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AGING Older Adults' Driving Behavior Using Longitudinal and Lateral Warning Systems

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Abstract

Objective: This study assessed older drivers' driving behavior when using longitudinal and lateral vehicle warning systems together.

Background: Advanced driver assistance systems (ADAS) can benefit drivers of all ages. Previous research with younger to middle-aged samples suggests that safety benefits are not necessarily additive with additional ADAS. Increases in following distance associated with the use of forward collision warning (FCW) decreased when drivers also used lane departure warning (LDW), likely due to attending to the LDW more than the FCW.

Method: The current study used a driving simulator to provide 128 older drivers experience with FCW and/or LDW system(s) during a ~25-minute drive to gauge their usage's effects on driving performance and subjective workload.

Results: There were no significant differences found in headway distance between older drivers that used different combinations of FCW and LDW systems, but those that used an FCW system showed significantly longer time-to-collision (TTC) when approaching the critical event than those who did not. Users of LDW systems did not show reductions in standard deviation of lane position. Analyses of subjective workload measures showed no significant differences between conditions.

Conclusion: Findings suggest that FCW could increase older drivers' TTC over the course of a drive. Contrary to previous findings in younger samples, concurrent use of FCW and LDW systems did not adversely affect older drivers' longitudinal driving performance and subjective workload.

Application: Potential applications of this research include the assessment of older drivers' use of vehicle warning systems and their effects on subjective workload.

Précis:

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Author contributions: DS designed and ran the study, performed analyses, and was primary author for the manuscript. NC assisted in the design of the study and plan for analysis. NR pre-processed all raw driving simulator data to extract metrics of interest, for each specific DCR, in order to produce all final datasets for analysis (including merging with secondary datasets) and performed analyses. HP assisted in running the study and in preparation of the data set.

Older drivers used different combinations of FCW and LDW systems over the course of a ~25-minute simulated drive and effects on driving performance and subjective workload were assessed. Pairing these two systems did not lead to reductions in headway distance or higher levels of subjective workload.

Keywords

Older Adults; Advanced Driver Assistance Systems; Forward Collision Warning; Lane Departure Warning

Introduction

Advanced driver assistance systems (ADAS) have been suggested as technological supports for older drivers (Eby et al., 2015; Bengler et al., 2014; Lees and Lee, 2009; Davidse, 2006). Hazard detection has been implicated as a major factor in older drivers' crash rate by some studies (Horswill, et al., 2008; older $n = 118$), though some studies dispute this (see Borowsky, Shinar, and Oron-Gilad, 2010; older $n = 16$). Older drivers might certainly benefit from automated warning of potentially dangerous situations on the road, but what is unclear is if the rapid influx of multiple ADAS and their different warnings might lead to unforeseen increases in workload for older drivers who might have increased difficulties dealing with distraction (e.g., Healey, Campbell, and Hasher, 2008; Lam, 2002). Indeed, Maltz, Sun, Wu, and Mourant (2004) have called for more research on the effects of multiple auditory signals on older drivers' performance, and Navarro and colleagues (2016) have called for further investigation of how multiple ADAS, forward collision warning (FCW) and lane departure warning (LDW) in particular, of different accuracies and onsets interact with each other.

FCW systems have been shown to be effective in helping drivers recognize and avoid imminent crashes (e.g., Ben-Yaacov, Maltz, and Shinar, 2002; Abe and Richardson 2004, Maltz and Shinar 2004). After reviewing the literature, Eby and colleagues (2015) rated FCW and crash mitigation systems' potential to help older drivers as high based on their ability to prevent crashes without negatively impacting driving behavior (e.g., increased speeding or higher levels of engagement in non-driving related tasks) as well as this population's favorable attitudes towards FCW. Naturalistic driving studies (Ervin et al., 2005; LeBlanc, Bao, Sayer, & Bogard, 2013; Sayer et al., 2010) and simulator research (Cotté, Meyer, & Coughlin, 2001; Kramer et al., 2007; Maltz and Shinar, 2004) have shown that FCW improved safety for all drivers, with older drivers found to drive with longer headways, therefore making collisions with lead vehicles less likely. Focus group and interview studies of FCW users have reported that FCW made them more conscious of their following distance, with some increasing their following distance when the system was in use (Braitman, McCartt, Zuby & Singer, 2010; Cicchino & McCartt, 2014; Eichelberger & McCartt, 2014a, 2014b; Strand, Nilsson, Karlsson, & Nilsson, 2011). Concerning older drivers' propensity to be involved in rear-end collisions, different methodologies have led to different results. A statistical modelling study by Yan, Radwan, and Abdel-Aty (2005) showed that the tendency to be involved in rear-end crashes decreases with age until after the age of 65, after which their accident involvement propensity increases. Stutts, Martell, and Staplin (2009) queried the General Estimates System (GES) and found that though older drivers were less likely to be involved in a rear impact; nearly half of their initial impacts in two-vehicle crashes were frontal impacts. Older age groups have been found to be less likely than younger age groups to be involved in rear-end collisions, but when involved in a rear-end collision, drivers over the age of 69 are just as likely to strike than to be struck (Singh, 2003).

Eby and colleagues (2015) rated LDW systems' potential to help older drivers as moderate based particularly on their potential ability to help older drivers on longer, fatigue-inducing trips, or those who are taking medications that might lead to drowsiness. They cited a dearth of real-world data with which to fully assess the safety benefits for older drivers and stressed the need for these systems to be more operationally robust (i.e., work under most driving conditions with low false alarm rates). Naturalistic driving studies investigating LDW systems have shown that drivers of all ages tended to stay closer to the center of their lane, use their turn signals more often, and have fewer lane excursions than when driving without the system (LeBlanc et al., 2006). Simulator research has shown that LDW system use helps older drivers reduce their reaction time for lane deviation corrections by 1.2 seconds (Aksan et al., 2015). Drivers over the age of 65 in a focus group study expressed concerns that the system might distract them from the driving task, or might not give them timely enough warnings for them to take corrective action (Regan et al., 2002).

On-road studies investigating the use of FCW and LDW systems have found that their safety benefits are not necessarily additive (i.e., increases in following distance observed in studies assessing FCW use were reduced when this system was paired with an LDW system). For instance, the Integrated Vehicle-Based Safety System (IVBSS) field operational test conducted by Sayer and colleagues (2010), found that when using the IVBSS (which included FCW, LDW, a blind spot detection system, a curve speed warning, and a lane change/merge warning) drivers departed their lanes less often (14.6 departures per 100 miles unassisted vs. 7.6 per 100 miles assisted) and spent less time out of their lanes (1.98s unassisted vs. 1.66s while assisted), but spent significantly more time (21% unassisted vs. 24% assisted) at headways of less than one second than when unassisted. Additionally, Portouli, Papakostopoulos, and Marmaras (2011) used an instrumented vehicle to compare four groups of drivers (FCW only, LDW only, both systems, or unassisted) and found longitudinal and lateral control benefits over the unassisted group when using a single system, but no significant benefit over the unassisted group when using both systems. They reported that participants who used both systems also gave lower satisfaction ratings than those who used just one of them, citing in a post-hoc telephone interview that trying to cope with both systems' warnings was frustrating. In a study that included a late middle age group (55–65), Son, Park, and Park (2015) investigated the effectiveness of an aftermarket combined FCW and LDW system, finding no significant difference in headway distance over unsupported controls. Assisted female drivers in this study adopted shorter headways than unassisted female drivers. Son and colleagues stressed the need for the recruitment of older participants to investigate the effects of concurrent FCW and LDW use on driving behavior.

It is clear from the literature that both FCW and LDW systems when assessed alone have potential to help drivers of all ages avoid frontal and off-path collisions. The few studies that assess driving behavior during concurrent use of FCW and LDW systems cited above employ younger to late middle age samples, who while at or near their peak driving and attentional abilities cited difficulty dealing with both systems' alerts and/or demonstrated reductions in following distance relative to unassisted drivers or to their own unassisted driving performance. These studies have also collected relatively small samples of older age drivers that have tended to be near to late middle age (Portouli et al., 2011; Sayer et al., 2010; Son et al., 2015). Older adults have been shown to have more difficulty than younger adults in dealing with additional workload (McDowd, Vercruyssen, and Birren, 1991; Rogers and Fisk, 2001; Coughlin and Reimer, 2006) and distractibility (Healey et al., 2008). Compensatory strategies such as increasing processing time to help deal with distraction (Wascher et al., 2012) are also likely unavailable in hazardous driving situations that might elicit FCW and LDW alerts. This simulator study sought to investigate a large sample of older drivers' concurrent use of FCW and LDW systems to assess any potential ill effects on their longitudinal and lateral driving performance that might arise when dealing with alerts from both systems. Hypotheses are as follows:

H_1: Participants using only FCW show longer time-to-collision (TTC) and headway distances than those who do not receive longitudinal warnings.

