



Gaze position modulates the effectiveness of forward collision warnings for drowsy drivers

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ABSTRACT

Advanced driver assistance systems (ADAS) have the potential to prevent crashes and reduce their severity. Forward collision warnings (FCW) are quickly becoming standard across vehicle lineups and may prevent frontal crashes by alerting drivers. Previous research has demonstrated the effectiveness of FCW for distracted drivers, but their effectiveness for other types of impairment remains unknown. Like distraction, drowsiness can impair driver response time and lead to crashes. The goal of the present study was to evaluate the effectiveness of FCW for moderately and severely drowsy drivers using a high-fidelity driving simulator. Drowsy drivers were divided into three warning conditions during a revealed stop vehicle forward collision event: An auditory alert, a haptic seat vibration, and a no warning baseline. Results indicate that FCW were effective at speeding drowsy driver response, but only when the drowsy drivers were looking away from the forward roadway at the onset of the event. These results have important implications for ADAS technology and driver state monitoring systems.

1. Introduction

Advanced driver assistance systems (ADAS), including forward collision warning (FCW), automatic emergency braking, and lane departure warning, are quickly becoming standard across vehicle lineups. This expanding availability of ADAS technology has the potential to reduce crashes and crash severity, particularly from different types of driver impairment. Rear-end collisions account for approximately thirty percent of fatal crashes (NHTSA, 2014). By reducing, or at least mitigating such crashes, FCW have the potential to yield a large safety benefit (e.g., Kusano and Gabler, 2012).

Visual distraction remains a major contributing factor in rear-end crashes, with up to 60% of rear-end collisions attributed to driver inattention (Knipling et al., 1993). FCW that can shift the driver's attention back to the forward roadway with sufficient time to execute a collision avoidance response therefore have the potential to substantially reduce rear-end crashes. The potential benefits of FCW for distracted drivers are well demonstrated. Lee et al. (2002), for example, showed a significant reduction in forward crashes, crash severity, and response time for distracted drivers with an auditory-visual FCW. Mohebbi et al. (2009) similarly showed reaction time benefits for both tactile and auditory warnings over no warning for distracted drivers. The existing body of research on FCW for distracted drivers demonstrates the effectiveness of both auditory and vibrotactile warnings

(Scott and Gray, 2008; Ho et al., 2007; Mohebbi et al., 2009; Kramer et al., 2007). It is worth noting that both unimodal and multimodal warnings have shown benefits for distracted drivers, although some research does suggest an additional benefit for multimodal alerts (Ho et al., 2007). While much of the FCW research has been performed in driving simulators, the results are generally consistent with on-road results. Lerner et al. (2015) reported consistent relative benefits of FCW across both test track and simulator platforms.

While FCW have a demonstrated benefit for distracted drivers, little is known about their impact during other types of impairment, such as drowsiness. Driver drowsiness is another major contributor to fatal crashes. 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 5021 fatalities.

Drowsiness has well-demonstrated deleterious effects on the process underlying safe driving performance, including basic cognitive functions, sustained attention, and response time (e.g., Doran et al., 2001; Jackson et al., 2013). Drowsiness, particularly in its later stages, is also associated with long eyelids closures and microsleeps (Wierwille and Ellsworth, 1994), which may interfere with the driver's ability to detect the onset of a forward collision event.

Unlike visual-manual distraction, however, drowsiness does not necessarily force a driver's eyes from the forward roadway, meaning

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that drowsy drivers may be more likely to detect the onset of a forward collision event and therefore show a muted benefit of FCW. Limited research has explored the effect of FCW on drivers with their eyes on the road at the time of the hazard event. Although they were presumably not drowsy, even undistracted drivers in the study by Lee et al. (2002) benefited from the presence of an auditory-visual FCW system, suggesting that forward collision alert may assist drivers even when they are already looking at the forward road. Kramer et al., (2007) found a similar benefit of auditory-visual FCW for both distracted and undistracted non-drowsy drivers, though there was no benefit of unimodal auditory, visual, or vibrotactile warnings relative to no warning.

