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Evaluating driver drowsiness countermeasures

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ABSTRACT

Objective: Driver drowsiness contributes to a substantial number of fatal and nonfatal crashes, with recent estimates attributing up to 21% of fatal crashes to drowsiness. This article describes recent NHTSA research on in-vehicle drowsiness countermeasures. Recent advances in technology and state detection algorithms have shown success in detecting drowsiness using a variety of data sources, including camera-based eye tracking, steering wheel position, yaw rate, and vehicle lane position. However, detection is just the first step in reducing drowsy driving crashes. Countermeasures are also needed to provide feedback to the driver, modify driver behavior, and prevent crashes. The goal of this study was to evaluate the effectiveness of in-vehicle drowsiness countermeasures in reducing drowsy lane departures. The tested countermeasures included different warning modalities in either a discrete or staged interface.

Methods: Data were collected from 72 young adult drivers (age 21–32) in the high-fidelity full-motion National Advanced Driving Simulator. Drivers completed a 45-min simulated nighttime drive at 2 time points, late night and early morning, where drowsiness was manipulated by continuous hours awake. Forty-eight drivers were exposed to one of 6 countermeasures that varied along 2 dimensions, type and modality. The countermeasures relied on a steering-based drowsiness detection algorithm developed in prior NHTSA research. Twenty-four drivers received no countermeasure and were used as a baseline comparison. System effectiveness was measured by lane departures and standard deviation in lateral position (SDLP).

Results: There was a reduction in drowsy lane departure frequency and lane position variability for drivers with countermeasures compared to the baseline no-countermeasure group. Importantly, the data suggest that multistage alerts, which provide an indication of increasing urgency, were more effective in reducing drowsy lane departures than single-stage discrete alerts, particularly during early morning drives when drivers were drowsier.

Conclusions: The results indicate that simple in-vehicle countermeasures, such as an auditory–visual coffee cup icon, can reduce the frequency of drowsy lane departures in the context of relatively short drives. An important next step is to evaluate the impact of drowsiness countermeasures in the context of longer, multiple-hour drives. In these cases, it may not be possible to keep drivers awake via feedback warnings and it is important to understand whether countermeasures prompt drivers to stop to rest. The next phase of this research project will examine the role of drowsiness countermeasures over longer drives using a protocol that replicates the motivational conditions of drowsy driving.

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Introduction

In 2014 there were 846 fatalities (2.6% of total fatalities) attributed to drowsy driving (NHTSA 2015). This total is likely an underestimation given challenges in crash reporting, and recent estimates suggest that drowsiness accounts for 6% of all crashes and 21% of fatal crashes (Tefft 2014; see also Klauer et al. 2006). Driver drowsiness is clearly quite prevalent, with 28% of drivers reporting having driven drowsy in the last month (National Sleep Foundation 2009).

In-vehicle driver state systems hold the promise of reducing drowsy driving crashes. These systems consist of 2 components, a detection system and a countermeasure. Detection systems use signals like erratic steering and lane departures to classify persistent conditions of drowsiness (Krajewski et al. 2009). Input data may also consist of camera-based eye measures (e.g., Dinges and Grace 1998), electric potential measures from the brain (e.g., Lin et al. 2005), or driver input to the vehicle such as steering wheel input (e.g., Brown et al. 2014; McDonald et al. 2014).

Current commercially available countermeasure systems provide feedback in the form of messages and alerts, the most common being the "coffee cup" interface, where a coffee cup icon appears on the instrument panel or infotainment system accompanied by an auditory alert. Some systems provide a binary alert (warning/no warning), whereas others provide continuous state information in the form of an "attentiveness" scale. Other systems provide vibrotactile feedback via the seat or steering wheel in conjunction with the visual icons. In most cases, drivers must

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acknowledge the warning messages by pressing a button to clear them.