H_2: Participants using LDW show smaller standard deviations in lane position (SDLP) than those who do not receive lateral warnings.

H_3: Participants using both FCW and LDW show shorter TTCs and headway distances than those who use only FCW.

H_4: Participants using both FCW and LDW report greater levels of workload than those in other conditions.

Method

Inclusion Criteria

Inclusion criteria for the study were: (1) a valid driver's license; (2) being over the age of 64; (3) driving at least 1 hour or 50 miles per week; (4) passing a pre-screen for dementia and/or memory impairment; and (5) no reported use of either FCW or LDW systems.

Participants

Participants were 135 community-dwelling older adults (M_{age} = 75.03) recruited from a database assembled by the Institute for Successful Longevity at Florida State University consisting of older adults age 60+ years who had expressed interest in participating in various aging research studies. Participants completed the driving simulator task in exchange for $15 compensation. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at Florida State University. Informed consent was obtained from each participant. Attrition from the study originated from two phases of the experiment: (1) during the familiarization drive preceding the main driving task (n = 7); and (2) during the main driving task (n = 5; see Table 1 for breakdown) and was wholly due to the onset of simulator sickness. The final analytic sample included 128 participants, of which five participants had varying levels of missing data due to differential time points of attrition. Age and gender breakdowns for each group are displayed in Table 2.

Experiment Design

This study used a 2×2 between-subjects design with lateral warnings (LDW vs. none) and longitudinal warnings (FCW vs. none) as factors. All groups also used a smart speedometer throughout their drive. Descriptions of each ADAS used in the study are provided below.

Equipment

Driving Simulator.—The driving scenarios used a fixed-base DriveSafety RS200 driving simulator, which consisted of a single bucket seat complete with a steering wheel, live instrument cluster, and brake and accelerator pedals with a 110° field of view provided by three 19” LCD retina-limited visual displays (1920×1080 resolution).

Simulated ADAS.—The three ADAS’ (i.e., smart speedometer, FCW, LDW) visual warnings were shown in a heads-up display (HUD) on the center display screen of the simulator, refreshed at 60 Hz, with graded warnings as described below (Figure 1). For thresholds used in generating graded FCWs and LDWs, see Tables 3 and 4.

Smart Speedometer.—The smart speedometer, displayed on the lower portion of the center display, provided the participant’s current speed in miles per hour, in a white sans-serif font. When the participant exceeded the posted speed limit by 1–9 mph, the numbers changed to yellow and an opaque warning triangle flashes next to their speed. When their speed exceeded the speed limit by 10 mph or more, the numbers turn red and an opaque warning triangle flashes next to them. The smart speedometer did not include any auditory alert.

Forward Collision Warning (FCW).—The FCW system employed in this study is similar to that used in Aksan et al. (2016), with the only difference being the auditory alert is changed to the perceptually harsher tone used in Cummings, Wang, and Ho (2006). The FCW issued a graded warning, with a visual alert in the form of a red rectangle near the center of the middle screen that increased in size as TTC decreased. After the TTC dropped below 2 seconds, the red rectangle was coupled with an auditory alert (~ 90 dB, peak frequency = 5 KHz).

Lane Departure Warning (LDW).—The LDW system provided a graded warning that began with a visual warning icon of a car departing a lane that increased in opacity with greater deviation from lane center. Once the participant passed a certain deviation from lane center, the fully opaque visual icon was accompanied by the auditory warning (~ 80 dB, peak frequency = ~2 KHz) used by Aksan et al. (2016), as it was less perceptually harsh than the tone used for the FCW.

Driving Scenario.—The primary driving scenario was developed using the HyperDrive authoring suite (v. 1.9.39) and consisted of a short drive (approximately 25 minutes; see Figure 2 for map of scenario with data collection regions—DCRs) through varied terrain (e.g., residential, rural, industrial, and urban landscapes), during which the driver gained experience using their experimentally-assigned ADAS (i.e., control, FCW-only, LDW-only, FCW+LDW).

The systems assigned to the participants' condition were demonstrated at the beginning of the drive while the participant drove at a low speed (25 mph) through a contrived situation. In the scenario, we placed a row of construction cylinders that cut into the participant's lane, necessitating a lateral correction that would trigger both the visual and auditory LDW alerts. The FCW demonstration consisted of an occluded car that suddenly pulled out in front of the driver and remained ahead of the participant so that they could assess the sensitivity of the FCW.

Non-linear road geometry provided the opportunity for participants to practice staying in their lane (with LDW feedback if that was their assigned condition). Programmed vehicles joined traffic ahead of the participant, providing the opportunity to implement the FCW system, by measuring headway distance between the participant's vehicle and the programmed vehicle.Table 5 shows the proportion of the drive that participants received visual and auditory warnings for both the LDW and FCW systems.

The driving scenario concluded with a critical situation, during which one of the programmed lead vehicles made a sudden and unexpected stop from 45 mph, after getting cut off by another car joining the roadway. This critical event was included to assess how different combinations of system use would affect drivers' responses in an unexpected hazard situation. We used only one critical event as learning effects from multiple critical events have been shown to create expectancies and anticipatory behavior (Aust, Engström, & Viström, 2013).

Measures

Driving Performance Measures.—We sampled driving performance measures at 60 Hz throughout the duration of the driving scenario. Performance variables of interest include: (1) *TTC* (i.e., time in seconds before a collision with the lead vehicle, calculated using the momentary speed of both vehicles); (2) *headway distance* (i.e., meters between front bumper of participant vehicle and lead vehicle); and (3) *lane position* (i.e., deviation from lane center, in meters; lane center = 0; negative values = leftward deviation, positive values = rightward deviation). We assessed the median values of *TTC* and *headway distance*. For *lane position* we were interested in the range and standard deviation.

Data collection regions (DCRs) were pre-defined using the driving scenario's Cartesian coordinates (x and y). These DCRs, implemented in R (version 3.5.0; R Core team, 2018), allowed us to assess performance measures in key areas of the drive, and in cases of repeated event types (i.e., follow, pullout) allowed us to take the median performance measures amongst similar DCR types. The different DCR types (each illustrated in Figure 2) included five "pullout" DCRs (where the lead vehicle joined the roadway), five "follow" DCRs (longer stretches during which the participant followed the lead vehicle), and five "exit" DCRs (where the lead vehicle exited the roadway). The fifth instance of each DCR type was the critical event, where a third occluded vehicle joined the roadway cutting off the lead vehicle causing it to stop suddenly. We defined a dummy-coded binary variable (i.e., *critical*) to denote the response in each outcome to the critical event.

NASA-Task Load Index (NASA-TLX).—The NASA-Task Load Index (NASA-TLX; Hart & Staveland, 1988) was administered upon completion of the drive, in order to assess if participants' perceived workload was affected when dealing with the feedback of multiple ADAS. The NASA-TLX, asks participants to provide ratings, on a scale with 21 gradations, across six domains of interest: mental demand, physical demand, temporal demand, performance, effort, and frustration as it related to the primary driving task.

Other Measures.

Demographics & Driving History Questionnaire.—Demographic information (birthdate and sex) and driving history were collected via a short questionnaire. Driving frequency (1 = "hardly ever" to 4 = "everyday") and estimated miles driven annually (1 = "less than 5,000 miles" to 5 = "greater than 20,000 miles"), were self-reported.

Useful Field of View (UFOV)® Subtest 2: Divided Attention.—Previous evidence highlights that UFOV (Ball & Owsley, 1993) performance predicts: (1) retrospective and prospective crash involvement, (2) on-road driving performance, and (3) driving simulator performance (Clay et al., 2005; Mathias and Lucas, 2009; Gentzler and Smither, 2012). The divided attention subtest, where participants are to report two distinct pieces of visual information, presented briefly, is often used alone for brevity purposes (Ball et al., 2006), and has been shown to be sensitive to driving outcomes (Edwards et al., 2006; on-road driving: Bowers et al., 2013; simulated driving: Molnar et al., 2007). Participant's scores reflect the exposure time in milliseconds at which they responded accurately 75% or more of the time.

Simulator Sickness Questionnaire.—The Simulator Sickness Questionnaire (SSQ; Kennedy, Fowlkes, Berbaum, and Lilienthal, 1992) was included to account for any performance declines due to symptoms associated with simulator sickness. Participants indicated the extent to which they experienced various symptoms of simulator sickness (e.g., dizziness, nausea) throughout the drive. We used the sum of their ratings across various symptoms to gauge the extent to which performance in the simulator might be compromised.