Alternatively, the so-called vision-for-action hypothesis suggests an automatic link between perception of an object or event and a specific predetermined action (see Tucker and Ellis, 1998). In the context of driving, this suggests that if drivers perceive an event, such as a lead vehicle swerving, this automatically primes a response, such as hard braking (Tijerina et al., 2010). This account would suggest that drowsy drivers who are looking forward at the time of the event might benefit less from FCW designed to reorient attention to the forward road.

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. These warning conditions were selected based on previous research on FCW methodology (Lerner et al., 2011) and were representative of some commercially-available FCW systems (e.g., the Tesla Model S), although the system did not include other ADAS such as automatic emergency braking. Drowsiness was manipulated via continuous hours awake, and post-hoc video coding was performed to classify drivers as moderately or severely drowsy.

We compared measures of hazard perception, response initiation, and collision avoidance across the three warning conditions and two drowsiness levels. Furthermore, we hypothesized that initial gaze position might be important in whether the FCW was effective. That is, drivers may only have benefited from the FCW if their eyes were off the road, either looking away or falling asleep. If this was the case, we expected to see an interaction between initial gaze position and warning effectiveness.

2. Method

2.1. Participants

Forty-eight licensed young adult drivers (ages 21–32; 50% male) provided informed consent and participated in the study. To confirm that drivers were indeed drowsy, drowsiness was recoded post-hoc video coding with the Objective Rating of Drowsiness (ORD) scale (Wierwille and Ellsworth, 1994) was performed in the sixty seconds preceding the lead vehicle reveal event. 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. Four drivers were classified as not drowsy and excluded from the analysis. Technical failures during the lead vehicle reveal event led to the exclusion of an additional six drivers. Finally, to ensure that event dynamics were consistent across drivers, seven drivers who were traveling less than 30mph were excluded from the analyses. These exclusions resulted in a final sample of thirty-one drivers. Table 1 provides a demographic breakdown of this final sample by FCW condition.

2.2. 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 inside which an entire car, a 1996 Malibu sedan, is mounted. The motion system, on

Table 1
Number of drivers (and crashes) by drowsiness level and gaze location.

	Auditory (N = 10)	Haptic (N = 12)	No Warning (N = 9)
Age (Years)	23.71 (2.14)	24.63 (3.58)	25.63 (3.20)
Male/Female	7/3	6/6	3/6
Moderately Drowsy (ORD level 3)	3	4	2
Severely Drowsy (ORD level 4 or 5)	7	8	7

which the dome is mounted, provides 400 square meters of horizontal and longitudinal travel and ± 330 degrees of rotation. Acceleration, braking, and steering motion cues are consistent with real driving. Data were sampled at 240 Hz.

2.3. Driving task

The driving task was designed to mimic a drive home from work late at night or early in the morning. The drive began with an urban segment (speed limit 25–40 mph), followed by an interstate segment (speed limit 70 mph), and then by a series of rural curves (speed limit 55 mph). The final section of the drive comprised a straight rural road with a 55 mph speed limit. This sparse roadway environment was designed to elevate drowsiness prior to the lead vehicle reveal event. Participants drove on the straight rural road for a fixed ten minutes. Auditory navigational cues guided the participant throughout 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.

2.3.1. Revealed stopped vehicle (RSV) event

The revealed stopped vehicle event occurred at the end of the thirty-five minute drive on the straight rural road. Following ten minutes on the 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 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 10.4 s to a target gap of 2.4 s. A researcher manually triggered the RSV event when at least 120 s passed, once headway time was between 0 and 2.7 s. Once triggered, a stopped vehicle was placed 216 feet in front of the driver. The original lead vehicle swerved left around the stopped vehicle (Fig. 1). No oncoming vehicles were present in the opposite lane.

2.3.2. 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 s.

2.4. Procedure

The study consisted of three visits. The first visit included a screening drive for simulator sickness, a health screening, and questionnaires to establish study eligibility. The next two sessions were overnight drives. Participants were asked to remain awake from 7 a.m. on the day of the visit until arrival for the study (between 5 p.m. and 7 p.m.) and asked to refrain from caffeine beginning at 12 p.m. the day of the visit. Wakefulness was monitored throughout the day via a

