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In-vehicle Drowsy Driving Detection and Alerting

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16. Abstract
Drowsy driving is a common phenomenon that increases the risk for fatal and injurious crashes. Technological innovations in the form of driver monitoring and notification systems may offer potential to reduce crashes due to drowsy driving. These systems monitor the driver's drowsy driving state and issue alerts when the driver is classified by the system as drowsy. Research shows that driver notification can be effective in improving performance over relatively short drives. However, the efficacy of such systems for improving performance and changing drowsy driver decision making over longer drives is unknown. The goal of this project was to evaluate the efficacy of two notifications, a lane departure warning (LDW) and a drowsiness notification with LDW (DN/LDW). The notification conditions were compared against a no-notification baseline during 4-hour overnight drives in a high-fidelity driving simulator with an incentive method designed to replicate the motivational tradeoffs common to drowsy driving, i.e., the desire to reach a destination versus one's own safety while driving drowsy. The combined DN/LDW, but not the LDW, was effective in reducing the frequency of lane departures and also in reducing the percentage of eyelid closure (PERCLOS) prior to lane departure events compared to baseline. There was no difference between the notification conditions and baseline with respect to the frequency or timing of breaks to rest, suggesting that although notifications improved driving performance, they did not alter decision making. These results suggest that notifications may aid drowsy drivers, but in-vehicle alerts may not be effective in changing the way drowsy drivers make decisions about whether and when to stop to rest.

17. Key Words
drowsiness, notification, driver support features, driving simulation, lane departure warnings

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Table of Contents

List of Figures

List of Tables

Executive Summary

Drowsy driving is a widespread phenomenon that contributes to fatal and injurious crashes in the United States. The Fatality Analysis Reporting System (FARS) attributed 667 fatalities (1.9% of total fatalities) in 2019 to drowsy driving (National Center for Statistics and Analysis, 2020), but these figures likely underrepresent the contribution of drowsiness. In a survey using a probability-based web panel, the AAA Foundation for Traffic Safety found that 17% of sampled drivers reported to have driven drowsy at least once in the last 30 days (i.e., "having driven while being so tired that they had a hard time keeping their eyes open") (2021). In addition, researchers estimate that 6% of all crashes involve drowsiness and 21% of fatal crashes involve drowsy drivers (Tefft, 2014). There is a clear need to identify strategies and countermeasures that can counter drowsiness, either by keeping drivers alert while driving or by informing their decision-making behavior about when to drive and when to stop to rest. To decrease drowsy driving crashes, several vehicle manufacturers have deployed drowsiness notification (DN) technologies in vehicles. For example, Ford developed its Driver Alert system, which uses lane position tracking to assess driver vigilance. BMW has introduced Attention Assistant, which uses driver inputs (e.g., steering) to assess drowsiness. These DN systems monitor the state of the drivers and their behaviors and provide alerts (or notifications) when the systems classify these behaviors as indicating drowsiness. Recent research suggests that DN alerts can be effective in decreasing the frequency of lane departures associated with drowsiness during short drives (1 hour or less) (Gaspar et al., 2017). Manufacturers also have widely introduced other driver support features that may decrease drowsiness. One example is lane departure warning (LDW), which provides alerts when the vehicle nears a lane marking. Although LDW do not target drowsiness, it may help prevent the run-off-road crashes associated with drowsiness.

Most of the research on drowsiness reduction has focused on relatively short drives, typically one hour or less. Many drowsy driving crashes, however, occur during long multi-hour overnight and early morning drives. It is therefore important to understand whether DN is effective over longer drives, both in terms of reducing the frequency of lane departures and in influencing decision making regarding stopping to rest. The goal of this project was to evaluate the efficacy of notification (LDW and DN) as countermeasures for improving driving performance, reducing percentage of eyelid closure (PERCLOS), which can be seen as a proxy for drowsiness, and altering the drivers' decisions regarding whether they should continue to drive during long trips.

Seventy-two males between the ages of 21 and 30 completed an overnight study drive in the high-fidelity National Advanced Driving Simulator (NADS-1 simulator). Drive duration was four hours and occurred between 2 a.m. and 6 a.m. To replicate the motivational tradeoffs of drowsy driving—continuing to drive to reach a destination versus stopping to rest—the study introduced an incentive methodology where monetary incentives were used to replicate the benefits of reaching a destination early, but with the potential of degraded driving performance. During the drive, participants had the option to stop driving and take breaks, during which they could engage in several different activities. Participants were evenly distributed and randomly assigned to one of three conditions: a condition with a lane departure warning (LDW), a condition with DN and an LDW (DN/LDW), or a baseline condition without notification. The critical measures of driving performance and behavior were the frequency of lane departures and the number and timing of breaks during the session.

Analyses focused on comparing behavior and driver state in the LDW and DN/LDW conditions with the driving behavior and driver state in the baseline condition. The DN/LDW condition had significantly less frequent lane departures compared to the baseline condition. The difference in lane departure frequency between the LDW and baseline conditions was not significant. The DN/LDW condition also resulted in reduced PERCLOS prior to lane departure events compared to baseline, whereas the LDW condition did not show a reduction in PERCLOS compared to baseline. For both notification groups, there was no difference from baseline in break taking behavior as measured by the frequency or timing of breaks during the drive.

These results show the DN/LDW notification was effective in reducing lane departures and reducing PERCLOS prior to lane departures compared to the baseline group. The results also show that the LDW was less effective on those measures. Although there was a nominal reduction in lane departure frequency relative to the baseline condition, this difference was not significant. The finding that the DN/LDW condition showed decreased drowsiness prior to lane departure events, but the LDW condition did not, suggests a mechanism in which the DN/LDW countermeasure reduced lane departure frequency by increasing alertness in situations where a lane departure was likely to occur. The finding that the LDW did not decrease drowsiness during these periods suggests that either the DN or some combined effects of the DN and LDW engendered the benefits observed in the DN/LDW condition.

These results also show that while notification improved driving performance, it did not alter drivers' decisions about whether to stop to rest. Participants in the notification conditions took a similar number of breaks at similar points in the drive as the participants in the baseline condition. This result suggests that in-vehicle notification can improve performance during driving but may not be effective at changing drowsy drivers' decision making.

This study extends previous research by demonstrating the potential effectiveness of notification for drowsy drivers in longer driving situations. Previous research showed that a DN (without LDW) effectively reduced lane departure frequency in shorter drives (Gaspar et al., 2017). This study shows that a similar DN system, paired with an LDW, yields a similar benefit for much longer drowsy driving situations. Notification does not appear to influence decisions about whether to continue to drive and few drivers considered it when deciding to stop to rest.

This research has important implications for driver support features targeted toward reducing drowsiness. Researchers designed the DN/LDW system in this study to mirror production driver support features, which often combine different safety systems. The results show that the pairing of these two systems was more effective at improving driving performance than a system that did not have a state monitoring and notification component.

Introduction

Drowsiness and Crash Risk

The precise number of drowsy driving crashes is difficult to estimate because drowsiness cannot be assessed after a crash and must instead be inferred from crash circumstances. The Fatality Analysis Reporting System (FARS) attributed 667 fatalities (1.9% of total fatalities) in 2019 to drowsy driving (National Center for Statistics and Analysis, 2020), but these figures likely underrepresent the contribution of drowsiness. Research from the AAA Foundation for Traffic Safety suggests the number of crashes and fatal crashes attributed to drowsiness is underreported (Tefft, 2014; Tefft, 2012). They estimate that 6% of all crashes and 21% of fatal crashes involve drowsy drivers. Similar estimates derived from the 100-car naturalistic driving study suggest drowsiness contributed to about 23% of observed crashes and near-crashes (Klauer et al., 2006).

Drowsy driving is a widespread phenomenon. A survey conducted by AAA Foundation for Traffic Safety found that 17% of drivers reported having driven drowsy, or “being so tired that they had a hard time keeping their eyes open” while driving, in the last month (2021; see also, Royal, 2003). Many drivers report feeling that they can “push through” their drowsiness to reach their destinations (e.g., Alvaro et al., 2018). This misunderstanding, combined with the difficulty of externally assessing the frequency of drowsy driving, highlights the potential benefit of in-vehicle technological solutions to the drowsy driving problem. In-vehicle countermeasures, in the forms of driver monitoring and drowsiness notification systems, have the potential to reduce drowsy driving and associated crashes.