Procedure

Upon the participants' arrival in the lab, we obtained informed consent, and administered a short demographic and driving history questionnaire. The participant then completed the UFOV assessment. Next, the participant completed a short training drive to assure a common-level of familiarity with the operation of the driving simulator before the main driving scenario began. Prior to beginning the main driving task, we randomly assigned the participant to one of the four groups (control, FCW-only, LDW-only, or FCW & LDW). Participants were told they would be driving a rental car equipped with the ADAS corresponding to their assigned condition and were given a short description of how the system(s) function. The descriptions were minimal, as it has been found that when a person has little information about how a system functions they tend to believe it will outperform them and rely upon it more (Dzindolet et al., 2003). The participant then completed the driving scenario outlined above, with instruction to stay on the current route and to follow traffic rules as they would if they were driving normally, all the while doing their best to maintain the speed limit. During the driving scenario, the experimenter stayed in the room with the participant.

The participant then filled out the NASA-TLX (i.e., to assess workload perceptions during the task), the SSQ (i.e., to gauge their level of simulator sickness symptoms), and other exploratory measures before being debriefed and compensated. Completion of the study took roughly 90 minutes.

Analyses

We modeled the outcomes of interest (i.e., lane keeping, driving headway), as repeated measures, within a DCR type, in a linear mixed effect modeling framework, including participants as a random effect in the model (using R package *nlme*; Pinheiro et al., 2018). For modeling each outcome, we included the following fixed effects:

- DCR sequence order (1–5)
- DCR type (i.e., pullout, follow, exit)
- The interaction of the relevant warning system for the outcome (i.e., FCW, LDW) and the critical event (i.e., to what extent is the effect of the system only seen in extreme situations and not in non-perturbed situations)

To control for the dependency between measurements in time (i.e., controlling for habituation to the simulator), we allowed for an autocorrelation structure of order 1, using the corAR1() function call in the *nlme* package in R.

We calculated pseudo-R^2 using R package *MuMin,* capable of providing marginal R^2, the variance explained by the fixed effects, as well as conditional R^2, the variance explained by the full model, including random effects.

For each outcome model, as specified above, we also conducted a complementary analysis, exploring the unconditional means model (no parameters, other than participant random effect), in order to establish: (1) to what extent further parameters were warranted in the model; and (2) establish measures of reliability.

Between-person (BP) reliability of the various outcome metrics was calculated based on the formula of Raykov & Marcoulides (2006), where Var(BP) is the total variance in the outcome measure that is between persons, and Var(WP) is the total variance in the outcome measure that is within persons, and n is the number of observations.

$$Between - person\ reliability = \frac{Var(BP)}{(Var(BP) + Var(WP)/n}$$

For determining the reliability of a single assessment of each performance metric, the above formula could be used, specifying n=1, resulting in the formula for the intraclass correlation (ICC)—representing the stability of the measurement, and expected correlation between two randomly sampled measurements from the same person.

Group differences in subjective workload ratings were analyzed using a 2×2 (longitudinal warnings vs. none, lateral warnings vs. none) MANCOVA, with the six NASA-TLX ratings serving as dependent variables and age and gender as covariates.

Results

Time-to-collision (median seconds)

Prior to model fitting, we visually inspected median TTC for assumptions of normality (Figure 3). As is common with response time variables (as TTC can be considered), there was a severe skewness in the data, so median TTC was log-transformed to meet the assumption of normality.

The ICC for median TTC, aggregated within each instance of each DCR, was 0.04, indicating that 4% of the variance in TTC was between persons (96% within-persons). The *ICC* for the log-transformed variant of median TTC was 0.17, indicating that 17% of the variance in TTC was between persons (83% within-persons), reflecting the increase in measure stability by log-transforming.

The full model (median TTC, predicted by fixed effects: instance order, DCR type, FCW-by-critical event interaction; participant as random effect) was evaluated, for both variance explained by fixed effects (i.e., pseudo marginal R^2), and variance explained by both fixed and random effects (i.e., pseudo conditional R^2). Fixed effects alone accounts for 14% of the variance (i.e., marginal $R^2 = 0.14$), while the full model accounted for 31% of the variance explained (i.e., conditional $R^2 = 0.31$).

The effects of DCR instance order was not significant ($p = 0.25$). The effects of DCR type were significant (p's < .001), as was the interaction of the FCW system and the critical event ($p = 0.025$). Participants followed significantly more closely in time to the lead vehicle during ‘Exit’ region types ($p < .001$), as compared with ‘Follow’ and ‘Pullout’ region types. Participants with the FCW system responded with more caution by allowing more time-to-collision during the critical event. Figure 4, depicts these results visually.

Headway Distance (*median* meters)

The ICC for median headway distance (meters), aggregated within each instance of each DCR (Figure 5), was 0.44, indicating that 44% of the variance in TTC was between persons (56% within-persons).

The full model (median headway distance, predicted by fixed effects: instance order, DCR type, FCW-by-critical event interaction; participant as random effect) was evaluated, for both variance explained by fixed effects, and variance explained by both fixed and random effects. Fixed effects alone account for 12% of the variance (i.e., marginal R^2= 0.12), while the full model accounted for 53% of the variance explained (i.e., conditional R^2= 0.53).

The effects of DCR instance order, DCR type, and the critical event were all significant (p's $< .001$). The effect of the FCW ($p = 0.29$) and the FCW-by-critical event interaction were not significant ($p = 0.99$). Echoing the result of the parallel TTC analysis, participants followed significantly more closely in distance to the lead vehicle during 'Exit' region types ($p < .001$), as compared with 'Follow' and 'Pullout' region types.

Standard Deviation of Lane Position

In order to capture the extent of lane-keeping bounds, we chose to model the SDLP, operationalized as the standard deviation of lane position observed within each instance of each DCR. We display the distribution of range of lane position and SDLP across DCR types in Figure 7.

The ICC for standard deviation of lane position (meters), aggregated within each instance of each data collection region, was 0.07 indicating that 7% of the variance in standard deviation of lane position was between persons (93% within-persons)—compared with 99% within-persons with range of lane position.

The full model (standard deviation of lane position, predicted by fixed effects: instance order, data-collection region type, LDW-by-critical event interaction; participant as random effect) was evaluated, for both variance explained by fixed effects, and variance explained by both fixed and random effects. Fixed effects alone account for 31% of the variance (i.e., marginal $R^2 = 0.31$), while the full model accounted for 41% of the variance explained (i.e., conditional $R^2 = 0.41$).

The effects of DCR instance order, DCR type (when type is "Follow"), and the critical event were all significant (p's $< .001$). The effect of the LDW ($p = 0.24$) and the LDW-by-critical event interaction were not significant ($p = 0.46$).

Workload Analyses

Complete NASA-TLX ratings are presented by group in Figure 9. A non-significant Box's test ($p = .14$) indicated homogeneity of variance across the groups. The multivariate test for the interaction was not found to be significant (Wilks' Lambda; $F(6, 117) = 1.14$, $p = .35$, $\eta_p^2 = .055$), nor were the main effects for longitudinal warnings (Wilks' Lambda; $F(6, 117) = .58$, $p = .74$, $\eta_p^2 = .029$) or lateral warnings (Wilks' Lambda; $F(6, 117) = 1.78$, $p = .11$, $\eta_p^2 = .084$) found to be significant.

Sensitivity Analysis

Analyses were run with and without the covariate SSQ total, and while it was only significant in the instance of headway distance, it did not affect the pattern of observed results.

Discussion

Overview

This study investigated the effect of a short-term, simulated exposure to a longitudinal and/or lateral warning system on older drivers' driving performance. In summary, ADAS systems in our simulator study had varying effects, depending on the system type, and outcome measure of interest. The key finding of our study was increased TTC in the situation of a contrived critical event. Regardless of ADAS condition, a majority of participants completed the drive (90^{+}%), without any issues. True to the literature on older drivers' careful and conservative driving style in the real world (Evans, 2004; Oxley, Charlton, and Fildes, 2003; Robertson and Aultman-Hall, 2001; Ball, et al., 1998; Stamatiadis and Deacon, 1995), participants also drove cautiously in the simulator (similar to the pattern observed by Ikeda et al., 2002). Participants drove with long enough headway distances that the planned critical event at the end of the drive failed to elicit the intended criticality. Participants only rarely needed to tap their brakes in the closest of cases. It is interesting that despite receiving very few FCWs during the course of the drive, participants assigned to FCW conditions showed significantly higher TTCs than those who did not use FCW.

Using a linear mixed effect modeling analytic framework conferred several benefits, namely the ability to allow for baseline differences amongst participants, and the ability to evaluate the psychometric properties of our outcomes. Evaluating the psychometric properties of each outcome provided valuable information as to the extent we might have even been powered to detect a reliable effect. In the situation of lane position, 93% of the variance is within-persons, yet our pre-specified models are attempting to evaluate a between-persons question (i.e., do people who receive a particular ADAS system drive notably different in a beneficial direction, as compared with those who do not receive the system?).