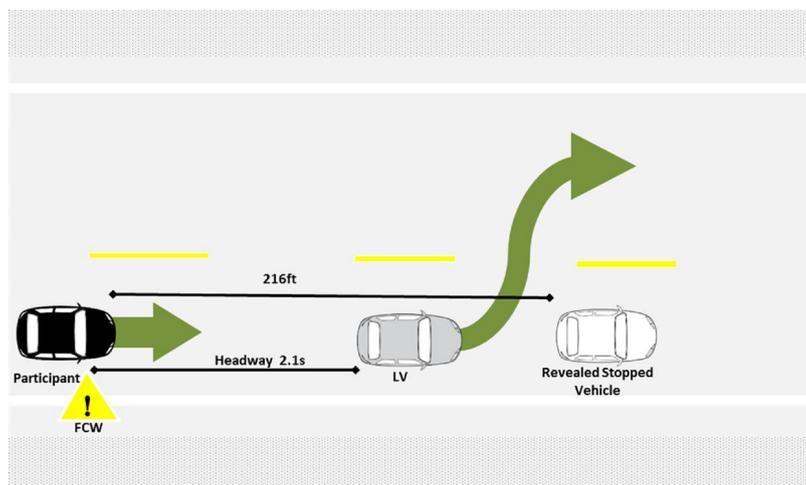


Fig. 1. Diagram of the revealed stopped vehicle.

Motionlogger Actigraph (Ambulatory Monitoring, Ardsley, NY). Upon arrival, activity data were confirmed and breath-alcohol (BAC) levels obtained with an Alco-Sensor IV (Intoximeters, Inc., St. Louis, MO). BAC levels over 0.00% disqualified participation. 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 10 p.m. and 2 a.m. and the other between 2 a.m. and 6 a.m. The drives were spaced at least a week apart and the order of the drive times was counterbalanced across participants. Importantly, drivers only received the RSV event in the final driving session. That is, each driver only experienced one RSV event at the end of the experiment. While it was predicted that drowsiness would be higher during the early morning drives, classification of drowsy state was made via post-hoc video coding, as described above, to provide a more accurate level of state classification. Table 1 shows a breakdown of drivers at each level of ORD-rated drowsiness, by FCW condition.

3. Results

3.1. Gaze location at event onset

We hypothesized the effectiveness of FCW would vary based on the driver’s gaze location at the onset of the revealed stopped vehicle event. That is, drowsy drivers who were not looking at the road because of a long eye closure or microsleep may have benefitted most from the re-orienting of attention with the FCW. To evaluate this hypothesis, we performed additional video coding of gaze position at the onset of the RSV event. Two independent raters coded driver gaze as either “Eyes Up” or “Eyes Down” at the onset of the FCW (or, in the case of the no warning condition, where the FCW would have triggered). If it is the case that forward collision warnings are beneficial for drowsy drivers whose eyes are off the forward roadway, we expected to find an interaction between warning presence (warning vs. no warning) and gaze location (eyes up vs. eyes down).

Table 2 shows a breakdown of driver gaze position by drowsiness level and crash outcome. All but one of the drivers with eyes down was rated as severely drowsy (ORD level 4 or 5). It is worth noting that all three crashes occurred with drivers who had their eyes down and were

Table 2
Number of drivers (and crashes) by drowsiness level and gaze location.

	Eyes Up (N = 20)	Eyes Down (N = 11)
Moderately Drowsy	8 (0 crashes)	1 (0 crashes)
Severely Drowsy	12 (0 crashes)	10 (3 crashes)

rated severely drowsy.

The following analyses were conducted as ANOVAs with drowsiness rating (moderately drowsy, severely drowsy), warning condition (auditory, haptic, no warning), and gaze location (eyes up, eyes down) as between-subjects factors. Paired comparisons with Bonferroni correction were performed to compare specific conditions or combinations of conditions, where appropriate.

3.2. Response time decomposition

To evaluate the impact of warnings on driver performance and safety, responses were decomposed into component segments (Lee et al., 2002). This decomposition comprised three measures: accelerator release time, accelerator-to-brake transition, and brake press time. Accelerator release time was the duration from the start of the event (i.e., the stopped vehicle reveal) until there was no longer force being applied to the accelerator pedal. This provides an index of initial hazard perception time. Accelerator-to-brake transition was defined as the time from the driver taking their foot off the accelerator until initial pressure, at least three pounds force, was applied to the brake pedal. Finally, time-to-maximum brake force was computed as the time from initial depression of the brake pedal to maximum depression of the pedal. These response thresholds were drawn from previous research using the NADS-1 simulator (e.g., Gaspar et al., 2016), and were selected to filter out “false alarm” responses such as the driver resting his foot on the brake. It is worth noting that twenty-eight of the thirty-one drivers executed a combined response consisting of: 1.) Releasing the accelerator, 2.) Pressing the brake, and 3.) Steering around the revealed stopped vehicle. The subsequent analyses focus on brake response behavior, consistent with previous FCW research (e.g., Lee et al., 2002).

