EXAMINING THE EFFECTIVENESS OF FORWARD COLLISION WARNINGS FOR DROWSY DRIVERS

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Summary: Forward collision warnings (FCW) offer the potential to reduce frontal crashes by alerting drivers and are becoming standard in vehicles. These systems are largely intended to alert distracted drivers, but a pending question is the efficacy of FCW alerts for other types of impairment that might slow reaction time. To that end, this study examined the effectiveness of auditory and haptic FCW for drowsy drivers using a high-fidelity motion-base driving simulator. Overall, there was no evidence of that FCWs altered the response behavior of drowsy drivers relative to a group of drowsy drivers that did not receive a warning. The results are discussed in terms of their implications for design of advanced driver assistance systems (ADAS) and driver state monitoring.

INTRODUCTION

Advanced driver assistance systems (ADAS) are rapidly becoming commonplace in new vehicles. One such ADAS system, forward collision warning (FCW), alerts the driver to an impending forward collision. Rear-end collisions account for approximately thirty percent of fatal crashes (NHTSA, 2014). Forward collision warnings therefore provide the potential to reduce crashes and mitigate crash severity. Importantly, FCWs do not take control of the vehicle from the driver, but instead require that the driver shifts his or her attention and selects and executes an appropriate response in a timely fashion.

A substantial body of research shows that FCW alerts are effective in reducing distraction-related crashes and mitigating crash severity. Lee and colleagues, for example, showed a significant reduction in forward crashes and crash severity with a FCW compared to no warning for distracted drivers. Interestingly, Lee and colleagues also found a benefit of FCW for undistracted drivers, suggesting that the warnings may speed responses even when drivers are focusing on the forward events. Mohebbi, Gray, and Tan (2009) similarly showed a benefit of both tactile and auditory warnings over no warning for distracted driver response time. The existing body of research on FCW for distracted drivers demonstrates the effectiveness of both auditory and vibrotactile warnings. Scott and Gray (2008) compared the effectiveness of auditory, visual, and tactile warnings in a driving simulator. Their results suggest that tactile warnings were most effective in reducing RT relative to a no-warning baseline (see also Ho, Reed, & Spence, 2006; Mohebbi et al., 2009). Ho, Reed, and Spence (2007) found that multimodal warnings resulted in significantly faster responses relative to unimodal warning conditions.

While the above research highlights the efficacy of FCW in distracted driving situations, the potential benefits of FCW alerts for other types of driver impairment are poorly understood.

Specifically, driver drowsiness is thought be a considerable contributor to annual crashes. A National Highway Traffic Safety Administration report of crash data from 2005 to 2009 attributed 83,000 crashes per year, and 886 fatal crashes per year, to drowsy, fatigued, or sleeping drivers (NHTSA, 2011). Over that five-year period, these factors contributed to 5,021 fatalities. Recent research using multiple imputation approaches on FARS and GES data suggest the number of drowsy driving crashes to be underreported (Tefft, 2014).

Like distraction, drowsiness and sleep deprivation impair cognitive function, sustained attention, and response time (e.g., Doran, Van dongen, & Dinges, 2001; Jackson et al., 2013). There is thus reason to hypothesize that FCW may speed driver responses to unexpected forward collision events by helping them detect the onset of the need to respond. Unlike distraction, however, drowsy drivers tend to be looking at the forward roadway and are therefore might be more likely to detect the onset of a forward collision event and thus show a reduced benefit of FCW relative to distracted drivers.

The goal of this study was to evaluate the effectiveness of forward collision warnings for drowsy drivers. Two warning modalities, an auditory alert and haptic seat vibration, were compared against a no warning condition in a high-fidelity driving simulator. If FCW proffer a benefit for drowsy drivers, we expected to find fewer crashes, reduced crash severity, and faster response initiation for drivers with the FCW compared to those without.