Hypotheses

Results supported H_1 within the context of the critical event, with drivers using FCW driving with significantly longer TTC than drivers who did not receive longitudinal warnings (unassisted & LDW-only groups), though this significant difference did not extend to the rest of the drive. Though this difference was significant, one should note that these values were quite high, and drivers who did not receive longitudinal warnings were still far from the hazardous event. It is possible that expectancies of surprise hazards stemmed from the demonstration of the FCW system's alerts in the first portion of the experimental drive and led to increasingly long following time distances over the course of the drive, as all participants assigned to FCW conditions received this demonstration, though only a few received subsequent FCWs.

Results did not support H_3, that drivers using FCW & LDW would have shorter headway distances than drivers using only FCW. This could be for a number of reasons. FCW alerts are relatively rare in on-road studies, with Najm and colleagues (2006) only observing .62 FCW alerts per 100 km travelled. This rarity of FCW alerts was amplified in the current study by the cautious and conservative driving style most participants adopted when driving in the simulator. Studies comparing distance estimation in real and virtual environments have found that subjects tend to underestimate the actual distance (Thompson et al., 2004; Willemson and Gooch, 2002). More recent work by Risto and Martens (2014) comparing headway choice between the real-world and a driving simulator, found that self-chosen headways did not differ between the simulator and real driving, therefore lending support for using simulators to study headway choice. In the current study, it was observed in piloting (and persisted into data collection) that some participants would brake several meters short of stop signs and brake suddenly for the lead vehicles joining the roadway at headway times that would not necessitate any braking if the subject was within 5 mph of the speed limit. It is possible that this underestimation of headway distance in the simulator exaggerated older drivers' already-conservative driving style, leading to few FCW alerts on which participants could: (1) differentially adjust their headway distance relative to non-longitudinally warned participants (H_1); or (2) choose to over-rely on, leading to shorter headway distances for drivers that also used LDW (H_3). Future naturalistic driving studies should investigate the nature of older drivers' modifications of their driving style when using ADAS systems, and the implications for how these systems issue their alerts. (e.g., to develop age-sensitive ADAS parameters).

The study by Aksan and colleagues (2016), from which the current study received its FCW script, suggested that older drivers might need warnings earlier than four seconds TTC, as a significant proportion of their older participants were still accelerating at this point when compared to younger and middle-aged participants. The low occurrence of FCW alerts issued in the current study (47.6% of participants using FCW did not trigger the system over the course of the entire drive) suggests that older drivers might need more sensitive FCW thresholds to even observe the system in action. The fact that the scripted FCW system issued alerts based on solely a relative speed measure (TTC), coupled with older drivers' conservative driving style, meant that only rarely did the participant's and the lead vehicle's acceleration/deceleration profiles ever come in conflict to generate a low enough TTC to trigger the FCW alert. An alternative interpretation is that FCW systems might be of limited usefulness to older drivers in crash-imminent situations unless they include autobraking functionality.

The data did not support the hypothesis that drivers using LDW would show smaller deviations from lane center (H_2). This is likely because 93% of the variance in lane keeping behavior was within-subjects, while we were assessing a between-subjects question. In driving simulation work, little guidance exists as to the appropriate or most sensitive features (i.e., variability, inertia) of behavioral performance metrics (i.e., brake force, lane deviation). While there have been efforts to standardize driving measures (Green, 2013; Society of Automotive Engineers, 2015), this practice has not become commonplace. Future work may explore to what extent features used in the literature are related (i.e., median lane position, standard deviation of lane position), and where relationships deviate from expectations.

Finally, levels of higher workload for participants using both FCW and LDW (H_4) were not observed, most likely due to the infrequency of FCW alerts, as with that infrequency participants using both systems in this study were effectively using just an LDW system. Perhaps a within-subjects design would have been better to discern workload-related differences between ADAS conditions, as NASA-TLX ratings were largely similar across groups. This hypothesis was based on on-road and naturalistic driving studies (Sayer et al., 2010; Portouli et al., 2011; Son et al., 2015), in which participants also had to deal with false alarms emitted by the systems. As there was less noise involved with the inputs that dictated whether or not alerts were issued by the simulator, participants in these real-world studies might have had to contend with significantly more false alarms, which could have had greater effects on driving performance, as well as subjective workload.

Limitations

First, we acknowledge the low FCW rate in this study as a limitation. While participants assigned to FCW conditions did receive a demonstration of its visual and auditory alerts on the first stretch of the experimental drive, many did not receive FCWs during the rest of the drive. It is possible that this initial demonstration of the system created an expectancy of other surprise hazards that lead to participants in FCW conditions to drive that much more cautiously than drivers in other conditions, culminating in the finding of significantly longer TTC when these groups approached the critical event at the end of the drive. Participants' underestimation of headway distance observed in the simulator and compensatory driving adjustments to following behavior that resulted led to extremely few instances where this alert was received, meaning that those participants assigned to the condition with both systems basically only received alerts from the LDW system. False alarms should be incorporated in future driving simulator research investigating the effects of multiple ADAS warnings on driving performance and workload, as they would increase the occurrence of this relatively rare alert and were the implicated source of poor ratings of the FCW system in the Sayer et al., (2010) IVBSS field operational test.

Second, the cross-sectional nature of the study provided a limited window to observe the effects of system usage on driving performance. While a longitudinal study would have provided more experience with the system(s), carrying out longitudinal simulator studies involving older populations raise considerable challenges. First, research has shown that individuals over the age of 70 experience greater levels of simulator sickness related symptoms than individuals under the age of 50 (Classen, Bewernitz, & Shechtman, 2011). This heightened propensity to develop symptoms of simulator sickness has also been linked to higher dropout rates. For example, a driver training study aimed at improving older drivers' performance—either through attention training or driving simulator training—found significantly higher dropout rates in the simulator-based training (Casutt et al., 2014). To help mitigate this, one potential solution is the use of several short scenarios (1–3 minutes), rather than one large scenario – spaced apart several hours, days, or more. Doing so, might lessen the susceptibility to sickness, and downstream data loss, while also identifying situations (e.g., making a left) or environmental factors (e.g., room temperature) consistently resulting in sickness.

Another limitation of the study arose because the experimenter stayed in the room with the participant during the drive. In this placement, the experimenter was positioned like a front seat passenger, but was instructed to avoid actively assisting the driver. Research has shown that front-seat passengers often help and support the driver by warning them of upcoming hazards (e.g., Vrkljan and Polgar, 2007). Importantly, the front-seat passenger in the Vrkljan and Polgar (2007) study was a usually a spouse or close friend that was an active co-pilot, not an unfamiliar experimenter as in the current study. It is possible the presence of a stranger sitting next to the participant could itself have led to more conservative driving. Other research looking at crash data has shown that there is a protective effect of the presence of passengers on the driver, and this protective effect has been found to be highest for drivers age 45–64 (Rueda-Domingo et al., 2004). Drivers are more likely: (1) to detect hazards with another person also attending to the road; (2) to drive slowly with longer headways; and (3) to wear their seatbelt (Evans and Wasielewski, 1983).

Another limitation was that participants were not screened for visual acuity, color deficiency, contrast, and/or hearing at the time of the study. A valid driver's license was required to participate in the study, so these sensory criteria at least needed to be within acceptable ranges at the time of the participants' latest license renewal (assuming a Florida driver's license, every 8 years for the general population and every 6 years for drivers aged 80+). All participants drove themselves to and from the experiment, and the researchers observed no severe impairment of vision or hearing. As older adults' sensory abilities can decline quite rapidly due to a variety of disease conditions, there remains the possibility that the observed results may be partially influenced by potential sensory deficits rather than the experimental manipulations; randomization and the large sample size would be expected to counter such influences.

Conclusions

Age-related declines in hazard perception are cited as a primary cause of older drivers' crash involvement, so supporting older drivers' ability to detect hazardous driving situations could potentially lead to substantial safety benefits. The use of ADAS has been proposed as one way of technologically automating hazard perception in this population. Work largely carried out in young to middle-aged populations has suggested that when FCW and LDW are used concurrently, some of their safety benefits are diminished, with drivers tending to over-rely on the longitudinal warning, as indicated by more time spent at shorter headway distances. Unlike patterns observed in studies with younger populations that used both longitudinal and lateral warning systems (Sayer et al., 2010; Son et al., 2015; Portouli et al., 2011), older adults using both FCW and LDW in the current study did not reduce their headway distance, but rather drove with long enough headways that the FCW system was rarely, if ever, activated. Concerns of increased workload when dealing with the feedback of multiple systems were not realized, as participants assigned to FCW conditions rarely received these alerts and all groups reported similar levels of mental, physical, and temporal demand.