Limited research has tested the effectiveness of feedback countermeasures for drowsy drivers. Berka and Lewindowski (2005) found that simple auditory warnings resulted in improved lane keeping. Fairclough and van Winwum (2000) showed that visual warnings improved lane keeping relative to no feedback. Grace and Steward (2001) presented drowsy drivers with combined auditory/visual warnings consisting of dashboard-mounted lieght emitting diode lights and an auditory tone, which improved driving performance and reducing subjective drowsiness over 4-h drives. Arimitsu and colleagues (2007) found that drowsiness-triggered seat belt vibration resulted in improved lane keeping and reduced subjective drowsiness (see also Heitmann et al. 2001; Takahasi and Yokoyama 2012). These previous studies suggest that several combinations of warning modality, particularly combinations of auditory, visual, and haptic, offer the potential to improve driving performance. Current commercial warning systems mainly consist of either discrete warnings (e.g., a coffee cup icon that appears when drowsiness is detected) or staged feedback, such as a scale that shows the level of driver attentiveness. The present study therefore included countermeasures consisting of different modalities and interface types (discrete, staged) to provide an accurate representation of current in-vehicle countermeasures.

The goal of the present study was to examine the effectiveness of drowsiness countermeasures for improving driving performance and reducing drowsiness. Countermeasures consisted of combinations of 2 interface types (discrete and stage) and 3 modalities (auditory–visual [AV], haptic, and combined AV + haptic), designed to simulate a range of current in-vehicle approaches to drowsiness mitigation. Drivers completed both early and late night drives with differing continuous hours awake to study countermeasure efficacy at different levels of drowsiness.

Drowsiness can be defined in a number of ways, including self-reports, subjective ratings, eye closures, and reaction time measures. In the present study, drowsiness was manipulated via continuous hours awake, with drivers being awake for at least 15 h preceding the driving study. Drowsiness-related crashes tend to be single-vehicle run-off-road events, often where no braking is observed prior to the crash (Knipling and Wang 1994). Interventions that reduce the risk of drowsy lane departures therefore have the greatest potential safety benefit. Therefore, lane departures where the driver was rated as drowsy using the Objective Rating of Drowsiness Scale (Wierwille and Ellsworth 1994) were used to define drowsy driving events to test countermeasure effectiveness. If countermeasures are effective at warning drivers or keeping them alert, we expected a reduction in drowsy lane departures and standard deviation in lateral position (SDLP) relative to a no-countermeasure group.

Method

Participants

Data included 72 licensed adult drivers (ages 21–32; 50% male) from 2 studies, who provided written informed consent. Participants in both studies underwent the same protocol with the exception of the drowsiness countermeasure. Forty-eight drivers received a drowsiness countermeasure and 24 drivers (collected in a previous data collection with identical procedures) received no countermeasure and functioned as a baseline group. Demographic data are provided in Table 1.

Table 1. Demographic data.

	Countermeasure condition	N	Male/female	Age M (SD)	Age Min	Age Max
	No countermeasure	24	12/12	26.58 (4.60)	21	34
Binary	Auditory–visual (A-V)	8	4/4	23.34 (1.60)	21	26
	Haptic	8	4/4	25 (2.33)	21	29
	Combined (A-V + Haptic)	8	4/4	26.13 (4.61)	21	34
Staged	Auditory–visual (A-V)	8	4/4	24.63 (3.34)	21	30
	Haptic	8	4/4	24.88 (1.81)	23	28
	Combined (A-V + Haptic)	8	4/4	27.63 (2.97)	23	32

Apparatus

Data were collected at the University of Iowa National Advanced Driving Simulator using the high-fidelity full-motion NADS-1 driving simulator (www.nads-sc.uiowa.edu). The simulator consisted of a 1996 Malibu sedan mounted inside a 24-foot dome. The motion system provides 400 square meters of horizontal and longitudinal travel and ±330° of rotation. The driver felt acceleration, braking, and steering cues much as if actually driving. Each of the 3 front projectors had a resolution of 1,600 × 1,200; the 5 rear projectors had a resolution of 1,024 × 768. Data were sampled at 240 Hz.

Driving task

The 45-min drive was composed of 3 nighttime driving segments. The drive started with an urban segment composed of a 2-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 4-lane divided expressway with a posted speed limit of 70 mph. The drives concluded with a rural segment composed of a 2-lane undivided road with curves. Other light traffic was present, but this traffic did not conflict with the driver. Participants received recorded audio navigational instructions to guide them through the route. To minimize learning effects, 3 versions of the drives were created and each participant was assigned to 2 of the 3 drives in a balanced order.