3.2.1. Accelerator release time

As expected, drivers with their eyes up released the accelerator faster than drivers with their eyes down, evidenced by a significant main effect of gaze location, $F(1,29) = 12.82, p = .002$ (Fig. 2). Importantly, there was a significant interaction between gaze location and warning condition, $F(2,28) = 8.81, p = .01$, with faster responses in both the auditory ($p = .03$) and haptic ($p = .07$) warning conditions than that no warning condition when drivers had their eyes down, but no significant difference between either the auditory ($p = .25$) or haptic ($p = .95$) warning conditions and the no warning condition when drivers had their eyes up. The main effect of drowsy rating approached significance, such that severely drowsy drivers responded slower than moderately drowsy drivers, $F(1,29) = 3.91, p = .06$. The main effect of warning condition was not significant, $F(2,28) = 0.32, p = .73$.

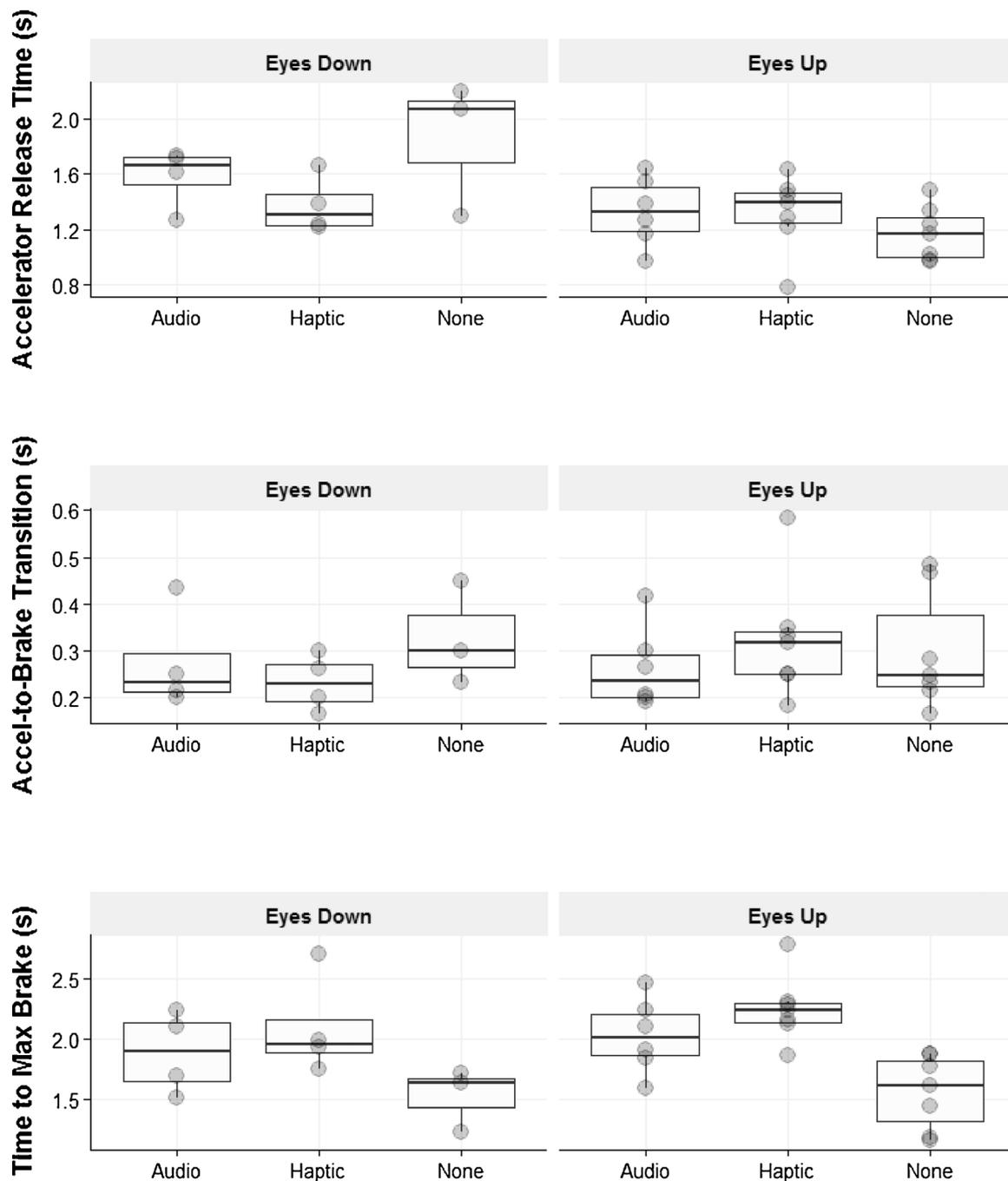


Fig. 2. Boxplots of response decomposition by warning condition and initial gaze location. Boxes represent medians and first and third quartiles. Points represent individual participants.

3.2.2. Accelerator-to-Brake transition

For accelerator-to-brake transition, neither the main effect of gaze location, $F(1,29) = 0.31, p = .58$, nor the interaction between gaze location and warning condition reached significance, $F(2,28) = 0.61, p = .56$. The main effect of warning condition was not significant, $F(2,27) = 0.28, p = .76$, as was the main effect of drowsiness rating, $F(1,29) = 1.72, p = .20$. Overall, as seen in Fig. 2, transition time was similar across warning conditions and gaze locations.