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References

Abe G. & Richardson J. (2004). The effect of alarm timing on driver behaviour: An investigation of differences in driver trust and response to alarms according to alarm timing. Transportation Research Part F, 7, 307–322.

Aksan N, Sager L, Lester B, Hacker S, Dawson J, Anderson SW, & Rizzo M. (2015, 6). Effectiveness of a heads-up adaptive lane deviation warning system for middle-aged and older adults. In Proceedings of the… International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design (Vol. 2015, p. 422). NIH Public Access.

Aksan N, Sager L, Hacker S, Marini R, Dawson J, Anderson S, & Rizzo M. (2016).Forward Collision Warning: Clues to Optimal Timing of Advisory Warnings. SAE International Journal of Transportation Safety, 4(1). doi:10.4271/2016-01-1439

Aust ML, Engström J, & Viström M. (2013). Effects of forward collision warning and repeated event exposure on emergency braking. Transportation research part F: traffic psychology and behaviour, 18, 34–46.

Ball K, & Owsley C. (1993). The useful field of view test: A new technique for evaluating age-related declines in visual function. Journal of the American Optometric Association, 64, 71–79. [PubMed: 8454831]

Ball K, Owsley C, Stalvey Roeneker D., Sloane M, & Graves M. (1998). Driving avoidance and functional impairment in older drivers. Accident Analysis and Prevention, 30(3), 313–322. [PubMed: 9663290]

Ball KK, Roenker DL, Wadley VG, Edwards JD, Roth DL, McGwin G, … & Dube T. (2006). Can High-Risk Older Drivers Be Identified Through Performance-Based Measures in a Department of Motor Vehicles Setting?. Journal of the American Geriatrics Society, 54(1), 77–84. [PubMed: 16420201]

Ben-Yaacov A, Maltz M, & Shinar D. (2002). Effects of an in-vehicle collision avoidance warning system on short and long-term driving performance. Human Factors, 44(2), 335–342. [PubMed: 12452277]

Bengler K, Dietmayer K, Farber B, Maurer M, Stiller C, & Winner H. (2014). Three decades of driver assistance systems: Review and future perspectives. IEEE Intelligent Transportation Systems Magazine, 6(4), 6–22.

Borowsky A, Shinar D, & Oron-Gilad T. (2010). Age, skill, and hazard perception in driving. Accident Analysis & Prevention, 42(4), 1240–1249. [PubMed: 20441838]

Bowers AR, Anastasio RJ, Sheldon SS, O'Connor MG, Hollis AM, Howe PD, & Horowitz TS (2013). Can we improve clinical prediction of at-risk older drivers?. Accident Analysis & Prevention, 59, 537–547. [PubMed: 23954688]

Braitman KA, McCartt AT, Zuby DS, & Singer J. (2010). Volvo and Infiniti drivers' experience with select crash avoidance technologies. Traffic Injury Prevention, 11, 270–278. [PubMed: 20544571]

Casutt G, Theill N, Martin M, Keller M, & Jäncke L. (2014). The drive-wise project: driving simulator training increases real driving performance in healthy older drivers. Frontiers in aging neuroscience, 6.

Cicchino JB & McCartt AT (2014). Experiences of Dodge and Jeep Owners with Collision Avoidance and Related Technologies. Arlington, VA: Insurance Institute for Highway Safety.

Classen S, Bewernitz M, & Shechtman O. (2011). Driving simulator sickness: an evidence-based review of the literature. American journal of occupational therapy, 65(2), 179–188. [PubMed: 21476365]

Clay OJ, Wadley VG, Edwards JD, Roth DL, Roenker DL, & Ball KK (2005). Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: Current and future implications. Optometry and Vision Science, 82(8), 724–731. [PubMed: 16127338]

Cotté N, Meyer J, & Coughlin JF (2001). Older and younger drivers' reliance on collision warning systems. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 45(4), 277–280.

Coughlin JF & Reimer B. (2006). New demands from an older population: An integrated approach to defining the future of older driver safety. In The Proceedings of SAE Convergence Conference, paper no. 2006–21-0008.

Cummings ML, Wang E, & Ho AW (2006). Integrating Multiple Alarms & Driver Situation Awareness. MIT Humans and Automation Laboratory.

Davidse RJ (2006). Older drivers and ADAS: Which systems improve road safety?. IATSS research, 30(1), 6–20.

Dzindolet MT, Peterson SA, Pomranky RA, Pierce LG, & Beck HP (2003). The role of trust in automation reliance. International Journal of Human-Computer Studies, 58(6), 697–718.

Eby DW, Molnar LJ, Zhang L, St Louis RM, Zanier N, & Kostyniuk LP (2015). Keeping Older Adults Driving Safely: A Research Synthesis of Advanced In-Vehicle Technologies, A LongROAD Study. Retrieved from AAA Foundation for Traffic Safety website: https://www.aaafoundation.org/keeping-older-adults-driving-safely-research-synthesis-advanced-vehicle-technologies-longroad-study

Edwards JD, Ross LA, Wadley VG, Clay OJ, Crowe M, Roenker DL, & Ball KK (2006). The useful field of view test: normative data for older adults. Archives of Clinical Neuropsychology, 21(4), 275–286. [PubMed: 16704918]

Eichelberger AH & McCartt AT (2014a). Toyota Drivers' Experiences with Dynamic Radar, Cruise Control, the Pre-Collision System, and Lane-Keeping Assist. Arlington, VA: Insurance Institute for Highway Safety.

Eichelberger AH & McCartt AT (2014b). Volvo drivers' experiences with advanced crash avoidance and related technologies. Traffic Injury Prevention, 15(2), 187–195. [PubMed: 24345022]

Ervin RD, Sayer J, LeBlanc D, Bogard S, Mefford M, Hagan M, Bareket Z, & Winkler C. (2005). Automotive Collision Avoidance System Field Operational Test Report: Methodology and Results. Report No. DOT HS 809 900. Washington, DC: US Department of Transportation.

Evans L. (2004). Traffic Safety. Science Serving Society, Bloomfield Hills, Michigan, USA.

Evans L. & Wasielewski P. (1983). Risky driving related to driver and vehicle characteristics. Accident Analysis and Prevention, 15, 371–382.

Flannagan C, LeBlanc D, Bogard S, Nobukawa K, Narayanaswamy P, Leslie A, Kiefer R, Marchione M, Beck C, & Lobes K. (2016). Large-scale field test of forward collision alert and lane departure warning systems (No. DOT HS 812 247).

Gentzler MD & Smither JA (2012). A literature review of major perceptual, cognitive, and/or physical test batteries for older drivers. Work, 41(1), 5381–5383. [PubMed: 22317557]

Green P. (2013, 10). Standard definitions for driving measures and statistics: overview and status of recommended practice J2944. In Proceedings of the 5th international conference on automotive user interfaces and interactive vehicular applications (pp. 184–191). ACM.

Hart SG, & Staveland LE (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. Advances in psychology, 52, 139–183.

Healey MK, Campbell KL, & Hasher L. (2008). Cognitive aging and increased distractibility: Costs and potential benefits. Progress in Brain Research, 169, 353–363. [PubMed: 18394486]

Horswill MS, Marrington SA, McCullough CM, Wood J, Pachana NA, McWilliam J, & Raikos MK (2008). The hazard perception ability of older drivers. Journal of Gerontology: Psychological Sciences, 63, 212–218.

Ikeda A, Katou T, Kinoshita M, & Aihara M. (2002). Study of driver characteristics using driving simulator considerations on difference in accident avoidance performance due to age. JSAE review, 23(2), 219–222.

Kennedy RS, Fowlkes JE, Berbaum KS, & Lilienthal MG (1992). Use of a motion sickness history questionnaire for prediction of simulator sickness. Aviation, Space, and Environmental Medicine, 63, 588–593.

Kramer AF, Cassavaugh N, Horrey WJ, & Mayhugh JL (2007). Influence of age and proximity warning devices on collision avoidance in simulated driving. Human Factors, 49, 935–949. [PubMed: 17915608]

Lam LT (2002). Distractions and the risk of car crash injury: The effects of drivers' age. Journal of Safety Research, 33, 411–419. [PubMed: 12405001]

LeBlanc D, Sayer J, Winkler C, Ervin R, Bogard S, Devonshire J, Mefford M, Hagan M, Bareket Z, Goodsell R, & Gordon T. (2006). Road Departure Crash Warning System Field Operational Test: Methodology and Results (Report No. UMTRI-2006–9-1). Ann Arbor, MI: University of Michigan Transportation Research Institute.

LeBlanc DJ, Bao S, Sayer JR, & Bogard S. (2013). Longitudinal driving behavior with integrated crash-warning system. Transportation Research Record: Journal of the Transportation Research Board, 2365, 17–21.