Experimental design

The study consisted of a 2 × 3 × 2 mixed design. Between-subject independent variables were countermeasure interface type (staged, discrete) and alert modality (audio/visual, haptic, combined audio/visual + haptic), which were crossed for 6 drowsiness countermeasure conditions. The within-subject independent variable was level of drowsiness manipulated by varying continuous hours awake via the drive start time (late night, early morning).

Figure 1. Visual component of countermeasures for the discrete (top) and staged (bottom) alerts.

Drowsiness countermeasures

Countermeasures consisted of a combination of 2 interface types and 3 alert modalities for 6 unique warning groups. Interface type was either a single-stage discrete warning or a 3-staged warning meant to convey a sense of increasing urgency. Alert modality was audio/visual–manual, haptic, or combined audio/visual–manual plus haptic. The driver had to press a button on the steering wheel to clear the alert after it appeared. Participants were randomly assigned to one of the 6 countermeasure groups. All countermeasures used the same state detection algorithm based on driver inputs (for more details, see Schwarz et al. 2015). Previous research showed that this algorithm could be used to predict drowsy lane departures 6 s before they occur (McDonald et al. 2014).

The countermeasures were designed to reflect different aspects of current in-vehicle countermeasures. The visual component of the alert is shown as the middle icon in Figure 1. The audio component was a 2-tone chime that coincided with the appearance of the icon. The haptic component of the discrete warning was a double vibration pulse on the left and right sides of the driver's seat bottom. All 3 alert modes fired at the same time in the combined condition.

The staged warning consisted of 3 binary alerts that were triggered in stages to reflect increased urgency the longer the driver remained drowsy. The visual component of the staged warning consisted of the 3 icons shown in Figure 1. The audio component had 3 sounds, one for each icon. The first stage had a single beep. The second stage had a 2-tone chime. The third stage had a loud repeating beep that lasted about 3 s. The haptic component of the staged warning consisted of 3 types of vibration patterns. The first stage had a single vibration pulse. The second stage had a double vibration pulse, aligned with the 2-tone chime. The third stage of the haptic alert was a repeating vibration pulse that aligned with the repeating beep of the audio alert. The discrete warning was a binary alert triggered when drowsiness was detected. The visual, auditory, and haptic components of the second stage of the staged alert defined the discrete alert.

Both the staged and discrete countermeasures were triggered based on the same algorithm (i.e., the staged alert did not fire more frequently than the discrete alert). The drowsiness algorithm issued assessments of awake or drowsy every 6 s. The countermeasure stage escalated from awake to stage 1, triggering the appropriate alert, when the algorithm exceeded the drowsiness threshold. If the algorithm output was "awake" when the countermeasure state expired after 60 s, the output returned to the previous stage. If drowsiness continued, the countermeasure stage escalated to the next stage (for the staged alert), triggering the next alert. If the countermeasure system was already in stage 3, an escalation simply retriggered the alert for that stage.

Procedure

Participants completed 3 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 2 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 Motionlogger Actigraph (Ambulatory Monitoring, Ardsley, NY). Upon arrival for each of the 2 overnight visits, activity data were confirmed and breath alcohol contents were obtained with an Alco-Sensor IV (Intoximeters, Inc., St. Louis, MO) breath alcohol testing instrument. Breath alcohol contents 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 10 p.m. and 2 a.m. (late night) and the other between 2 a.m. and 6 a.m. (early morning). The distribution of predrive scores on the Stanford Sleepiness Scale (Hoddes et al. 1972) in the drowsiness manipulation was effective, with drivers in the early morning drives reporting higher subjective drowsiness prior to the drive, on average, than in the late night drive. The 2 drowsy driving sessions were spaced at least one week apart. Video of the driver's face, feet and pedals, cab interior, and forward view were captured for post hoc reduction and analysis.

The primary outcome measures were lane departures and SDLP. Post hoc manual video coding was performed by 2 independent raters to identify classify drowsy and alert lane departures. Lane departures were recorded each time the wheels of the driver's vehicle crossed one of the lane lines. Video coding was performed to distinguish any lane departures not associated with drowsiness. For each lane departure flagged in the data stream, a researcher rated the preceding 60 s of video using the Objective Rating of Drowsiness Scale (Wierwille and Ellsworth 1994). Lane departures where the driver was coded at level 2 or above were classified as drowsy lane departures. Drowsy lane departures were approximately half as frequent as nondrowsy lane departures.

