzed.

Driver models, in particular assumptions of driver reaction times and response inputs, are essential in assessing the ability of FCW systems to reduce collisions (Brown, Lee, & McGehee, 2001; McLaughlin, Hankey, & Dingus, 2008). Brake response is more relevant to FCW benefit assessment than steer response as drivers are more likely to respond by braking even in situations where steering would have been more effective in avoiding collision (Adams, 1994). Crucial to the effectiveness of a given FCW system is driver brake reaction time (Brown et al., 2001), brake deceleration and brake jerk. Simply, the earlier and harder the brakes are applied, the higher the speed reduction. For the Euro NCAP safety benefit assessment of car-to-car FCW systems, brakes are applied by a driving robot with brake characteristics specified by the car manufacturer to achieve a deceleration of 4 m/s^2 within 0.2 to 0.4 s (Euro NCAP, 2015c). The specification of these characteristics for pedestrian FCW systems needs to reflect true driver behavior. Such behavior has attracted little attention thus far.

1.1. Brake response for car-to-car FCW

Braking reaction times to FCW have been studied for a variety of FCW systems in simulated car-to-car rear-end collisions (overviews for example in Campbell et al., 2007; Green et al., 2008; Mayer et al., 2011). When warned, drivers must take notice of the warning, decode and understand it, and respond (Ho & Spence, 2008).

Most FCW systems on the market use a combination of visual and auditory warnings (ADAC, 2011). Almost all existing FCW systems in passenger cars use visual displays in the instrument cluster (i.e. near the speedometer) while a few use head-up displays (HUD) projecting the warning signal onto the windscreen area (Wege, Will, & Victor, 2013). Visual displays can readily indicate distinctive threats using icons, but may not be noticed if the driver's view is diverted (Ho, Spence, & Tan, 2005). Head-Up Displays (HUD) can be located closer to the natural gaze direction of the driver to the forward roadway and may be less likely to divert driver attention from the traffic scene compared to displays in the instrument cluster, but it remains unclear whether HUD improves driver reaction compared to instrument cluster warnings (Wege et al., 2013). One aim of this study is to quantify the potential benefits of an added HUD to an audio-visual warning for pedestrian encounters.

Haptic warnings have only been recently introduced as warning interfaces; studies show a potential for improved driver reactions (Ho & Spence, 2008). Some haptic warnings are always noticeable (e.g. seat vibration, or brake pulse) and were shown to be effective in car-to-car rear-end collision driving simulator experiments (Chun, Han, Park, Seo, & Choi, 2012; Mohebbi, Gray, & Tan, 2009; Scott & Gray, 2008). Other haptic warnings depend on the driver being in contact with the warning interface (e.g. pedal vibration), which reduces their overall effectiveness (Campbell et al., 2007).

The findings for the effectiveness of a short brake pulse, as one specific type of haptic warning, are inconclusive. In a car-to-car rear-end collision driving simulator experiment, significantly lower absolute maximum brake deceleration for a brake pulse warning compared to an audio-visual warning was reported. Further, both audio-visual and brake pulse warnings were reported to elicit faster brake reaction than no warning at all by trend (approximately 0.4 s reductions), but the difference was not significant. (Lerner et al., 2011).

Brown et al. (2005) reported a reduced number of potential collisions due to driver braking for brake pulse warnings compared to no warnings in an intersection car-to-car collision warning test track study; however, brake reaction times are not significantly shorter for the brake pulse warning.

Kiefer et al. (1999) reported longer reaction times for brake pulse warnings combined with other warning modalities. Brake pulse–visual warnings lead to longer reaction times than audio-visual warnings alone in a car-to-car forward collision warning track study. In a driving simulator experiment of car-to-car rear-end collisions, Ljung Aust (2014) reported belt–pretensioning–audio and brake pulse–audio warnings having similar effectiveness in significantly reducing reaction times by approximately 0.3 s compared to an audio-visual warning. In a test track experiment of car-to-car rear-end collisions, Kolke, Gauss, and Silvestro (2012) reported reaction times shortened by one-third (approximately 0.3 s, non-significant) when a brake pulse was added to an audio-visual warning.

No studies can be found that measured brake reaction times for brake pulses warnings, separate or when combined with other warnings, in car-to-pedestrian conflicts. Another aim of this study, therefore, is to quantify potential benefits of adding a brake pulse to an audio-visual warning for pedestrian encounters.

1.2. Brake response for pedestrian FCW

Pedestrians are different from cars and the perceived criticality of and driver reactions to car-to-car FCW and pedestrian FCW are not necessarily the same. Pedestrians often enter the driver's field of view from the side (Wisch, Pastor, Zander, & Lorenz, 2012; Yanagisawa et al., 2014), and are a threat smaller in size than a car-to-car collision threat. Event criticality has been shown to influence driver reaction to FCW (Ljung Aust, Engström, & Viström, 2013). Thus, one cannot necessarily assume that the time needed to decode the warning and the driver response is equal for car-to-car and pedestrian threats. Maag, Schneider, Lübbeke, Weisswange, and Goerick (2015) studied drivers approaching vehicle and non-vehicle (including pedestrian) threats and found that driver response is stronger for vehicle threats. It seems thus necessary to study driver behavior in pedestrian encounters in order to obtain a driver model for pedestrian FCW assessment.

The differences observed between warning timings in car-to-car FCW and car-to-pedestrian FCW provides another motivation to study pedestrian FCW. For car-to-car FCW studies, typical ranges are from 2 to 5 s TTC (Jenkins, Stanton, Walker, & Yong, 2007); for example, TTC is 5 s in Mohebbi et al. (2009), 4 s in Chun et al. (2012) and both 3 and 5 s in Scott and Gray (2008). Car-to-pedestrian FCW was measured to activate at a TTC of 1.8 s in a production vehicle (Matsui, Han, & Mizuno, 2011), and thus appears to warn later. Warning time is known to influence driver reaction (e.g. Hirst & Graham, 1997; Scott & Gray, 2008).

Studies of driver reaction times to pedestrian collisions in simulated vehicles are sparse. Straughn, Gray, and Tan (2009) reported steering reaction times for pedestrian FCW. For a warning given at 4 s TTC, haptic

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