Driver Monitoring and Drowsiness Notification

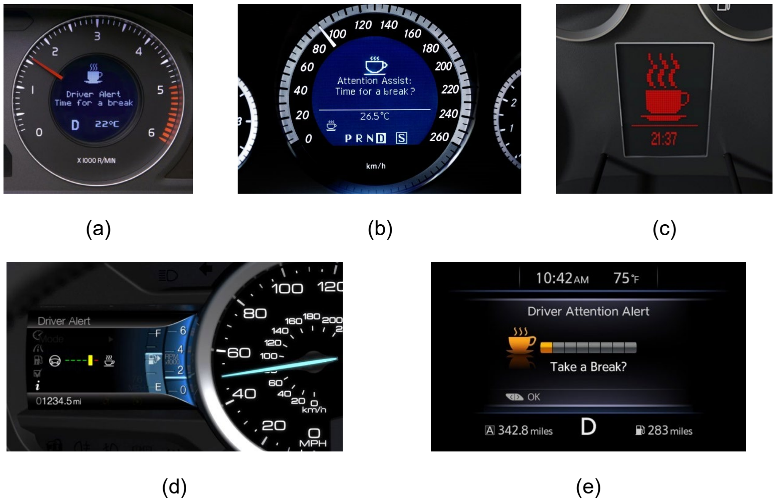
Some vehicle systems have two components: a state detection system (or driver monitoring system) and a countermeasure. Considerable research and development efforts in the last 10 years focused on detecting and classifying driver state using different measures. This work generally succeeded in generating several approaches to accurately classifying driver drowsiness using combinations of driver inputs (e.g., steering; McDonald et al., 2014) and driver state sensing (e.g., eye closures; Dinges & Grace, 1998). Limited research, however, has focused on understanding the efficacy of the second part of the vehicle system, the countermeasure.

Countermeasure Taxonomy

Researchers have evaluated many different countermeasures for decreasing drowsiness. Countermeasure approaches fit into one of two categories: those that focus on changing the driver’s state (state-based) and those that focus on driving behavior (performance-based). State-based strategies focus on altering the physiological state of the driver, with the goal to keep the driver alert and engaged or to wake the driver up once drowsiness is detected (e.g., DN systems). Unlike state-based strategies, performance-based strategies target improving behavior and performance changes associated with drowsiness. For example, LDW or lane keep assist systems do not focus on recognizing that a driver is drowsy before issuing an alert or intervene.

Production Countermeasures

Most production countermeasures provide state-based alerts to the driver in the form of the “coffee cup” interface, shown in Figure 1. A coffee cup icon appears on the instrument panel or infotainment system, often accompanied by an auditory alert. Sometimes, this alert is preceded by feedback in the form of an “attention” scale, meant to convey gradual changes in driver alertness. The modality of the alerts varies. Some systems provide only a visual coffee cup icon, some also provide an auditory message, and others provide vibrotactile feedback such as seat or steering wheel vibration. Certain systems also require the driver to acknowledge the alert by pressing a button on the steering wheel to clear the message.



(a) (b) (c)

(d) (e)

Figure 1. Examples of drowsiness notification interfaces: (a) Volvo Driver Alert Control, (b) Mercedes Attention Assist, (c) Bosch Driver Drowsiness Detection, (d) Ford Driver Alert, (e) Nissan Driver Attention Alert

Research Objective

Much of the research on drowsiness countermeasures has focused on relatively short periods of driving, typically one hour or less. Research showing the potential safety impact of countermeasures in this situation is important because it speaks to whether certain strategies can keep drivers awake long enough to reach their destinations (see Gaspar et al., 2017). On long road trips or commercial driver work shifts, drivers may be unable to just “push through” and reach their destinations because the destinations might be hours away. Instead, the only behavior with demonstrated effectiveness is to stop to rest or nap (Armstrong et al., 2010). The goal of this study was to compare the effectiveness of a representative state-based drowsiness alerting countermeasure and an LDW system with a baseline condition with no countermeasure. The study consisted of 4-hour drives in a high-fidelity motion base driving simulator with a sample of sleep-deprived younger male drivers.

Method

Participants

Eighty-one participants passed phone screening for eligibility, i.e., the participants were eligible to take part in the research (see "criteria" for eligibility below). Those participants then completed a screening session involving a short drive in the NADS-1 simulator. Nine participants (11%) failed the screening session due to simulator sickness. The final sample included 72 experienced male drivers 21 to 30 years old. The researchers limited participation to younger, male drivers to reduce variability in driving performance that may be due to age and sex differences, thus increasing statistical power, and because research suggests that those who are younger and male are more likely to engage in drowsy driving (Wheaton et al., 2013, 2014). Caution should be applied when generalizing results to the larger, U.S. population. Demographic data for each condition is shown in Table 1. All participants signed written informed consent and video release forms. All participants met the following criteria:

- Were between 21 to 30 years old.
- Held valid U.S. driver licenses with no restrictions for vision.
- Drove at least 10,000 miles per year.
- Drove without special equipment.
- Lived within 30 minutes of University of Iowa Research Park.
- Had normal sleep patterns.
- Did not have obstructive sleep apnea.
- Had not been diagnosed with serious illness or were taking any medication that impairs driving or induces drowsiness.
- Reported no history of motion sickness.
- Reported no history of neck and/or back pain.
- Had not participated in previous simulator studies on drowsy driving at the National Advanced Driving Simulator.
- Were able to participate in an overnight study visit of up to 9 hours and refrain from sleep after 8 a.m. the day of the study visit.
- Were willing to complete an activity log the day of the study visit.
- Refrained from consuming caffeine after 1 p.m. the day of the study visit.
- Passed breath-alcohol tests when they arrived for the study visits.

Table 1. Demographic Data

Condition	N	Age (SD)
Baseline	24	25.0 (3.4)
LDW	24	23.4 (2.2)
DN/LDW	24	23.6 (1.9)

Apparatus

The study used the high-fidelity, full-motion NADS-1 simulator at the National Advanced Driving Simulator at the University of Iowa (Figure 2). The simulator consists of a 24-foot diameter dome enclosing a full-size 2014 Toyota Camry sedan with active steering and pedal feedback. A 13-degree of freedom motion system provides participants acceleration, braking, and steering cues as if they were driving. Sixteen high-definition (1,920x1,200) LED projectors display seamless imagery on the interior walls of the dome with a 360° horizontal field of view.

Figure 2. Exterior and interior views of the NADS-1 simulator

Screening Drive

Enrolled participants completed a screening drive at the start of the study session. The 15-minute screening drive was along a four-lane highway interstate with sparse ambient traffic. Participants practiced setting the cruise control and changing lanes via audio instructions programmed in the drive.

Study Drive

Participants not excluded after the screening drive completed the study drive in an overnight session that same day. The study drive contained a 40-mile interstate loop repeated five and a half times for a total of 220 miles. The road network consisted of four lanes of separated interstate (two in each direction) with a 65-mph speed limit. The route contained two rest areas, approximately 40 miles apart, where participants could stop to rest. A solid paved shoulder extended beyond the roadway. The surrounding visual environment was a sparse, rural region. Occasional ambient traffic occurred in participants' direction of travel, with ambient vehicle speed varying such that participants occasionally passed and were passed by other vehicles. Signage and ambient vehicles changed with each loop. All participants could engage standard cruise control via buttons on the steering wheel.

Incentive Method

Participants were (intentionally) given false information about a system of monetary incentives for the study drive. Researchers intended the incentive structure to replicate the motivational tradeoffs of a drowsy driving situation—that is, the desire to reach a destination versus one's own safety. Prior to the study drive, the research team informed participants they would start with a possible compensation of $85 for their participation in the study and that they would lose the entire amount (-$85) if they departed the road or collided with another vehicle during their drive. Researchers defined a road departure as any instance where more than half of a vehicle departed the road surface onto the shoulder. Researchers defined a crash as any collision with another vehicle or object in the roadway, or a maneuver that caused an error in the simulator's motion system (e.g., running completely off the roadway). The research team stopped the drive for complete roadway departures resulting in motion system failure or for crashes involving other vehicles on the road. The research team told participants that the goal was to reach the "Springfield" exit in under 4 hours and that the exit was approximately 220 miles away.

At 65 mph, the drive took approximately 3.5 hours without stopping. The research team told participants they would earn bonus compensation for reaching the destination in less than 4 hours, prorated at $1 per minute under the time limit, up to $50. This forced participants to consider a tradeoff between continuing to drive if they experienced drowsiness and risking their compensation or stopping at rest areas to avoid road departures and crashes but potentially losing the time bonus.

Table 2 provides the payment structure presented to participants prior to the study drive. Regardless of performance or whether participants reached the destination safely or under the time limit, all participants received the same reimbursement ($150 total). The research team debriefed participants regarding the purpose of this study at the end of the session.