METHOD

Participants

Forty-eight licensed adult drivers (ages 21-32; 50% male) participated in the study. Participants provided written informed consent prior to participating in the study. Seventeen participants were excluded from the analysis for the following reasons, resulting in a final sample of thirty-one drivers:

- Drivers were not identified as alert (i.e., not drowsy), based on the Objective Rating of Drowsiness scale (ORD; Wierwille & Ellsworth, 1994) score of 2 or less.
- The FCW event failed to fire due to technical issues (two participants)
- Drivers failed to receive the FCW alert due to technical failures (four participants)
- Speed was less than 30mph when the event was triggered, which interfered with event dynamics (seven participants)

Apparatus

Data were collected at the University of Iowa National Advanced Driving Simulator using the high-fidelity full-motion NADS-1 driving simulator. The simulator consists of a 24-foot dome in which an entire car is mounted. All participants drove the same vehicle, a 1996 Malibu sedan. The motion system, on which the dome is mounted, provides 400 square meters of horizontal and longitudinal travel and ±330 degrees of rotation. The driver feels acceleration, braking, and steering cues much as if he or she were actually driving a real vehicle. Each of the three front projectors has a resolution of 1600 x 1200; the five rear projectors have a resolution of 1024 x 768. Data were sampled at 240 Hz.

Driving Task

The driving task was composed of three nighttime driving segments. The drive started with an urban segment composed of a two-lane roadway through a city with posted speed limits of 25 to 45 mph with signal-controlled and uncontrolled intersections. An interstate segment followed and consisted of a four-lane divided expressway with a posted speed limit of 70 mph. The drives concluded with a rural segment composed of a two-lane undivided road with curves. These three segments mimicked a drive home from an urban parking spot to a rural house via an interstate. Participants received recorded audio navigational instructions to guide them through the route. To minimize learning effects, three versions of the drives were created and each participant was assigned to two of the three drives in a counterbalanced order.

Lead Vehicle Reveal (LVR) Event.

The LVR event occurred at the end of the thirty-five minute drive in the rural portion of the route. Following ten minutes of driving along a straight two-lane rural road, participants passed a 40mph speed limit sign and heard an audio prompt telling them to follow the vehicle ahead at the posted speed limit. A lead vehicle (LV) then pulled out in front of participants from a parked location with an initial time headway of fifteen seconds. The lead vehicle then slowly reduced its headway from 10.4s to a target gap of 2.4s. A researcher manually triggered the LVR event when at least 120 seconds passed, once headway time was between 0 and 2.7 seconds, and the driver was identified as drowsy based on an online rating from the ORD scale or seven minutes had passed. Once triggered, a stopped vehicle was placed 216 feet in front of the driver. The original lead vehicle swerved around the stopped vehicle, requiring the driver to execute a rapid response to avoid a collision (Figure 1). No vehicles were present in the opposite lane.

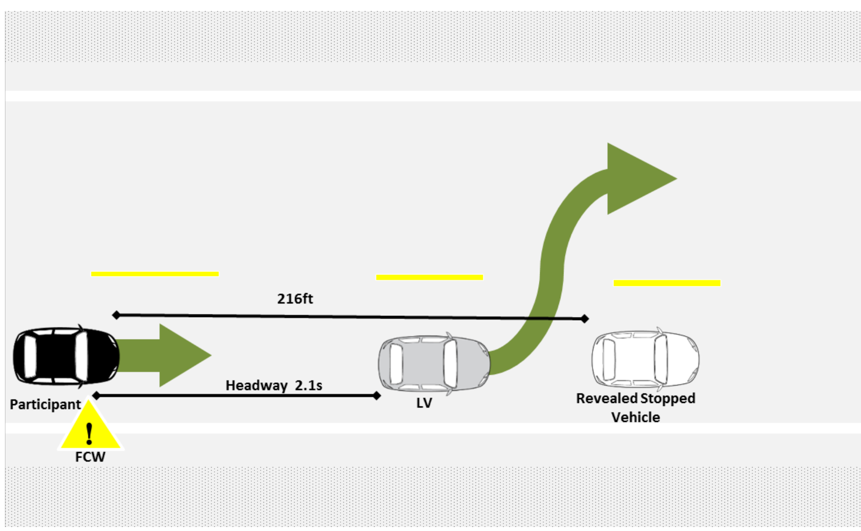

Figure 1. Diagram of the lead vehicle reveal event

Forward Collision Warnings.

The study was a between-subjects design with three warning conditions. One-third of the drivers received no FCW, referred to hereafter as the no-warning condition. One-third of drivers received an auditory alert consisting of a series of several loud beeps. The final third of participants received a haptic warning consisting of a series of rapid pulses in the front portion of the seat. Both the audio and haptic alerts triggered when time-to-collision from the revealed stopped vehicle was 2.1 seconds.