3.2.3. Time-to-maximum Brake

For time to reach maximum brake force, there was a significant main effect of warning condition, $F(2,28) = 12.73, p = .002$. Independent of initial gaze position, drivers in the no warning condition reached maximum brake force faster than drivers in either the auditory ($p = .01$) or haptic ($p = .0004$) warning conditions. This finding is

consistent with the results of Lee et al. (2002), who found larger time-to-max brake force values with a FCW than without. The main effect of initial gaze position was not significant, $F(1,29) = 0.49, p = .49$, nor was the interaction between gaze position and warning condition, $F(2,27) = 0.17, p = .84$. The main effect of drowsiness rating also failed to approach significance, $F(1,29) = 0.28, p = .60$.

3.3. Collision avoidance

Collisions were defined as any portion of the driver's vehicle intersecting with any portion of the revealed stopped vehicle. Collisions were infrequent, with just three of the thirty-one drivers colliding with the revealed stopped vehicle. Adjusted minimum time-to-collision (AMTTC) was calculated and used as a measure of severity. AMTTC is defined as the time that a driver has to avoid a crash (Lee et al., 2002;

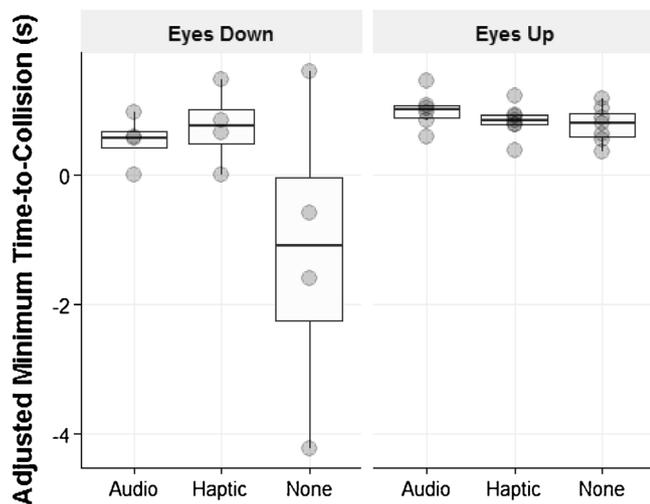


Fig. 3. Boxplots of adjusted minimum time to collision (AMTTC) by gaze location and warning condition. Circles represent individual data points. Boxes represent medians and first and third quartiles. Points represent individual participants.

Brown, 2005). Positive values represent the time to collision or available safety margin. Negative AMTTC represents how much sooner the driver would have needed to respond to avoid a collision.