Table 2. Incentive Payment Structure

Session	Starting Compensation	Rewards	Penalties
1	$15	N/A	N/A
2	$85	$1.00 per minute under 4 hours, up to $50	-$85 for road departure or crash

Experimental Design and Notification Conditions

The experiment was a between-subjects design with three drowsiness notification conditions (Baseline, LDW, and DN with LDW). Twenty-four participants were each randomly assigned to one of the three conditions, with a total of 72 participants (24 per condition).

The baseline condition, which served as the control for the study, completed the drive without any notification. A second condition completed the drive with an active lane departure warning (LDW), which triggered an auditory/visual alert when the vehicle came within 12 inches of a lane line without signaling. Figure 3 shows the LDW icon that appeared on the instrument cluster display.

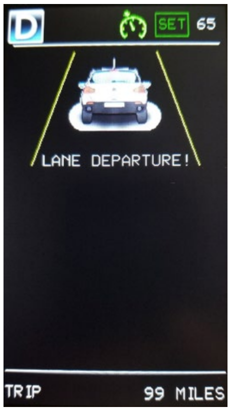


Figure 3. Lane departure warning icon

The third condition had both the LDW and a DN system. The study leveraged the drowsiness detection algorithm developed for the NHTSA Driver Inattention and Impairment using Vehicle Equipment research, which used temporal steering information and eye tracking to classify driver state (Schwarz et al., 2015). The algorithm provided a continuous estimate of drowsiness. The interface consisted of two parts, and researchers based it on a review of production drowsiness notification systems (Figure 4). Throughout the drive, the interface presented participants with a continuous “attention” scale, from high to low. The second component of the DN was a drowsiness warning, consisting of a coffee cup icon, an auditory alert, and text prompting the participant to consider taking a break. This warning occurred when the attention scale reached the low level (i.e., drowsiness was estimated as high). The coffee cup icon was displayed above the attention level display on the instrument cluster, and the visual and auditory alerts persisted until cleared via a button the participant pressed, regardless of whether they stopped to rest.

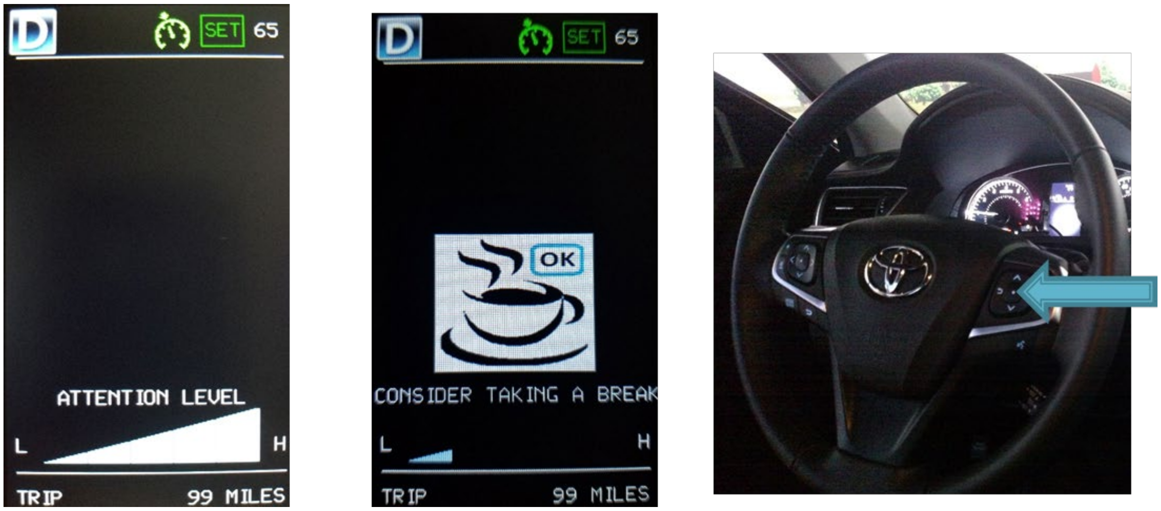


Figure 4. Drowsiness notification displays and button to clear alerts

Procedure

Before beginning data collection, the research team received approval from the Office of Management and Budget (OMB Control No. 2127-0736). This project recruited participants from the NADS participant registry, and a research assistant contacted potential participants via phone. During this call, participants provided consent as approved by the University of Iowa Institutional Review Board. Participants also completed a video release form, and the research assistant verified their driver’s licenses. Research assistants assigned participants a time for their drive. Beginning 36 hours prior to their drive, participants completed a food and activity log. The purpose of this was to confirm that they were awake by 8 a.m. the day of the visit and did not sleep during the day or consume caffeine after 1 p.m. A timeline of the study visit is shown in Figure 5.

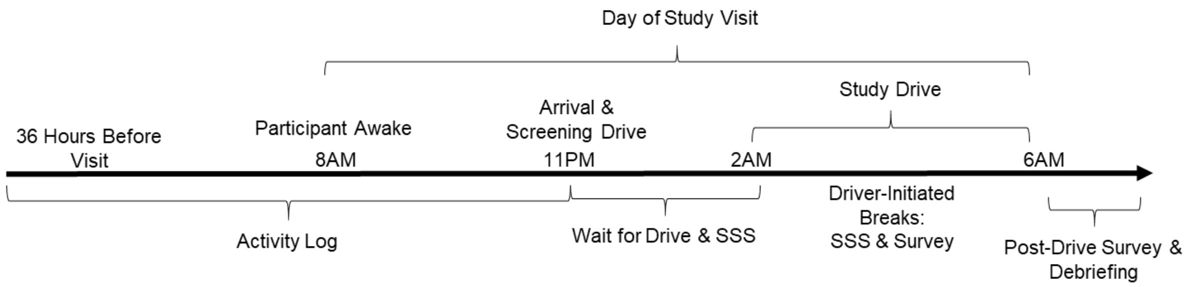


Figure 5. Study procedures on day of visit

On the day of their study visit, participants arrived for their drive at 11 p.m. Participants watched a PowerPoint instructional presentation and then completed a short screening drive followed by a wellness survey to evaluate simulator sickness. Researchers excluded those who showed symptoms of simulator sickness from further participation and compensated them for their time. After the screening drive, a research assistant escorted participants to a private room with a comfortable chair, and they remained awake until starting the study drive at 2 a.m. During this time, participants completed the Stanford Sleepiness Scale (SSS) (Figure 6), a subjective sleep questionnaire, every 30 minutes leading up to the drive.

Degree of Sleepiness	**Scale Rating**
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not at peak; able to concentrate	2
Awake, but relaxed; responsive but not fully alert	3
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7
Asleep	X

Figure 6. Stanford Sleepiness Scale

The simulator drives lasted until participants had traveled 220 miles (a 40-mile loop repeated five and a half times) or until participants reached the 4-hour time limit (i.e., at 6 a.m.). During the drives, participants had the option to stop to rest at either (or both) of two rest areas in each loop. At the start of a voluntary break, participants completed a questionnaire that contained the SSS and an open-ended question about the reason for taking a break.

During breaks, participants had the option to remain in the vehicle or exit the simulator. If they exited the simulator, they had access to a private room that included a comfortable chair. They could take a nap, use the restroom, walk around the hall or outside the building, and consume coffee (8 oz.) or other foods. There was no cap on the length of a break. Participants completed another SSS at the end of each break.

After the drive, participants completed questionnaires to understand their acceptance, trust, and perceptions of the drowsiness notification experienced in the study drive. Researchers debriefed participants on the incentive method and told them that they would receive full reimbursement regardless of performance. After the participants received their compensation, the research team provided transportation home.

Results

Data Reduction and Analysis

Data sources for this project included simulator data (DAQ) files, video captures, eye-tracking data, survey data, and experimenter notes/observations from experimenter logs. Raw data from the simulator and eye tracker were synchronized and converted to MatLab files and reduced using custom software and scripts. Survey data were recorded in electronic spreadsheets from Qualtrics Data analysis. Researchers performed data analysis and visualization in R.

The goal of the analysis was to understand whether driving performance, driver state, and decision making differed among the three conditions. Table 3 shows the specific research questions addressed in the analysis, the data measures used to address the question, and the interpretation of the measure. Unless stated otherwise, analyses were performed using analysis of variance (ANOVAs)[1] with condition (Baseline, LDW, DN/LDW) as between-subjects factors. When appropriate, individual condition means were compared using Dunnett's post-hoc tests.