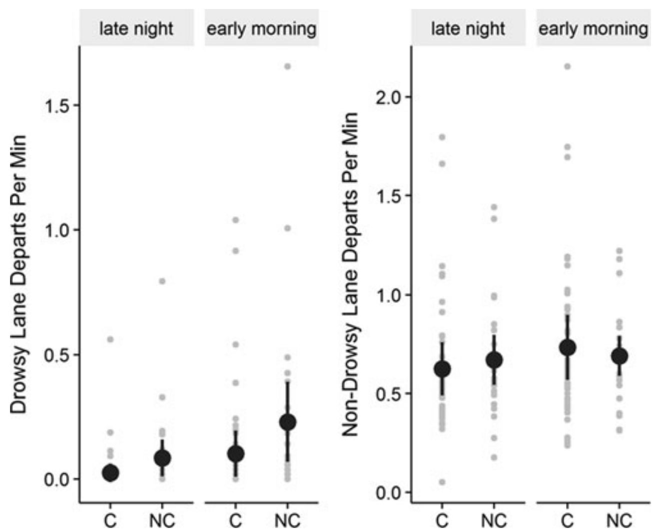

Figure 2. Means, 95% confidence intervals, and individual data points of drowsy (top) and nondrowsy (bottom) lane departures per minute. C = Countermeasure, NC = no countermeasure.

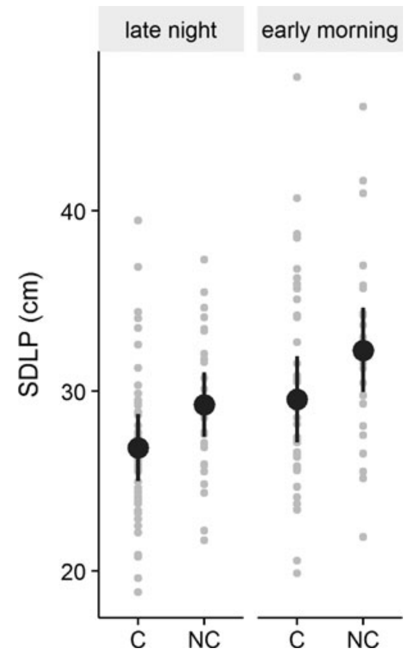

Figure 3. Means, 95% confidence intervals, and individual data points of standard deviation in lane position. C = Countermeasure, NC = no countermeasure.

Results

Countermeasure effectiveness

A majority of drowsy lane departures occurred during the interstate and the dark straight rural section at the end of the drive. The following analyses were therefore limited to those combined driving segments. To normalize lane departures based on speed, we calculated lane departure frequency as the number of lane departures divided by drive duration.

To determine whether the presence of countermeasures reduced drowsy lane departures, data from participants in all countermeasure conditions was grouped and compared against the no-countermeasure baseline using a mixed-factor analysis of variance (ANOVA) with countermeasure (countermeasure, no countermeasure) as a between-subjects factor and drowsiness level (moderate, severe) as a within-subjects factor. Cohen's d effect sizes are also reported for significant effects. As expected, there was a higher rate of drowsy lane departures per minute during early morning drives than during late night drives, $F(1,68) = 17.59$, $P < .001$, $d = 0.51$. Importantly, there was also a marginally significant main effect of countermeasure such that drivers in the countermeasure conditions fewer drowsy lane departures per minute than drivers without countermeasures, $F(1,68) = 3.76$, $P = .057$, $d = 0.50$ (Figure 2). The interaction between countermeasure and drive time was not significant, $F(1,68) = 1.59$, $P = .21$.

To evaluate whether countermeasures simply caused drivers to be generally more cautious, we also compared the frequency of nondrowsy lane departures as a function of drive time and countermeasure condition. Nondrowsy lane departure frequency did not vary as a function of either drive time, $F(1,68) = 2.06$, $P = .16$, or countermeasure, $F(1,68) = 0.01$, $P = .95$. The interaction between drive time and countermeasure was also not significant, $F(1,68) = 0.99$, $P = .32$. This suggests that the countermeasures had a targeted effect in reducing drowsy lane departures.