Lees MN, & Lee JD (2009). Enhancing safety by augmenting information acquisition in the driving environment In: Castro C, ed. Human Factors of Visual and Cognitive Performance in Driving, 167–182. Boca Raton, FL: CRC Press.

Maltz M. & Shinar D. (2004). Imperfect in-vehicle collision avoidance warning systems can aid drivers. Human Factors, 46(2), 357–366. [PubMed: 15359683]

Mathias JL & Lucas LK (2009). Cognitive predictors of unsafe driving in older drivers: A meta-analysis. International Psychogeriatrics, 21(4), 637–653. [PubMed: 19470197]

McDowd JM, Vercruyssen M. & Birren JE (1991). Aging, divided attention, and dual-task performance In Damos D. (Ed.) Multiple task performance. Taylor & Francis Ltd., pp. 387–414.

Molnar FJ, Marshall SC, Man-Son-Hing M, Wilson KG, Byszewski AM, & Stiell I. (2007). Acceptability and concurrent validity of measures to predict older driver involvement in motor vehicle crashes: An Emergency Department pilot case–control study. Accident Analysis & Prevention, 39(5), 1056–1063. [PubMed: 17854579]

Najm WG, Stearns MD, Howarth H, Koopmann J, & Hitz J. (2006). Evaluation of an automotive rear-end collision avoidance system (No. DOT-VNTSC-NHTSA-06–01).

Navarro J, Yousfi E, Deniel J, Jallais C, Bueno M, & Fort A. (2016). The impact of false warnings on partial and full lane departure warnings effectiveness and acceptance in car driving. Ergonomics, 59(12), 1553–1564. [PubMed: 26916010]

Oxley J, Charlton J, & Fildes B. (2003). Self-regulation of older drivers: A review. (Report No. AP-R221/03). Sydney, Austroads.

Pinheiro J, Bates D, DebRoy S, Sarkar D and R Core Team (2018). nlme: Linear and Nonlinear Mixed Effects Models. R package version 31–137, https://CRAN.R-project.org/package=nlme.

Portouli E, Papakostopoulos V, & Marmaras N. (2011). On-road pilot study on the need for integrated interfaces of in-vehicle driver support systems. In International Conference on Universal Access in Human-Computer Interaction (pp. 316–325). Springer Berlin Heidelberg.

R Core Team (2018). R: A language and environment for statistical computing R Foundation for Statistical Computing, Vienna, Austria URL https://www.R-project.org/.

Raykov T, & Marcoulides GA (2006). On multilevel model reliability estimation from the perspective of structural equation modeling. Structural Equation Modeling, 13(1), 130–141.

Regan MA, Mitsopoulos E, Haworth N, & Young K. (2002). Acceptability of in-vehicle Intelligent Transport Systems to Victorian car drivers. Clayton, Australia: Monash University Accident Research Centre.

Risto M, & Martens MH (2014). Driver headway choice: A comparison between driving simulator and real-road driving. Transportation research part F: traffic psychology and behaviour, 25, 1–9.

Robertson S, & Aultman-Hall L. (2001). Impact of road conditions on elderly drivers. Journal of transportation engineering, 127(3), 244–246.

Rogers WA, & Fisk AD (2001). Understanding the role of attention in cognitive aging research In Birren JE and Schaie KW (Eds.) Handbook of the Psychology of Aging. Elsevier Science, pp. 267–287.

Rueda-Domingo T, Lardelli-Claret P, de Dios Luna-del-Castillo J, Jiménez-Moleón JJ, García-Martín M, & Bueno-Cavanillas A. (2004). The influence of passengers on the risk of the driver causing a car collision in Spain: Analysis of collisions from 1990 to 1999. Accident Analysis & Prevention, 36(3), 481–489. [PubMed: 15003593]

Singh S. (2003). Driver attributes and rear-end crash involvement propensity (DOT HS-809 540).

Society of Automotive Engineers. (2015). Operational Definitions of Driving Performance Measures and Statistics.

Son J, Park M, & Park BB (2015). The effect of age, gender and roadway environment on the acceptance and effectiveness of Advanced Driver Assistance Systems. Transportation research part F: traffic psychology and behaviour, 31, 12–24.

Stamatiadis N. and Deacon JA (1995). Trends in highway safety: effects of an aging population on accident propensity. Accident Analysis & Prevention, 27(4), 443–459. [PubMed: 7546059]

Strand N, Nilsson J, Karlsson ICM, & Nilsson L. (2011). Interaction with and Use of Driver Assistance Systems: A Study of End-User Experiences. In Proceedings of the 18th ITS World Congress Washington, DC: ITS America.

Stutts J, Martell C, & Staplin L. (2009). Identifying behaviors and situations associated with increased crash risk for older drivers (No. DOT HS 811 093). United States National Highway Traffic Safety Administration. Office of Behavioral Safety Research.

Thompson WB, Willemsen P, Gooch AA, Creem-Regehr SH, Loomis JM, & Beall AC (2004). Does the quality of the computer graphics matter when judging distances in visually immersive environments?. Presence: Teleoperators and Virtual Environments, 13(5), 560–571.

Vrkljan BH, & Polgar JM (2007). Driving, navigation, and vehicular technology: Experiences of older drivers and their co-pilots. Traffic injury prevention, 8(4), 403–410. [PubMed: 17994495]

Wascher E, Schneider D, Hoffman S, Beste C, & Sanger J. (2012). When compensation fails: Attentional deficits in healthy ageing caused by visual distraction. Neuropsychologia, 50, 3185–3192. [PubMed: 23044276]

Willemsen P, & Gooch AA (2002). Perceived egocentric distances in real, image-based, and traditional virtual environments. In Virtual Reality, 2002. Proceedings. IEEE (pp. 275–276). IEEE.

Yan X, Radwan E, & Abdel-Aty M. (2005). Characteristics of rear-end accidents at signalized intersections using multiple logistic regression model. Accident Analysis & Prevention, 37, 983–995. [PubMed: 15946637]

Key points:

- Using FCW led to significantly longer TTC when approaching the critical event.
- Using both FCW and LDW did not lead to shorter minimum headway distances for older drivers, with similarly long headway distances observed across conditions.
- No significant differences in subjective workload were found between older drivers who were unassisted, used FCW-only, LDW-only, or both FCW and LDW.

Figure 1.
Left: Visual ADAS warnings for FCW (red bar), LDW (translucent car with warning icon) and smart speedometer (warning icon and yellow speed in mph). Right: Close-up of LDW.