Table 3. Research Questions and Corresponding Data

Research Question	Data	Source	Interpretation
Does notification reduce lane departure frequency?	Number of lane departures divided by total driving time	Simulator	Frequency of lane departures over time
Does notification reduce lane departure severity?	Maximum lane exceedance distance	Simulator	How far the vehicle drifted out of the lane
Does notification decrease response time to lane departures?	Time to stabilization in the lane	Simulator	How quickly drivers regain stable control
Does notification reduce PERCLOS?	Percentage of eye closure (PERCLOS)	Eye tracking	Larger values indicate greater eyelid closure
Does notification increase the likelihood of taking rest breaks?	The number of rest breaks divided by the total time (hours) in the experiment	Break survey	How frequently drivers stop to rest
Does notification increase the duration of rest breaks?	Duration of rest breaks	Break survey	How long drivers stopped to rest
Does notification reduce subjective drowsiness?	SSS at start of break	Break survey	Self-rated drowsiness
Did drivers consider DN when deciding to stop to rest?	Survey responses	Post-drive survey	Number of drivers who said DN influenced decisions

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[1] ANOVA is a statistical test used to determine whether two or more means are equal.

Research Question	Data	Source	Interpretation
Do drowsy drivers find LDW and DN annoying?	Survey responses	Post-drive survey	How annoying drivers found notification
Do drivers accept LDW and DN?	Survey responses	Post-drive survey	How likely drivers would be to follow notification alerts
Did the experimental incentive structure replicate the tradeoff between wanting to get home quickly versus driving safely?	Survey responses	Post-drive survey	How much did the incentive replicate drowsy driving motivational tradeoffs

Lane Departures

Lane Departure Frequency

Previous research demonstrates that DN reduced lane departures in shorter drives (Gaspar et al., 2017). The first analysis focused on whether LDW and DN/LDW reduced the frequency and severity of lane departure events, as well as response time to lane departures in longer drives (i.e., 4 hours). Analysts identified every lane departure in the data set by searching for any instance of the vehicle's tires crossing a lane boundary.

For each participant, researchers calculated lane departure frequency in units of lane departures per minute (i.e., the number of lane departures/total drive time). To meet the normalization assumption, the frequency of lane departures per minute was transformed to its logarithm. Figure 7 and Table 4 show the lane departure frequency for each of the three conditions.

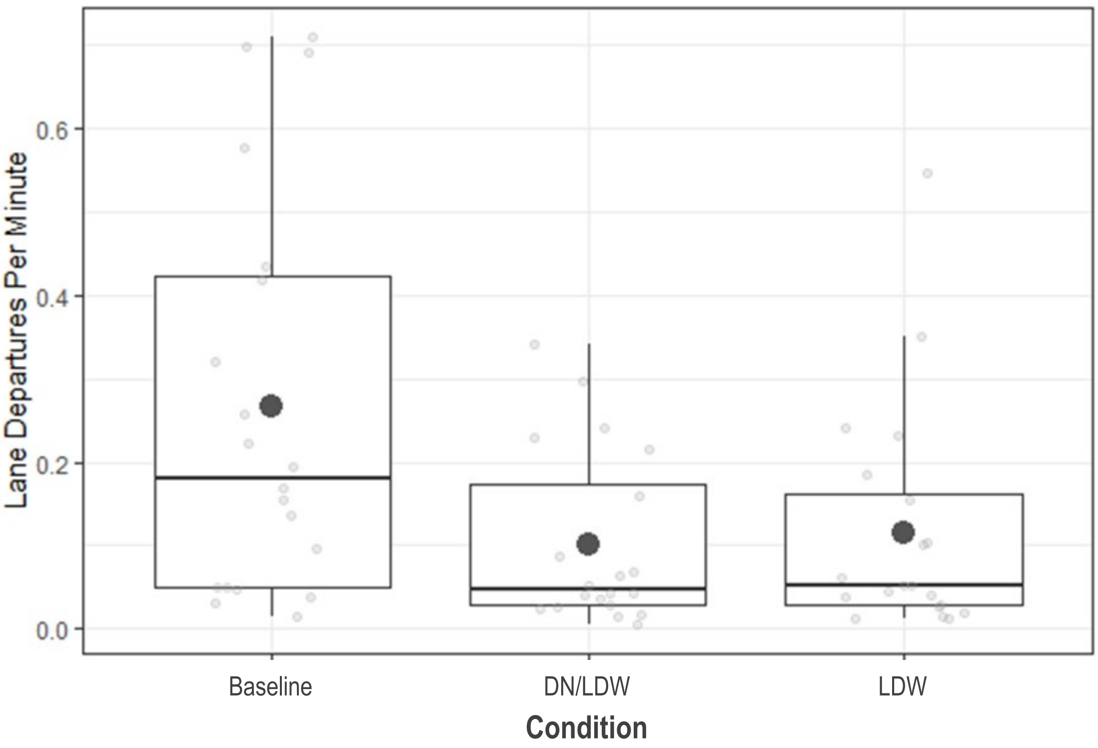

Figure 7. Lane departures per minute by condition. Dark circles represent condition means and small light circles represent individual participant means.

Table 4. Descriptive Statistics for Lane Departures Per Minute

Condition	Mean	Median	SD
Baseline	0.266	0.181	0.241
DN/LDW	0.104	0.048	0.108
LDW	0.115	0.051	0.138

There was a statistically significant main effect of condition on lane departure frequency (*F*(2, 69) = 4.532, *p* = 0.015). Dunnett's post-hoc tests were performed to compare the LDW and DN/LDW conditions against the baseline. The DN/LDW condition had statistically significantly fewer lane departures per minute compared to the baseline condition (*t*(47) = 2.290, *p* = 0.049). The LDW condition did not show a statistically significant difference in lane departures per minute compared to baseline (*t*(47) = 2.190, *p* = 0.061). These results suggest that the DN/LDW condition, but not the LDW condition, was effective in reducing the frequency of lane departures compared to the baseline condition.

Lane Departure Severity

In addition to the frequency of lane departures, departure severity was measured by the magnitude of each lane departure excursion in feet. To meet the normalization assumption, analysts transformed the lane departure magnitude to its logarithm. The main effect of condition on lane departure severity was not statistically significant ($F(2, 69) = 1.169$, $p > .05$). This finding suggests that although the DN/LDW condition reduced the frequency of lane departures, there was no difference between conditions in the severity of lane departures when they occurred.

Lane Departure Response Time

Finally, researchers compared response time to lane departures across the three conditions. Analysts quantified responses to lane departures by locating the first window of at least 1.5 seconds during which the center of the driver's vehicle regained and maintained a lane deviation of less than 0.5 feet in either direction. The time from the start of the departure to the start of the stabilized window is called time to stabilization. To meet the normalization assumption, analysts transformed time to stabilization to its logarithm. Figure 8 and Table 5 show the mean time to stabilization across the three conditions.

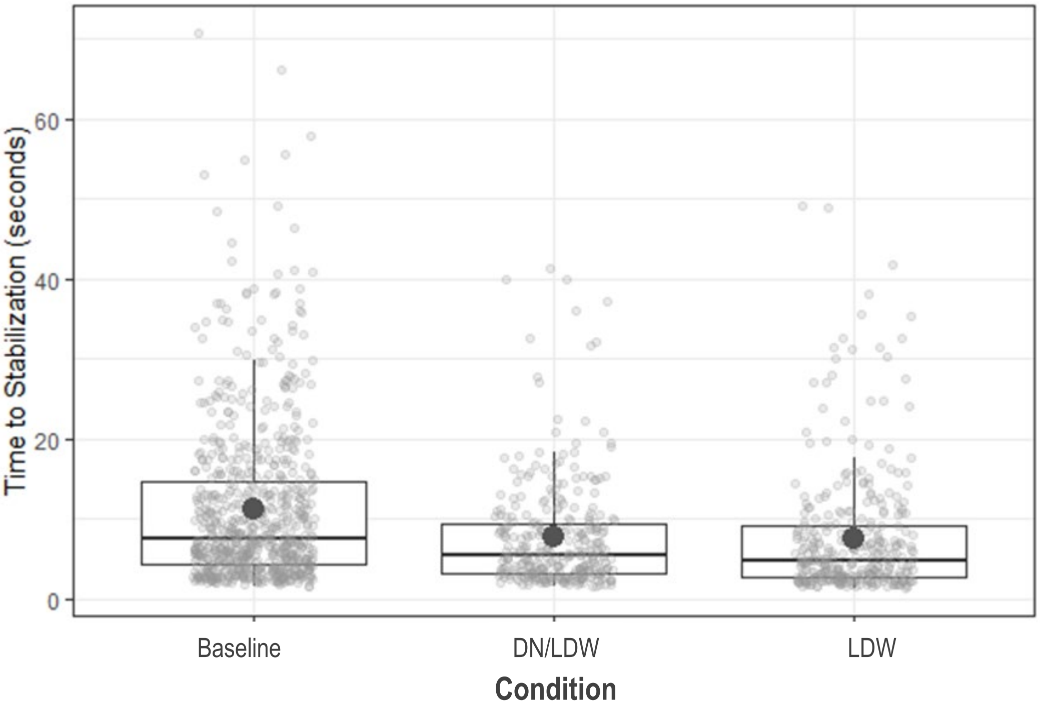

Figure 8. Time to stabilization in lane (seconds). Dark circles represent condition means and small light circles represent individual participant means.