We also examined variability in lateral vehicle position by comparing SDLP (Figure 3). As expected, SDLP increased from the late night drive to the early morning drive, $F(1,68) = 21.88$, $P < .001$, $d = 0.52$. Critically, SDLP was significantly lower for drivers with the countermeasures than for those without, $F(1,68) = 7.92$, $P = .006$, $d = 0.53$, and there was no interaction between drive time and countermeasure, $F(1,68) = 0.14$, $P = .70$.

Comparison of countermeasures

The next step was to compare the different countermeasures against one another. Drowsy lane departures were compared using a repeated measures ANOVA with interface type (discrete, staged), alert modality (AV, haptic, combined), and drive time (late night, early morning) as within-subjects factors. As expected, there was a significant main effect of time of day, $F(1,39) = 7.57$, $P = .01$, $d = 0.20$. Importantly, the main effect of interface type was significant, with staged alerts resulting in less frequent drowsy lane departures than discrete alerts, $F(1,39) = 4.41$, $P = .04$, $d = 0.50$. There was a significant interaction between interface type and time of day, such that staged alerts resulted in fewer drowsy lane departures per minute than discrete alerts primarily during the early morning drives when drivers were expected to be most drowsy, $F(1,39) = 5.56$, $P = .02$, $d = 0.49$ (Figure 4). The main effect of alert modality was not significant, $F(2,38) = 0.07$, $P = .92$, nor were any interactions involving modality, $P > .60$, suggesting that the benefits of staged alerts were observed across all 3 modalities.

To determine whether this was a general alerting effect or specifically targeted drowsiness, we also compared the countermeasure conditions with respect to nondrowsy lane departures. There was a marginal increase in the frequency of nondrowsy lane departures in the early morning drives, $F(1,39) = 3.05$, $P = .08$, $d = 0.22$. However, there were no significant differences between either the interface types or alert modalities, nor were there significant interactions involving either of these factors,

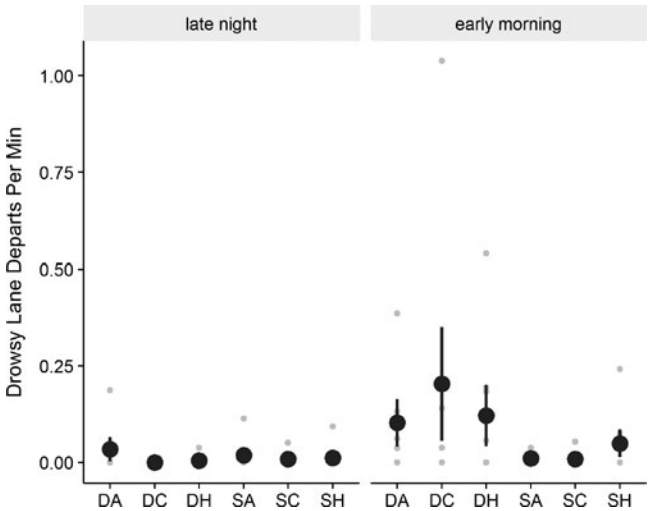

Figure 4. Means, 95% confidence intervals, and individual data points of drowsy lane departures per minute by countermeasure condition. D = Discrete, S = staged, A = auditory–visual, C = combined AV + Haptic, H = haptic.

$P > .15$. This suggests that the benefit of staged alerts over discrete alerts was specifically targeted to drowsiness-related events and not a general alerting effect.

Subjective drowsiness

To determine whether countermeasures reduced subjective drowsiness, we compared postdrive responses on the Stanford Sleepiness Scale. Subjective scores were compared with a mixed-factor ANOVA with countermeasure condition (countermeasure, no countermeasure) as a between-subjects factor and drive time (late night, early morning) as a within-subjects factor. One subject from the countermeasure group was excluded because of technical failures that prevented recording a postdrive Stanford Sleepiness Scale during the early drive. Subjective sleepiness scores increased as anticipated from the late night to early morning drives, $F(1,67) = 55.02$, $P < .001$, $d = 0.78$. However, the main effect of countermeasure was not significant, $F(1,67) = 2.79$, $P = .10$, nor was the interaction between drive time and countermeasure, suggesting that countermeasures did not increase subjective alertness.