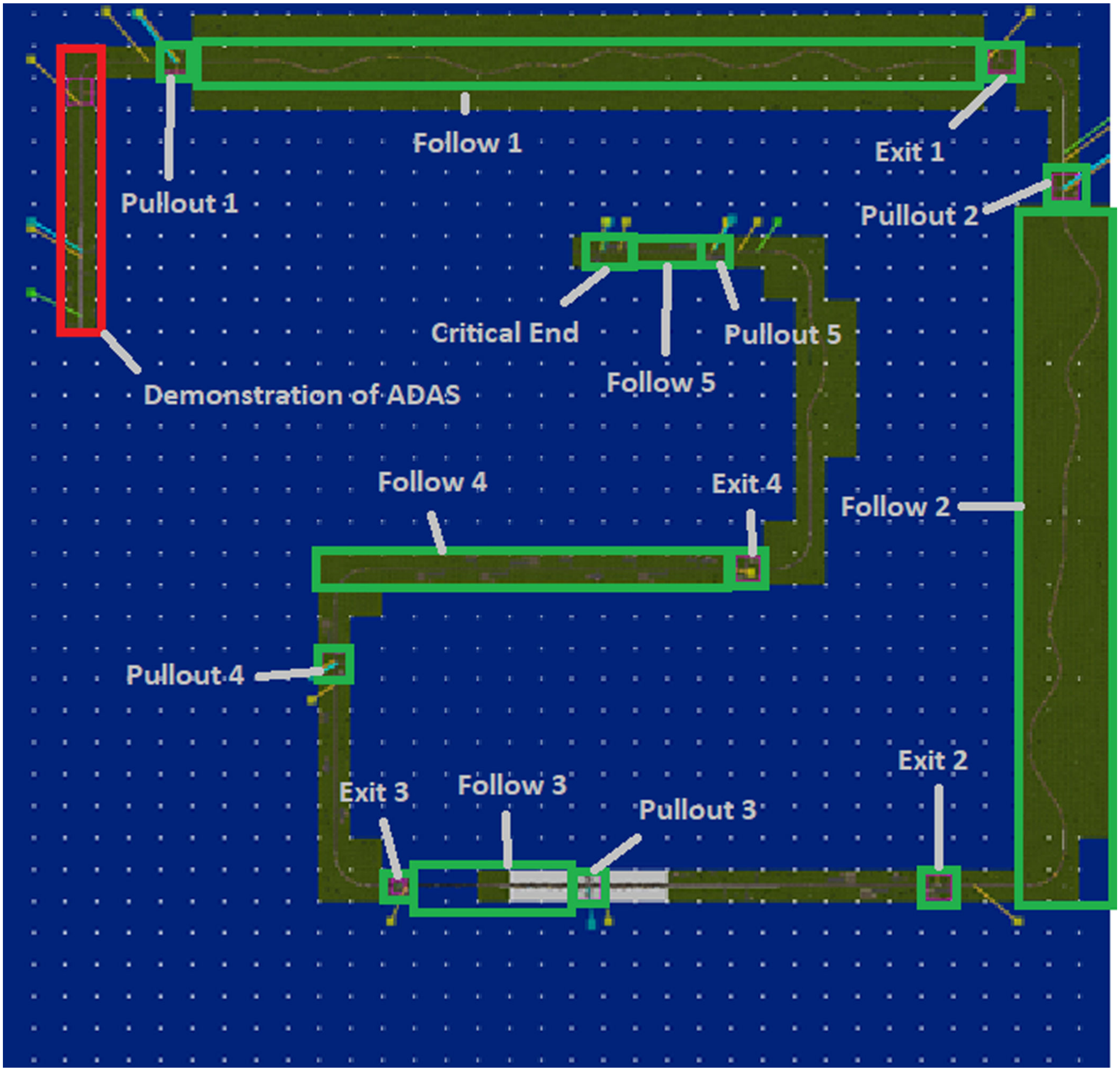

Figure 2.
Map of Simulated Drive with DCRs. One grid square = 500 m.

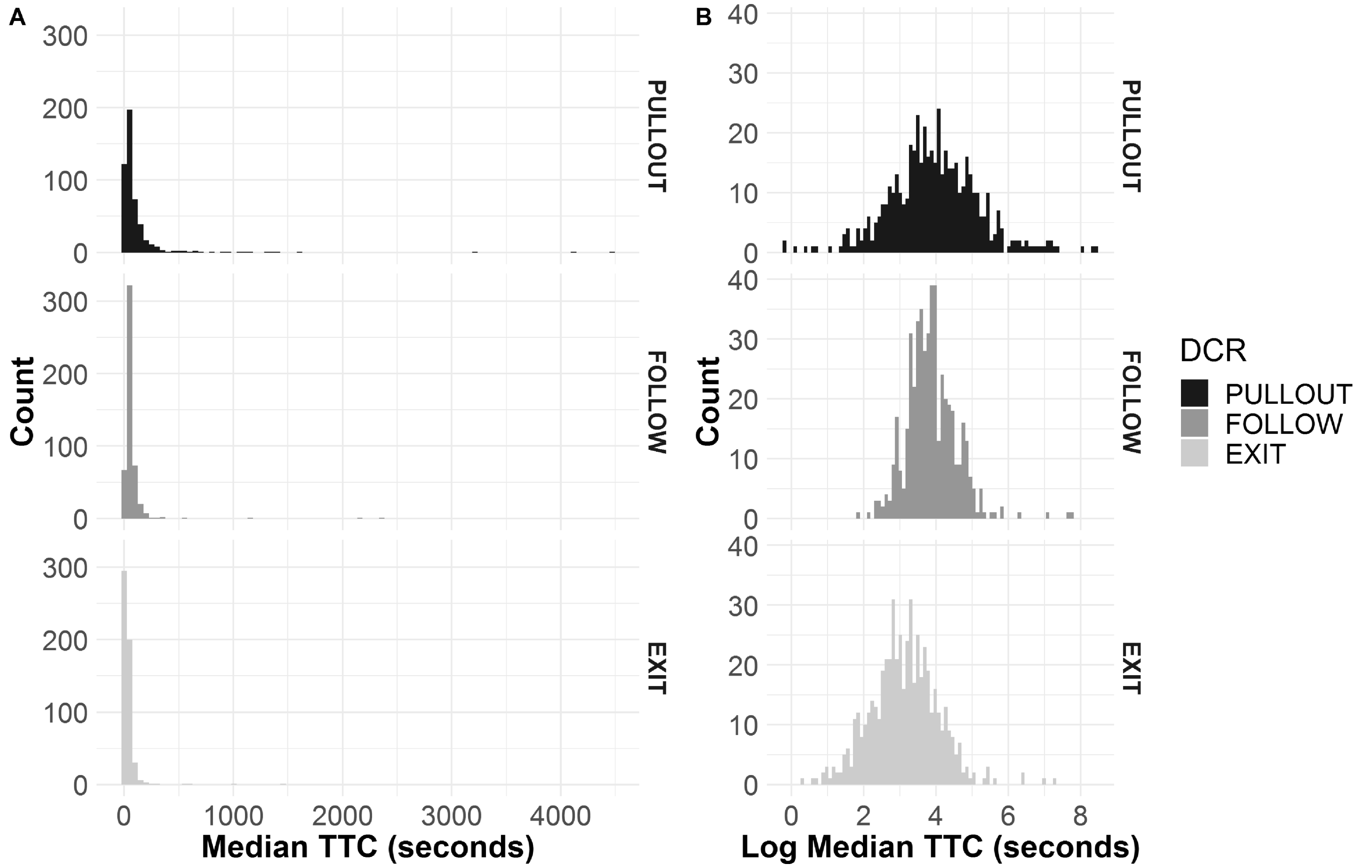

Figure 3.

Distribution of median time-to-collision (TTC) across DCR types. Panel A reflects median TTC. Panel B reflects log-transformed median TTC.

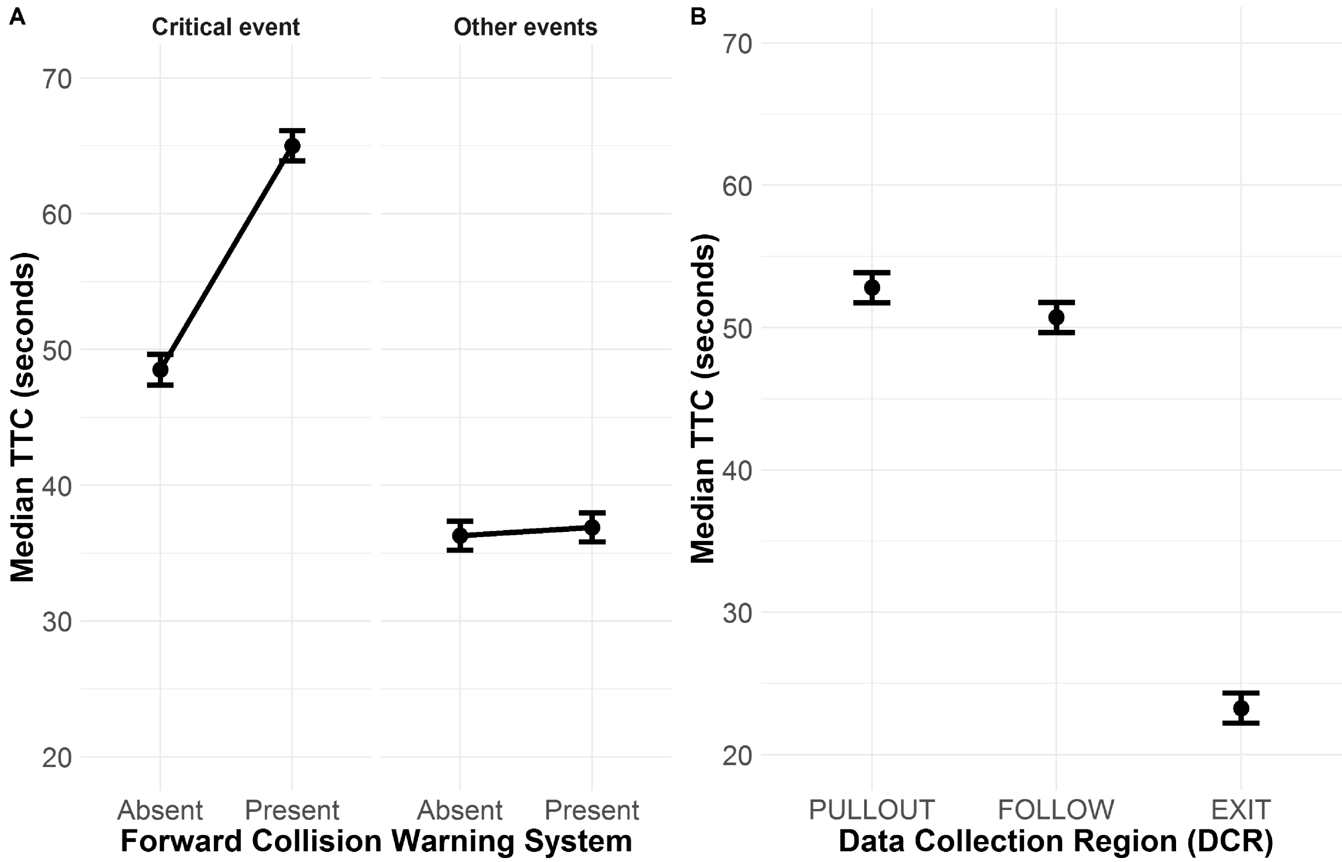

Figure 4.