Table 5. Descriptive Statistics for Time to Stabilization in Lane (seconds)

Condition	Mean	Median	SD
Baseline	11.187	7.617	10.009
DN/LDW	7.654	5.500	6.712
LDW	7.619	4.800	7.836

There was a statistically significant main effect of condition on time to stabilization ($F(2, 69) = 45.628$, $p < 0.001$). Dunnett's post-hoc test found that the DN/LDW condition had a statistically significantly faster time to stabilization compared to the baseline condition ($t(47) = 4.872$, $p <$

0.001). The LDW condition also had a statistically significantly faster time to stabilization compared to the baseline condition (*t*(47) = 2.788, *p* = 0.011). These results suggest that both the DN/LDW and LDW conditions resulted in faster responses to lane departures compared to the baseline condition.

PERCLOS

A related set of analyses focused on the question of whether the DN/LDW and LDW conditions reduced PERCLOS compared to the baseline condition. Analysts extracted and compared two time points, prior to the lane departure events (i.e., in the 60 seconds preceding each lane departure) and, in the time window, leading up to each rest area, across the three conditions. Analysts included lane departures because they represented the performance metric of interest. The hypothesis was that PERCLOS prior to lane departures should be lower for the notification conditions compared to the baseline condition because of increasing alertness in situations where lane departures are likely to occur. The second set of time windows where analysts calculated PERCLOS was leading up to each rest area to provide a sample of drowsiness at points where participants were making decisions about whether to stop to rest or continue driving. For both windows, larger PERCLOS values represent greater eyelid closure and increased drowsiness. Analysts removed individual windows where mean PERCLOS equaled 0 from the analyses because they indicate instances where eye tracking data was lost for that respective window.

PERCLOS During Lane Departures

To determine if the DN/LDW and LDW conditions decreased lane departure frequency by decreasing PERCLOS in the moments leading up to and during a lane departure situation, analysts calculated PERCLOS for the 60 seconds prior to each lane departure event. Figure 9 and Table 6 show PERCLOS prior to lane departures for each of the three conditions.

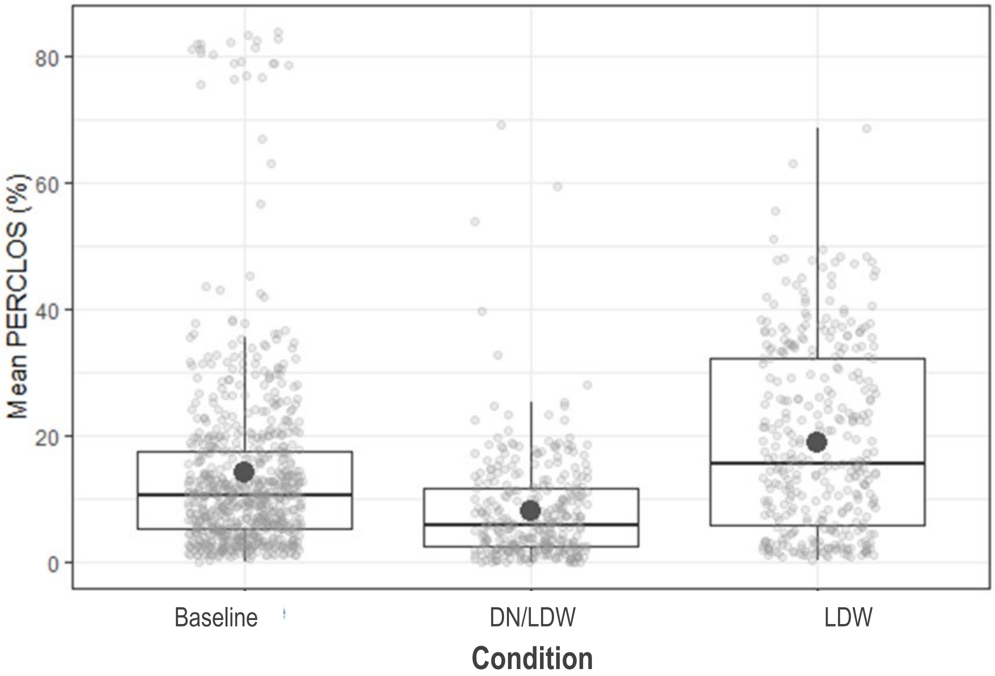

Figure 9. PERCLOS (%) prior to lane departures. Dark circles represent condition means and small light circles represent individual lane departure events.

Table 6. Descriptive Statistics for PERCLOS (%) Prior to Lane Departures

Condition	Mean	Median	SD
Baseline	14.161	10.503	14.918
DN/LDW	8.079	5.853	8.320
LDW	19.051	15.713	14.471

There was a statistically significant main effect of condition on PERCLOS prior to lane departures ($F(2, 69) = 55.912$, $p < 0.001$). Dunnett's post-hoc test showed that the DN/LDW condition had statistically significantly lower PERCLOS prior to lane departures compared to the baseline condition ($t(47) = 5.301$, $p < 0.001$). The LDW condition was not statistically different from the baseline condition ($t(47) = 0.483$, $p = 0.832$). These results indicate that the DN/LDW condition may have reduced PERCLOS prior to lane departure events compared to baseline. The LDW condition did not result in lower levels of PERCLOS compared to the baseline condition.

Drowsiness Before Rest Areas

Participants chose to stop at some rest areas but passed most of them without stopping. To answer the question of whether the LDW and DN/LDW reduced drowsiness, analysts extracted data 1-minute prior to passing each rest stop. The 1-minute segments prior to rest stops represent points in the drive where participants were deciding whether to stop to rest. Analysts calculated PERCLOS for each segment using data from the eye tracker. The main effect of condition on PERCLOS prior to the rest areas was not statistically significant ($F(2, 69) = 2.061$, $p = 0.129$).

Break Taking

Analysts performed an additional set of analyses on break-taking behavior. One of the primary objectives of the project was to understand whether the DN/LDW and LDW conditions increased the likelihood that participants would stop to take breaks or would otherwise change their behavior with respect to stopping to rest.

To determine whether drivers took more frequent breaks with notification than without, for each participant analysts recorded the number of breaks during the test session and divided it by the total drive time in minutes. The frequency of breaks by condition is shown in Figure 10 and Table 7. The main effect of Condition was not statistically significant ($F(2, 69) = 1.108$, $p > .05$), suggesting that neither the DN/LDW nor the LDW conditions increased the likelihood that participants would take more breaks compared to the baseline condition.