There was a significant main effect of initial gaze location on AMTTC, with drivers with their gaze down having significantly lower AMTTC than drivers with their gaze up, $F(1,29) = 8.56, p = .008$. Furthermore, there was a marginally significant interaction between initial gaze location and warning condition, $F(2,28) = 2.83, p = .08$. Fig. 3 shows that drivers in the no warning condition with their eyes down had lower AMTTC than drivers in either the auditory ($p = .045$) or haptic ($p = .58$) warning conditions. There was also a significant main effect of drowsy rating, with drivers rated as severely drowsy having lower AMTTC than drivers rated as moderately drowsy, $F(1,29) = 6.78, p = .02$.

4. Discussion

The goal of this study was to evaluate the effectiveness of forward collision warnings for drowsy drivers. Previous research has shown a benefit of forward collision warnings for distracted drivers, particularly in situations where the driver is engaged with visual secondary tasks (e.g., Lee et al., 2002). Our results suggest that the effectiveness of FCW for drowsy drivers depends on where the driver is looking at the onset of the hazard event. That is, FCW significantly reduced initial response time and increased safety margins for drivers who were looking down or had their eyes closed at the start of the revealed stopped vehicle event. These benefits of FCW were absent for drivers who were looking up when the hazard began.

Previous studies found a benefit of FCW for distracted drivers (e.g., Lee et al., 2002). The present study shows a similar benefit for drowsy drivers who were looking away at the onset of the forward collision event. The response time decomposition suggests that the benefit of FCW for drivers not looking at the road was the result of faster hazard perception, evidenced by faster accelerator pedal release. For these drivers, the FCW did not speed subsequent brake response processes, either transitioning from the accelerator to brake pedal or increasing the force applied to the brake pedal. In fact, drivers with the FCW were slower to apply maximum brake force than drivers with no warning. For drivers whose eyes were on the road at the onset of the event, there were not significant differences in response behavior with and without a FCW, suggesting that there were no costs associated with the presence of the FCW, even though it did not speed response time. This result supports the inclusion of FCW in vehicles. That is, when drivers are

looking away from the road or closing their eyes, the FCW can reorient attention and speed response. When drivers are looking up at the driving scene, the FCW does not hamper response to a forward collision event. Care should be taken, however, to consider the potential impact on driver acceptance and trust. Warnings that occur too frequently or when the driver is already attending are likely to be perceived as false alarms or nuisance warnings, and may prompt system disuse (Parasuraman and Riley, 1997). Additional research is also needed to understand how warnings capture attention for drowsy drivers with regard to non-hazard events (see Rusch et al., 2013; Spence and Driver, 1994). That is, do the forward collision warnings produce exogenous orienting to both hazard and non-hazard targets in the environment, or is the effect of the FCW target-specific?

One surprising finding is the lack of a benefit of FCW for drivers looking up at the road. This finding is consistent with the vision-for-action processing stream (Tijerina, 2015) but somewhat inconsistent with previous studies that showed a benefit of FCW for undistracted alert drivers (Lee et al., 2002; Kramer et al., 2007). While many factors may have contributed to this difference in results, three specific factors are discussed below.

The first obvious difference between the present study and previous FCW research is that the present study examined drowsy drivers whereas drivers in the previous studies are assumed to have been normally-rested and alert. The complex physiological and cognitive changes associated with drowsiness could have changed the way drivers responded to warnings in both the eyes up and eyes down situations. As this is the first study to explore the effects of FCW on drowsy drivers, additional research is needed to replicate this finding.

The nature of the warnings also differed between these past studies and the present research. Lee et al. (2002) and Kramer et al. (2007) used multimodal auditory-visual alerts, whereas the present study used unimodal auditory and haptic alerts. Furthermore, Kramer et al. (2007) showed no benefit of unimodal warnings on alert undistracted drivers. Research on warning modality also suggests that multimodal alerts show advantages relative to unimodal alerts (Ho et al., 2006). Additional research is needed to explore whether multimodal FCW are beneficial for drowsy drivers with their eyes up in situations where unimodal alarms are ineffective. It is also worth noting that many currently-deployed FCW systems consist of multimodal warnings, strengthening the need to understand the impact of different combinations of warning modalities and timings across impairment types. Warning modality is also important to consider to the extent which it influences driver acceptance of FCW technology (Flanagan et al., 2016).