Procedure

Participants completed three visits. The first visit consisted of a screening drive for simulator sickness, a health screening for blood pressure, heart rate, drug use, and pregnancy, and questionnaires to establish study eligibility. The next two sessions were overnight drives. Participants were asked to remain awake from 7am on the day of the visit until arrival for the study (between 5pm and 7pm) and asked to refrain from caffeine beginning at 12pm the day of the visit. Wakefulness was monitored throughout the day via a Motionlogger Actigraph (Ambulatory Monitoring, Ardsley, NY). Upon arrival for each of the two overnight visits, activity data was confirmed and breath-alcohol (BAC) levels were obtained with an Alco-Sensor IV (Intoximeters, Inc., St. Louis, MO) breath alcohol-testing instrument. BAC levels over 0.00% disqualified participation in the study. Participants then entered a darkened conference room where they were asked to remain awake until their study drive. To manipulate drowsiness levels, each participant completed one drive between 10pm and 2am and the other between 2am and 6am. The order of these drives was counterbalanced across participants and drivers only received the final LVR event during the drive in their final session. The two drowsy driving sessions were spaced at least one week apart. To confirm that drivers were indeed drowsy during the final event, drowsiness was recoded post-hoc in the sixty seconds preceding triggering of the event using the Objective Rating of Drowsiness (ORD) scale (Wierwille & Ellsworth, 1994). Video was reviewed by two independent raters and a third rater settled any differences. Only drivers rated as moderately drowsy (ORD level 3) or extremely drowsy (ORD levels 4 and 5) were included in analyses.

RESULTS

The goal of this study was to evaluate the potential safety benefit of FCW for drowsy drivers. Analyses were conducted as ANOVAs with FCW condition and drowsiness level (moderately drowsy, severely drowsy) as between-subjects factors. The following sections address whether FCW alerts reduced crashes and speeded driver response times relative to the no-warning group.

Do FCW Alerts Reduce Crashes and Crash Severity?

Crashes were defined as any portion of the driver's vehicle intersecting with any portion of the revealed stopped vehicle. Crashes were infrequent; of the thirty-one drivers included in the sample, only two collided with the revealed vehicle. One crash occurred in the no-warning group and one in the haptic group. Adjusted minimum time-to-collision (AMTTC) was calculated as a measure of severity. AMTTC is defined as the time that a driver has to avoid a crash (Brown, 2005). Positive values represent the time to collision and negative values indicate collisions, with more negative values corresponding to greater collision severity. The main effect of FCW condition was not significant, $F(2,27) = 0.39$, $p = 0.68$ (Figure 2), nor was the main effect of drowsy level, $F(1,27) = 1.56$, $p = 0.22$, or the interaction between FCW mode and drowsiness, $F(2,27) = 0.60$, $p = 0.56$.

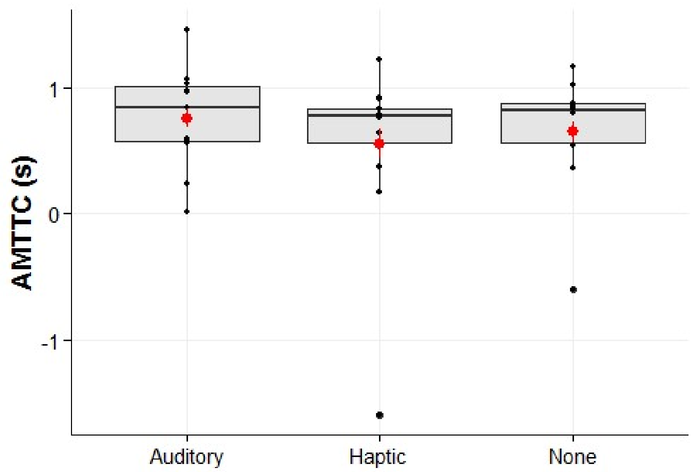

Figure 2. Adjusted minimum TTC by FCW warning type. Boxplots represent medians, first and third quartiles, with whiskers representing outliers. Red points represent means with standard error bars.

Do FCW Speed Response Time?