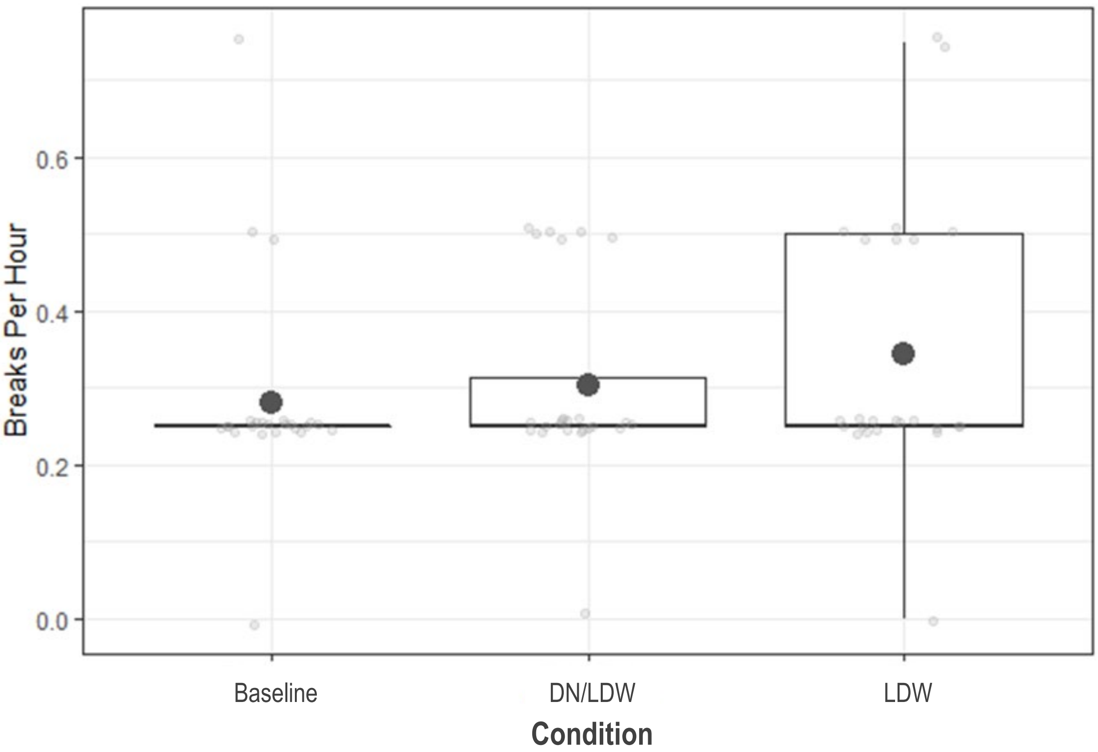

Figure 10. Breaks per hour by condition. Dark circles represent condition means and small light circles represent individual participant means.

Table 7. Descriptive Statistics for Breaks per Hour and Mean Number of Breaks

Condition	**Mean**	**Median**	**SD**	**Mean Number of Breaks**
Baseline	0.281	0.250	0.134	1.125
DN/LDW	0.302	0.250	0.127	1.208
LDW	0.344	0.250	0.178	1.375

To determine if participants in the notification conditions took longer breaks than participants in the baseline condition, analysts computed the average duration of breaks for each participant. The main effect of condition was not statistically significant ($F(2, 68) = 0.726$, $p = 0.487$). Researchers were also interested in whether participants driving with notifications took breaks earlier in the drive compared to participants driving without notifications. The difference between conditions was not statistically significant ($F(2, 68) = 1.952$, $p = 0.15$). These results suggest that break-taking behavior, both the frequency and timing of breaks, was not different in the notification conditions compared to the baseline condition.

Subjective Drowsiness

Researchers examined the extent to which notification may have increased or decreased subjective drowsiness relative to the baseline condition. Analysts measured subjective drowsiness by the SSS at points where participants decided to stop to rest. Figure 11and Table 8 show SSS scores at the start of voluntary rest breaks. Analysts compared the mean SSS scores across the three conditions. Subjective drowsiness at the start of breaks was not statistically different between the conditions (*F*(2, 68) = 0.597, *p* = 0.553).

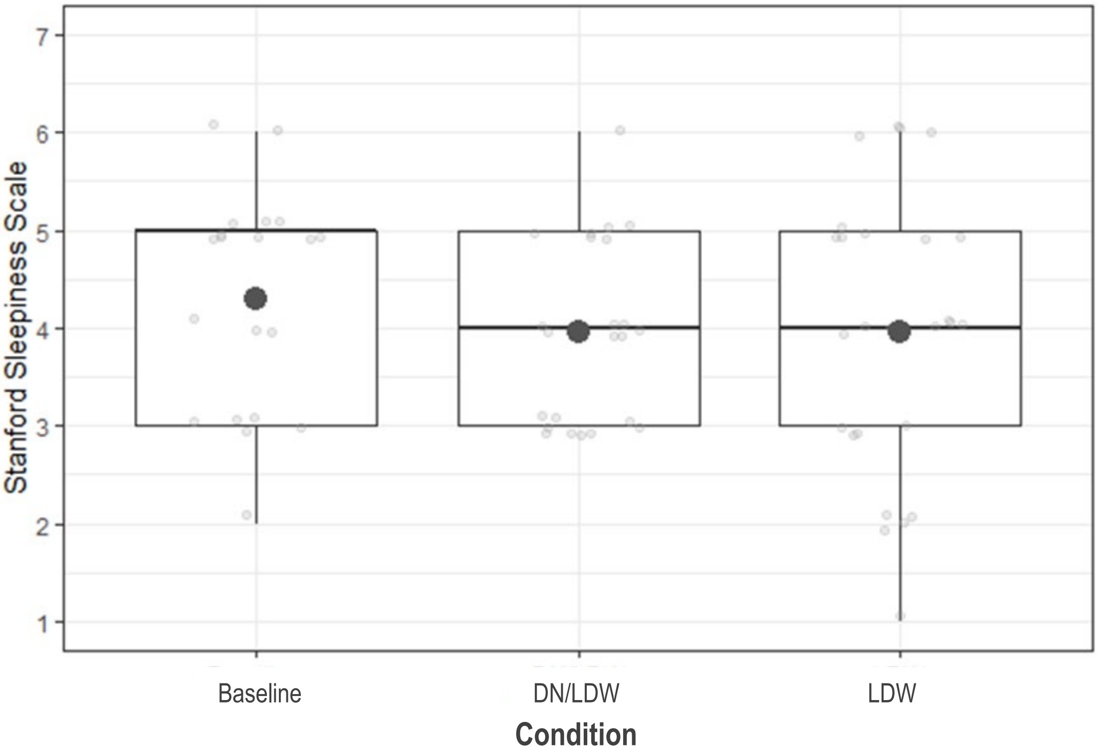

Figure 11. SSS scores collected at break start. Dark circles represent condition means and small grey circles represent individual participants.

Table 8. Descriptive Statistics for SSS at Break Start

Condition	**Mean**	**Median**	**SD**
Baseline	4.300	5.000	1.129
DN/LDW	3.960	4.000	0.889
LDW	3.962	4.000	1.428

Post-Drive Survey

After the drive, participants completed a survey assessing their perceptions of the notifications (if applicable), their decision-making during the drive, and their impressions of the incentive methodology. Analysts analyzed a subset of the questions to address these research questions. Table 9 shows the questions included in the analysis and their corresponding response scales.

Table 9. Post-Drive Survey Questions and Scales

Question #	Question	Scale
12	To what extent did you find the lane departure warning annoying?	*Not Annoying 1 2 3 4 5 6 Very Annoying 7*
13	If a lane departure warning were available in your vehicle, how likely would you be to keep it on so that it provided warnings?	*Not At All Likely 1 2 3 4 5 6 Very Likely 7*
20	To what extent did you find the drowsiness notification[2] annoying?	*Not Annoying 1 2 3 4 5 6 Very Annoying 7*
21	If a drowsiness notification were available in your vehicle, how likely would you be to keep it on so that it provided warnings?	*Not At All Likely 1 2 3 4 5 6 Very Likely 7*
1	During the drive you just completed, were you more or less likely to stop to rest than if you were actually driving in a similar situation in the real world?	*Much less likely 1 2 3 Just as likely 4 5 6 Much more likely 7*

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[2] The original version of the questionnaire contained the word “mitigation.” This was replaced within the body of this report to “notification” to describe the system mechanism.

Question #	Question	Scale						
3	Did the incentives for the session make you more or less likely to stop to rest than in the real world?	*Much less likely* *1*	*2*	*3*	*Just as likely* *4*	*5*	*6*	*Much more likely* *7*

The questionnaire asked participants in the DN/LDW and LDW conditions to indicate the extent to which the LDW was annoying. Participants responded on a scale from 1 to 7, where 1 was "Not Annoying" and 7 was "Very Annoying." The questionnaire also asked participants the extent to which they would choose to use the LDW if it was available on their vehicle. Participants responded on a scale from 1 to 7, where 1 was "Not at all Likely" and 7 was "Very Likely." Figure 12 shows histograms of responses to these two questions, and Table 10 shows corresponding data. Participants found the lane departure warning slightly annoying (mean = 4.125). Participants in the two notification conditions also reported being somewhat likely to adopt and use lane departure warnings if they were available in their vehicle (mean = 4.354).