Discussion

The goal of this study was to evaluate the effectiveness of drowsiness countermeasures improved lane keeping over a short 45-min drive. The data demonstrate that countermeasures reduced drowsy lane departures and variability in lane position relative to no countermeasure. Importantly, the data indicate that staged warnings may be more effective than discrete alerts, particularly during early morning drives where drowsiness was most severe. This is not necessarily surprising, because the staged alerts were intended to convey more information, namely, an escalating level of alarm, than were the discrete warnings. In addition, the final stage of the staged warnings was intended to be more alarming than the second stage, which was the same used for the discrete warnings. Additional data are needed to identify whether a similarly alarming discrete warning could provide the same benefits as the staged warning.

It is also worth noting that there was no evidence of a change in postdrive subjective drowsiness between the countermeasure and no countermeasure conditions. Though there was no difference in subjective alertness with and without the countermeasures following the drive, there was a significant decrease in SDLP throughout the drive, suggesting that the benefits of countermeasures may have been more general. Additional research with more sensitive continuous drowsiness metrics would help to pinpoint the factors driving the benefit in performance. It is also worth considering at what drowsiness level the system was designed to intervene. The algorithm was specifically based on drowsiness associated with lane departure events (Brown et al. 2014; McDonald et al. 2014). It is possible that algorithms could be tuned to detect specific levels of drowsiness and present earlier or later warnings than those in this study (see May and Baldwin [2009] for a discussion). It may be possible to warn a driver well before a critical event, but such strategies also run the risk of being perceived as false alarms or nuisance warnings. When considering future drowsiness countermeasures, it will be important to understand the ideal point at which the system should intervene (see Roberts et al. 2016). It is also important to point out that countermeasures did not entirely eliminate drowsy lane departures, suggesting that additional adjustments to the detection algorithm or warning interface might increase safety.

It is also worth considering driver perceptions of the drowsiness countermeasures. Although the system may be able to alert drivers prior to a lane departure, such "preemptive" warnings may be perceived as false alarms by the driver and decrease trust in the system (e.g., Parasuraman and Miller 2004). Future research should also consider drivers' subjective responses and interpretations of drowsiness mitigation systems (e.g., Navarro et al. 2016). If drivers are not confident in the accuracy and reliability of a system, they are unlikely to utilize it. Alternatively, drivers might become overreliant on the countermeasure system to keep them safe in an impaired state. Similarly, additional research is needed to identify the impact of drowsiness countermeasures on alert (i.e., nondrowsy) drivers.

A few limitations of the present study are worth noting. First, the study is based on a relatively small sample and used a between-subjects design to assess the drowsiness countermeasure. This is important to consider with respect to the interindividual variability in drowsiness and its effects on driving performance. Accounting for individual differences in driver state may help improve algorithm classification and better identify the appropriate countermeasure for each particular driver. Second, the key performance measure, drowsy lane departures, represents only a small portion of the driving task. Though continuous SDLP also indicated a benefit of drowsiness countermeasures, identifying additional continuous measures of both driving performance and driver state would potentially help evaluate countermeasure efficacy. Finally, future research should consider the interaction with other driver states, such as mind wandering, whether they can be reliably distinguished from drowsiness, and the implications for fluctuating driver states with regard to countermeasures.

A critical remaining question is the effectiveness of these drowsiness countermeasures over the course of longer drives, such as a multihour road trips. In these situations, it may be difficult to keep the driver alert long enough to safely reach a destination, so countermeasures may need to promote the driver to take a break to rest. It is unclear what type of feedback might work best to promote longer-term behavioral change (though see Aidman et al. 2015). The next phase of this NHTSA-sponsored research program is currently investigating the effectiveness of drowsiness countermeasures over longer drives. The project will first develop simulator test protocols that replicate the complex motivational conditions of drowsy driving—wanting to reach home versus stopping to avoid a crash—and then use the protocol to evaluate countermeasures over longer drives. Countermeasures offer the potential to reduce driver drowsiness and perhaps to change decision making in the context of drowsy driving, but more research is needed to understand the full impact of these technologies on traffic safety.

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