To examine the effect of FCW on driver response time, we examined both accelerator release and brake press RT. Reaction times were calculated from the time at which the LVR event was triggered. Accelerator release time was defined as the time to fully release the accelerator pedal and provides an index of response initiation. The main effect of FCW condition was not significant, $F(2,27) = 0.39$, $p = 0.68$, nor was the main effect of drowsy level, $F(1,27) = 0.08$, $p = 0.79$, or the interaction between FCW mode and drowsiness, $F(2,27) = 1.04$, $p = 0.37$. Brake press reaction time was defined as the time it took the driver to depress the brake pedal with three or more pounds of force. Brake RT provides a measure of response execution. The main effect of FCW condition was not significant, $F(2,27) = 1.14$, $p = 0.34$. The main effect of drowsy level was marginally significant, $F(1,27) = 3.38$, $p = 0.08$, with severely drowsy drivers braking slower than moderately drowsy drivers (Figure 4). The interaction between FCW mode and drowsiness was not significant, $F(2,27) = 1.04$, $p = 0.37$.

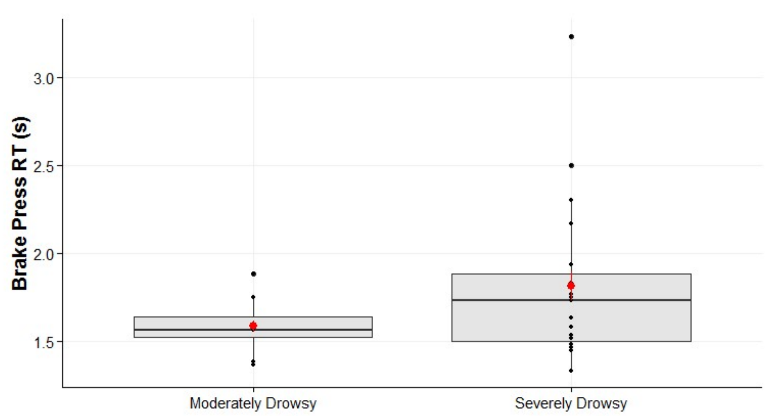

Figure 3. Boxplots brake press response time across FCW conditions. Boxplots represent medians, first and third quartiles, with whiskers representing outliers. Red points represent means with standard error bars.

DISCUSSION

The goal of this study was to evaluate the potential safety benefit of FCW alerts for drowsy drivers. Whereas previous research has shown reduced crashes and faster response time with an FCW for distracted drivers, the present study found no evidence of a benefit for drowsy drivers. That said, the present results also fail to show evidence of a cost associated with FCW alerts. Drivers in the present study tended to respond similarly with or without forward collision warnings, both auditory and haptic.

As predicted, drowsiness had a detrimental effect on driver response time, with drowsier drivers (based on ORD score) showing delayed brake response times relative to less drowsy drivers. This result is consistent with previous literature showing degraded attention resulting from sleep deprivation and fatigue (e.g., Wierwille & Ellsworth, 1994). The present results indicate that moderately and severely drowsy drivers showed no difference in accelerator release time but a significant difference in brake response. This suggests that drivers at both levels of drowsiness took the same time (on average) to detect the threat, but severely drowsy drivers took longer to transition and execute a brake response.

The lack of an effect of FCW on drowsy driver response is interesting given the previous findings of a benefit for distracted drivers. A number of potential explanations could account for this finding. Unlike distracted drivers, drowsy drivers may have already been looking forward toward the location of the lead vehicle reveal event. This may have mitigated the potential orienting benefits of the FCWs. The vision-for-action processing stream is sensitive to basic visual stimuli such as looking and operates largely outside of conscious processing (Tijerina, 2015). Such a visual processing stream may have been at play with drowsy drivers, allowing drivers to respond appropriately to the lead vehicle reveal threat in spit of impaired cognitive functioning.

Interestingly, Lee and colleagues (2002) showed a benefit of FCW even for undistracted drivers, who presumably were looking at the forward roadway much like drowsy drivers. It is unclear why drowsy drivers failed to show a similar benefit. One possibility is that cognitive impairment associated with drowsiness interfered with interpretation of the warning signal such that by the time drivers interpreted the warning they were already responding to the event.

Two limitations are worth mentioning in the FCW results. First, sample size was relatively small after removing non-drowsy drivers and dividing the sample based on level of drowsiness. This small sample may have limited the ability to detect effects, particularly given the inter-individual variability associated with drowsiness. Second, the above analyses lacked a true non-drowsy, non-distraction baseline control, so it is difficult to interpret whether drowsiness slowed overall response behavior.

In sum, these results provide no evidence of either a benefit or cost for FCW alerts for drowsy drivers. As ADAS become more common in vehicles, it will be important to consider the interaction between different driver states and advanced safety technology.

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