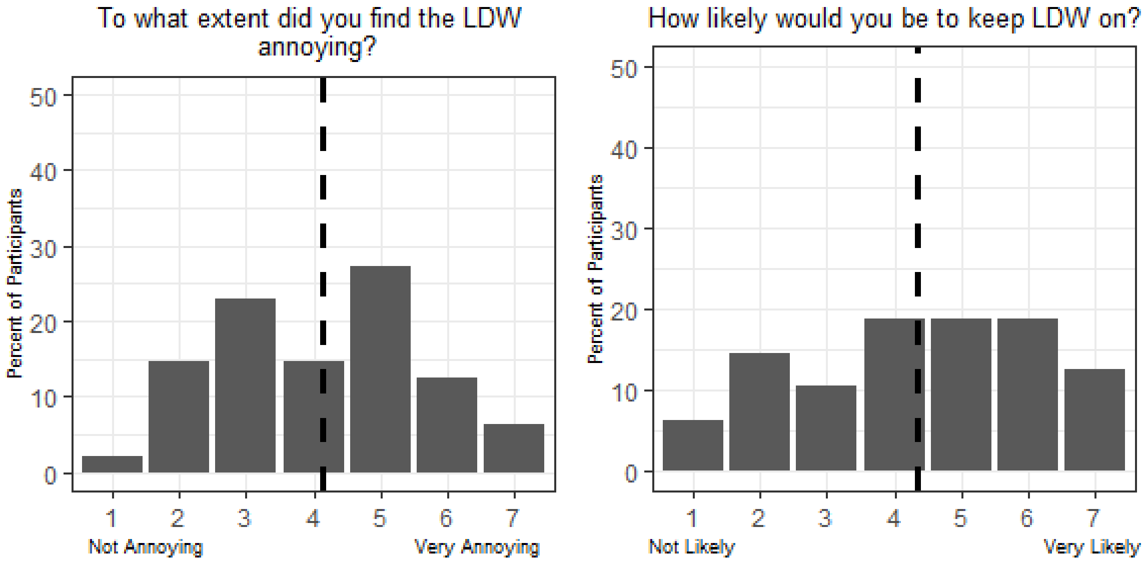

Figure 12. Histograms of responses to questions about annoyance and adoption of LDW. Dashed lines represent means.

Another set of questions asked participants in the DN condition about their perceptions of the drowsiness notifications. Figure 13 and Table 10 show the relative frequency of responses to questions about the DN. The questionnaire asked participants the extent to which they found the DN alerts annoying. Participants responded on a scale from 1 to 7, where 1 was "Not Annoying" and 7 was "Very Annoying." The questionnaire also asked participants how likely they would be to keep the alerts on if they were available in their vehicles. Participants responded on a scale from 1 to 7, where 1 was "Not at all Likely" and 7 was "Very Likely." Participants found the DN alerts mildly annoying (mean = 3.833). They also reported being somewhat likely to keep alerts on if available in their own vehicle (mean = 3.667). Finally, when asked whether the drowsiness notification changed their decision making, 4 of the 24 participants in the DN/LDW condition said the drowsiness notification changed their driving behavior. Two of those participants reported that the drowsiness notification prompted them to stop and rest. A third participant said they began to rely on the drowsiness notification to evaluate whether they were too drowsy to continue driving.

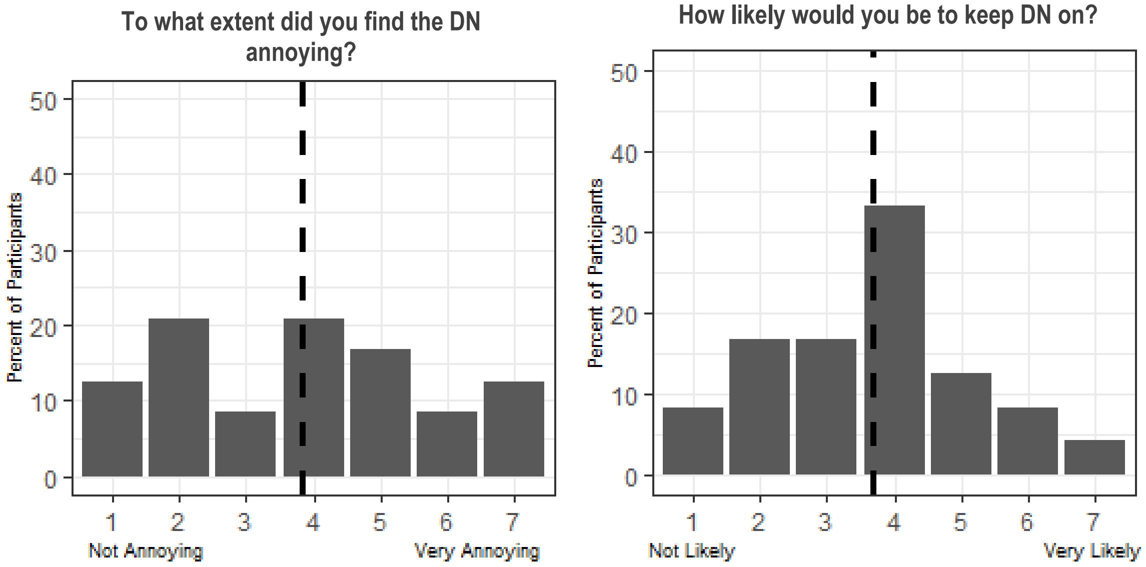

Figure 13. Histograms of responses to questions about annoyance and adoption of DN. Dashed lines represent means.

The final analysis focused on the impact of the incentive method on drowsy driver decision making. The objective of the incentive scheme was to replicate the motivational tradeoffs involved in long drowsy driving situations. Analysts examined responses to two survey questions to gain insight into whether participants felt similar motivational tradeoffs during the study as they would during real driving. One question asked participants to identify the extent to which they thought they were more or less likely to stop driving in the simulator versus the real world. A second question asked participants to indicate the extent to which the incentive method made it more or less likely that they would stop to rest compared to the real world. For both questions, participants responded on a scale from 1 to 7, where 1 was “Not at all Likely” and 7 was “Very Likely” (Figure 14 and Table 10). Most participants reported that they were just as likely to stop to rest in the simulator compared to a real-world situation (mean = 3.767). Participants reported that they were somewhat less likely to stop to rest based on the incentive method (mean = 3.192).

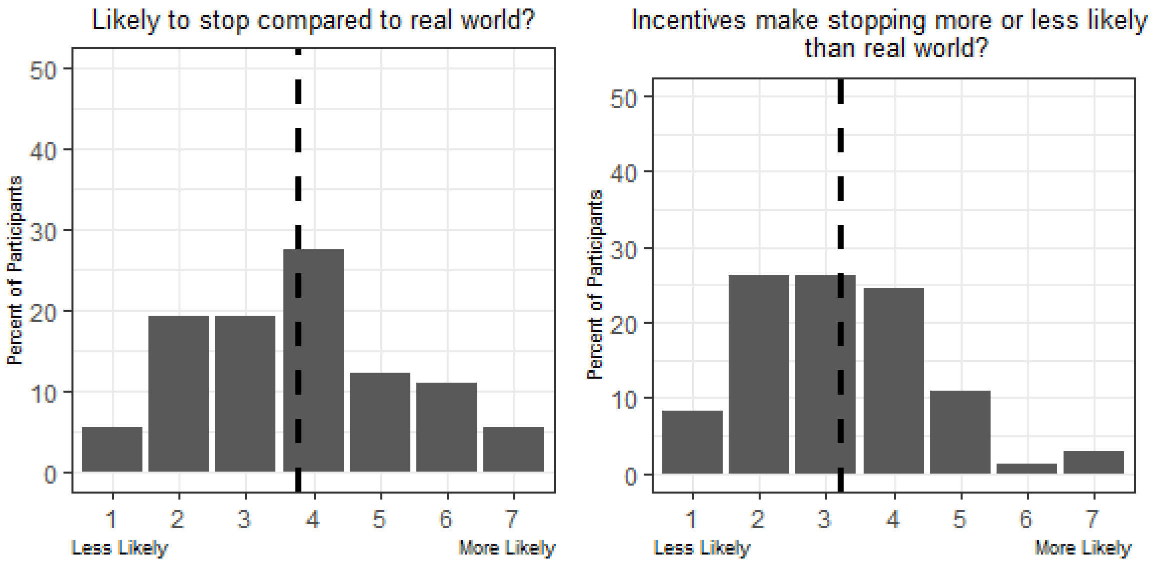

Figure 14. Histograms of responses to questions about whether participants were more likely to stop in the simulator than real-world and whether the incentive made stopping to rest more or less likely. Dashed lines represent means.