One final difference in methodologies is worth exploring. Lee et al. (2002) used a lead vehicle braking event and Kramer et al. (2007) presented a stopped vehicle in the road, whereas the current study used a revealed stopped vehicle event. The reveal event offers an additional visual cue, the lead vehicle swerving around the stopped vehicle, which attentive drivers may have been able to utilize to detect the onset of the event. Furthermore, the FCW used by Lee et al. (2002) also occurred at a shorter warning range, approximately 137ft, than the FCW in the present study that occurred at approximately 216ft. This means that drivers in the present study had slightly longer to respond than drivers in the Lee et al. (2002) study, and this additional time may have been most beneficial to drivers who were looking up at the onset of the event.

These results also speak to the potential importance of driver state monitoring in the context of ADAS technology. Driver state detection is now feasible using camera (driver-based) and vehicle-based data (e.g., McDonald et al., 2014). Drive state information could be used to augment warning systems, such as only providing a forward collision warning when the driver is classified as drowsy or distracted. Such state-contingent systems may be able to avoid alarms perceived as nuisance alerts. Although some research has explored the possibility of using driver state to augment ADAS (e.g., Tijerina et al., 2010), additional research is needed to compare such state-contingent systems with

more persistent technologies that do not consider driver state (see Rauch et al., 2009).

Nearly all of the drivers with their eyes down at the time of the event were rated as severely drowsy. This is not surprising, as long eye closures are one of the symptoms used to indicate higher levels of drowsiness on the ORD scale (Wierwille and Ellsworth, 1994). Given the nature of the stopped lead vehicle task, having eyes off the forward roadway was the most critical behavior leading to drivers failing to detect the onset of the event. Future research should explore the potential impact of other ADAS technology, such as lane departure warning and lane keeping systems, on drowsy driver performance. Lateral control ADAS has the potential to reduce single-vehicle run-off-road crashes, which are common among drowsy drivers. However, recent research suggests a possible lack of trust and acceptance in lane departure warning systems (Reagan and McCartt, 2016).

Our results are consistent with the larger body of drowsiness and fatigue work showing detrimental effects on human performance. Higher levels of drowsiness resulted in significant increases in reaction time, consistent with previous literature showing degraded attention resulting from sleep deprivation and fatigue (e.g., Wierwille and 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.

Several limitations in the present study are worth noting. First, sample size was small and consisted only of young adult drivers. To account for the small sample, warning conditions were combined for a warning/no-warning evaluation, which prevented comparison of the warning modalities. Follow-up research with a larger, more diverse sample across a broader range of drowsiness conditions will be an important next step in understanding the interaction of ADAS and driver drowsiness. Older drivers, for instance, often show specific physical and neurocognitive deficits that could influence the effectiveness of particular warning systems, although research with alert drivers suggests that both young and older drivers benefit from the presence of FCW (Kramer et al., 2007).

The present study compared moderate and severe levels of drowsiness in terms of response to the revealed stopped vehicle event. Additional research, utilizing the same testing environment, event parameters, and warning conditions, should investigate the key differences between drowsiness and other types of impairment, such as distraction or alcohol intoxication. Furthermore, understanding the interrelationship between different types of impairment (e.g., drowsiness and alcohol) will be an important next step in understanding the safety potential of ADAS technology. Finally, drowsiness classification was based on ratings from the ORD scale. While this is an established and validated research tool, it is important to understand drowsiness in terms of other, more objective, ground truth measures.

It is also worth considering that the present study utilized a high-fidelity driving simulator to estimate the potential benefits of FCW for drowsy drivers. Previous research suggests a high correspondence between simulator and test track results with respect to the relative benefits of forward collision warnings. In particular, Lerner et al. (2015) found similar FCW results using a test track and the NADS-1 simulator, the same simulator used in the present study. Future research should, however, identify whether the results observed with drowsy drivers also translate to on-road performance.

In summary, this study demonstrated the effectiveness of FCW for drowsy drivers whose eyes are off the road, with no evidence of an effect of FCW on drowsy drivers who were gazing at the forward roadway. These results express the importance of understanding driver state as ADAS technology continues to improve and becomes more common across vehicle fleets.

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