Table 10. Relative Frequency of Likert Responses on Post-Drive Survey

	Relative Frequency (%)						
Question	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Q12: To what extent did you find the LDW annoying?	2.08	14.58	22.92	14.58	27.08	12.50	6.25
Q13: If LDW were available in your vehicle, how likely would you be to keep it on so that it provided warnings?	6.25	14.58	10.42	18.75	18.75	18.75	12.50
Q20: To what extent did you find the drowsiness notification annoying?	12.50	20.83	8.33	20.83	16.67	8.33	12.50
Q21: If a drowsiness notification were available in your vehicle, how likely would you be to keep it on so that it provided warnings?	8.33	16.67	16.67	33.33	12.50	8.33	4.17

Question	Relative Frequency (%)						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Q1: During the drive you just completed, were you more or less likely to stop to rest than if you were actually driving in a similar situation in the real world?	5.56	19.44	19.44	27.78	12.50	11.11	5.56
Q3: Did the incentives for the session make you more or less likely to stop to rest than in the real world?	8.33	26.37	26.39	25.00	11.11	1.39	2.78

Discussion and Conclusions

The objective of this project was to evaluate the effectiveness and effect of drowsiness countermeasures on drivers' driving ability and rest-taking behavior in long drowsy driving situations. The study implemented a novel incentive method to replicate the motivational tradeoffs of a drowsy driving situation in 4-hour drives on the high-fidelity NADS-1 driving simulator. The study compared a representative DN/LDW and LDW conditions against a baseline condition with no notification. Researchers used a combination of driving performance, eye tracking, and questionnaire data to evaluate the effectiveness of DN/LDW and LDW compared to a group of participants who experienced no notification (baseline condition). When considering the results of this study, it is important to note that the participants were males 21 to 30 years old, which may limit the generalizability of the study to the larger U.S. population.

These results indicate that notification was effective at reducing lane departures in the context of a long drowsy driving situation in this sample. The DN/LDW reduced the frequency of lane departures and PERCLOS prior to lane departures compared to the baseline condition. The LDW condition did not show a reduction in lane departures compared to the baseline condition, nor was PERCLOS reduced for the LDW condition compared to baseline. This research builds on the previous finding by Gaspar and colleagues (2017) that DN is effective in reducing lane departures over relatively short drives. The present study demonstrates that a representative notification, consisting of a combined DN and LDW, reduces lane departures over the course of much longer 4-hour drives. Importantly, the finding that lane departure frequency was not lower in the LDW condition than the baseline condition suggests that the LDW alone, a performance-based countermeasure, may not be sufficient to improve drowsy driving performance in the current study. It is important to note that there was no difference between the notification conditions and baseline in the severity of lane departures when they did occur. All conditions showed similar lane departure magnitudes. This suggests that the key benefit of the DN/LDW countermeasure was mainly preventive.

The reduced PERCLOS in the 60 seconds prior to lane departures for the DN/LDW group suggests a mechanism by which notification improved performance. The DN/LDW condition reduced PERCLOS (i.e., increased alertness) in lane departure situations, improving lane keeping performance and decreasing the probability of lane departures. Increased alertness in the DN/LDW condition also appears to have speeded responses to lane departures when they did occur, as evidenced by shorter time-to-stabilization in the DN/LDW condition compared to baseline. The finding that the LDW did not decrease PERCLOS prior to lane departure events suggests that participants may have become acclimatized to the LDW or, perhaps, were unable to respond fast enough to the alert in a drowsy state to prevent a lane departure. The LDW did reduce response time to lane departures (i.e., lane stabilization), suggesting that it aided earlier detection and response to lane departure situations compared to baseline. The difference between DN/LDW and LDW conditions suggests that the DN/LDW offers earlier alerts while drowsiness is still developing, working to prevent decreased performance to some degree. LDW did not show that lane departure frequency lessened or a corresponding reduction in PERCLOS prior to lane departures compared to baseline. This finding suggests that, unlike the DN/LDW, the LDW only offered alerts when lane departures were about to happen. It is also worth highlighting that researchers also measured PERCLOS in the periods preceding each rest area (whether participants stopped to rest or not), but the DN/LDW reduced PERCLOS only for the lane departure event windows.

A key component of this study was developing a methodology for studying decision-making over long drowsy drives. Participants had the opportunity to stop to rest and could engage in self-selected behaviors during rest breaks. Furthermore, researchers designed an incentive methodology to mimic the motivational tradeoffs of drowsy driving, i.e., deciding to stop versus continuing to drive to reach a destination. This study is the first to utilize such an incentive scheme in the context of a long drowsy driving situation. Responses to the post-drive survey questions suggest that participants felt their decision making—with respect to stopping—was similar on average to decisions in a real-world drowsy driving context. Participants indicated a tendency toward saying the incentives made them less likely to stop than they would have in the real world. This methodology offers a promising step toward understanding drowsy decision making in longer driving situations in controlled simulator environments.

There was no evidence related to differences in stopping behavior for either notification condition compared to baseline. Participants with the DN/LDW and LDW did not take more frequent breaks, earlier breaks, or increase the duration of their breaks compared to the baseline condition. These results suggest that although notification improved driving performance, it did not influence decisions about whether and when to stop to rest. It should also be noted only 4 of the 24 drivers in the DN/LDW condition reported that the notification motivated them to stop to rest. This further suggests that, for most drivers, although the DN/LDW may have decreased PERCLOS, the notification did not factor into drivers' decisions to stop to rest.

This research has important implications for the design and deployment of driver support features targeted toward reducing drowsiness. It shows that a representative system comprised of both alerting and performance-based countermeasure strategies may be effective in improving driving performance when drivers are drowsy, although it ultimately does not alter their decision making about stopping to rest. Notification may provide a safeguard against lane departure and run-off-road crashes, the most frequent type of crash attributed to drowsy driving.

Because the study focused on evaluating countermeasures representative of those on production vehicles, the decision was made to combine DN with LDW rather than evaluating DN in isolation. All production vehicles that included DN also included driver support features, typically consisting of a combination of LDW and FCW. Therefore, it is reasonable to assume that these technologies will continue to be paired and that the DN/LDW is a good approximation of production technology. It does, however, prevent the determination of which aspects of the countermeasure led to the benefits observed in this study. It may have been that the DN itself reduced PERCLOS in the lane departure situation or that some interplay between the DN and LDW led to changes in performance and driver state. What is most important is that this combined system was effective in combating the performance degradation associated with drowsy driving. During the lane departure situations, the difference in PERCLOS prior to lane departure events suggests that the DN may have provided an additional benefit to that of the LDW alone.

The representative DN component of the DN/LDW in this study consisted of several parts: an attention bar, a coffee cup alert, and the requirement to clear the alert via a button on the steering wheel. Researchers designed this interface to convey different types of information to drivers with different levels of urgency, with the hypothesis that drivers are more likely to choose to stop before getting alerts (i.e., when the attention bar drops) than after. However, it appears that these different types of information did not have an impact on drowsy driver decision making.

Research may also seek to understand the potential for unintended consequences associated with DN. One such example might be false positives during daytime drives or situations where the driver is not actually drowsy. Willingness to adopt specific technologies is another critical topic in this area. Research suggests that drivers may be unwilling to adopt support technologies if those technologies are perceived as annoying or providing mostly nuisance alerts. Reagan and McCartt (2016), for example, found that many drivers deactivated LDW even though these alerts may confer a safety benefit to drivers. In this study, a questionnaire asked participants how annoying they found the LDW and the DN (if applicable). Furthermore, while participants were generally accepting of both the DN and LDW, longer-term studies that track exposure and preferences to different systems are needed to fully understand adoption of assistance technology.

Several limitations in the current study are worth discussing. First, researchers conducted this study in a driving simulator. Although the simulator was high-fidelity and included motion feedback, it is important to understand how these results generalize to different, more complex driving situations. Second, this study focused on young male drivers, as this group is particularly high-risk for drowsiness-related crashes. Although the drives in this study were longer than nearly any other drowsy driving study to date, participants, on average, took just one to two breaks during the drives. More work is needed to understand the complex context in which drowsy driving decisions happen. The incentive scheme developed for this study can translate to other situations, perhaps those including a series of drives where longer-term behavior must be considered. Finally, there are significant differences in how production DN technologies detect and respond to drowsiness, from the data used for state classification to the human-machine interfaces to interact with the driver.

In conclusion, this study extends previous research by demonstrating the potential safety benefit of DN/LDW for drowsy drivers in longer driving situations. It is important to remember, however, that participants still departed the lane with both the DN/LDW and LDW conditions. At a certain point, taking a nap or getting adequate sleep is the only true countermeasure against drowsiness. The results of this study suggest that neither DN/LDW nor LDW conditions increased the frequency or timing of break taking, suggesting that these countermeasures may best be considered as short-term solutions that improve but do not eliminate the consequences of drowsiness.

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