Panel A: Interaction effect of FCW system and critical event. Panel B: Effect of DCR type on log-transformed median time-to-collision (TTC). Log(Median TTC) was inversed for facilitating the visualization process. Error bars represent +/− 1 standard error.

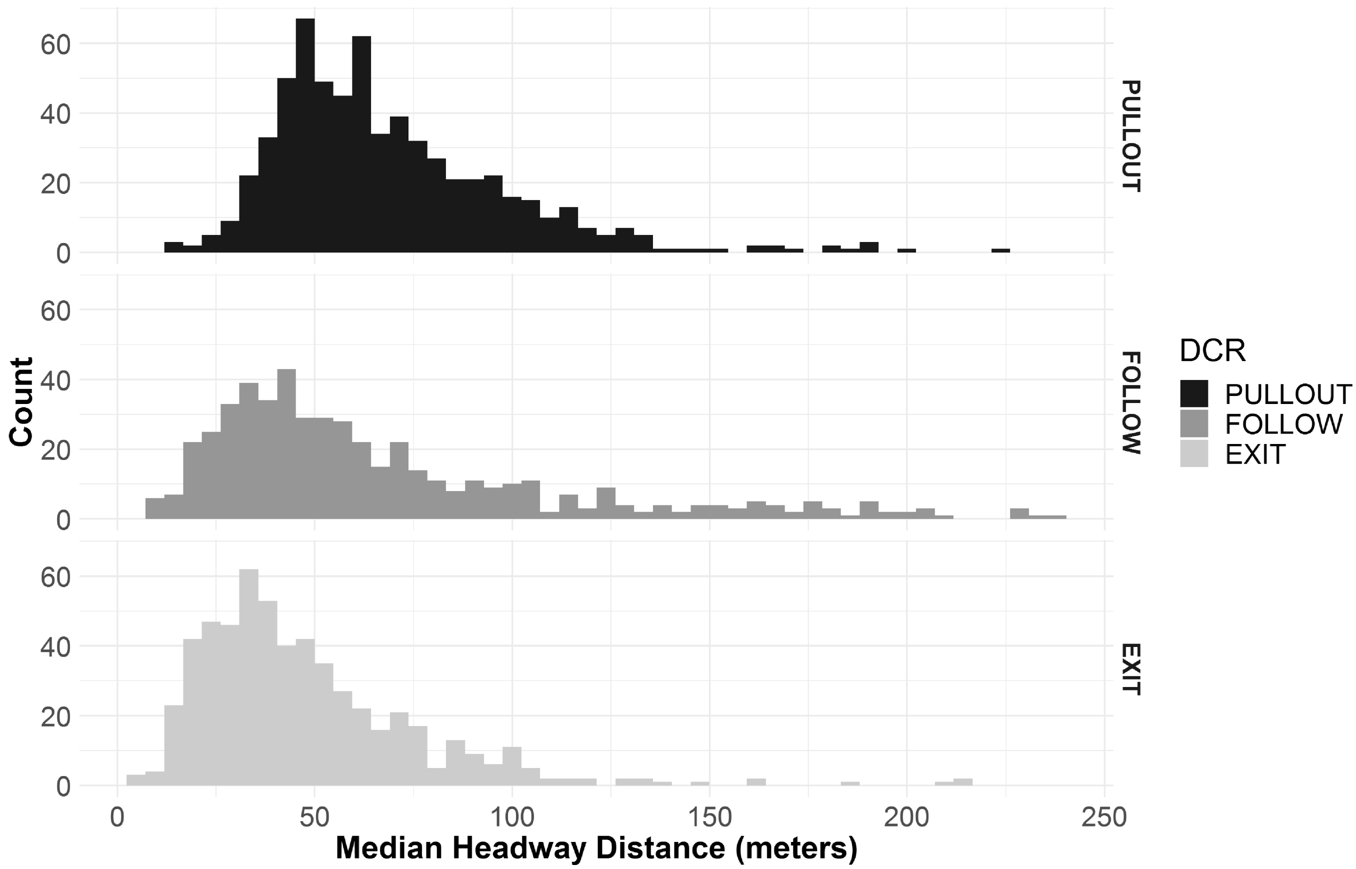

Figure 5.
Distribution of median headway distance across DCR types.

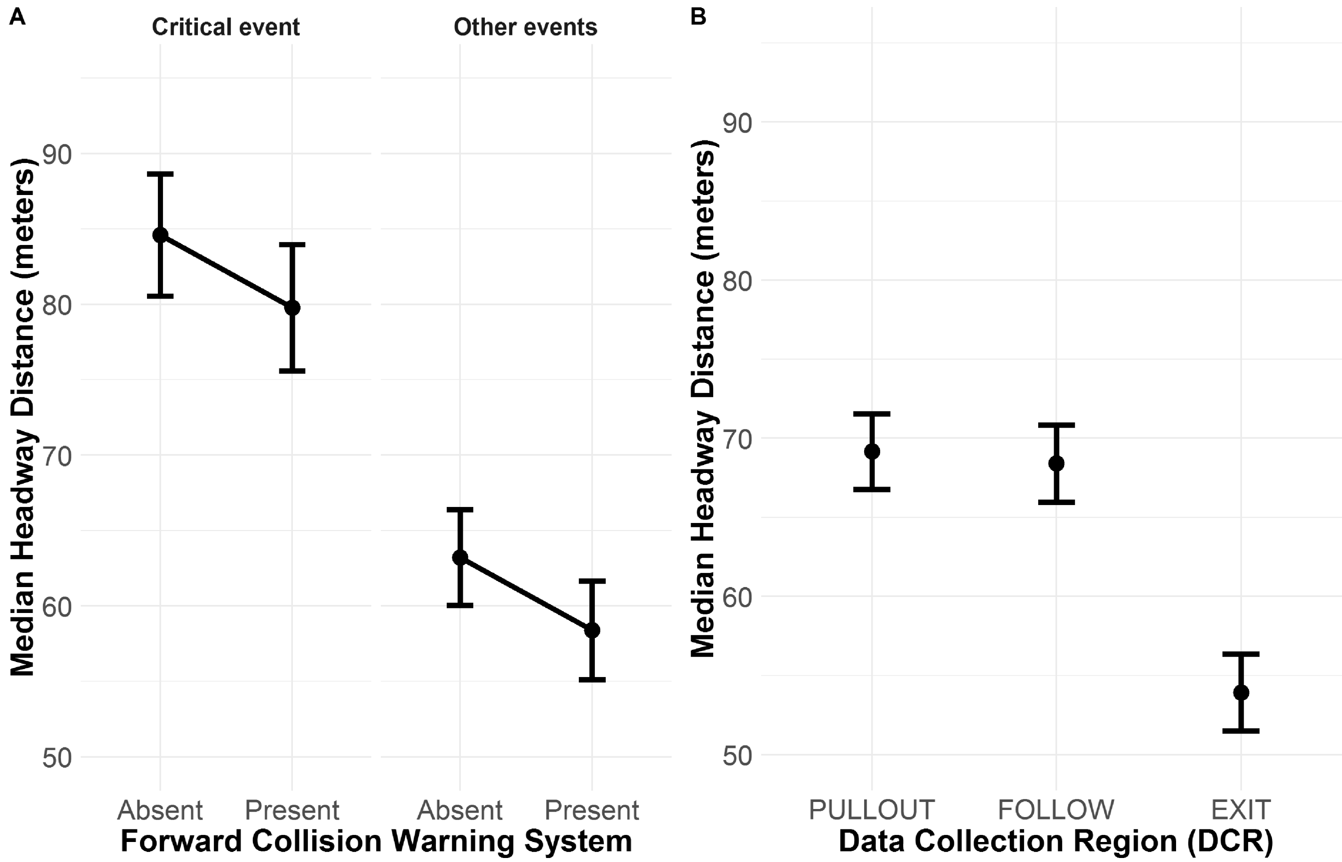

Figure 6.

Panel A: Main effect of critical event. Panel B: Effect of DCR type on median headway distance (meters). Error bars represent +/− 1 standard error.

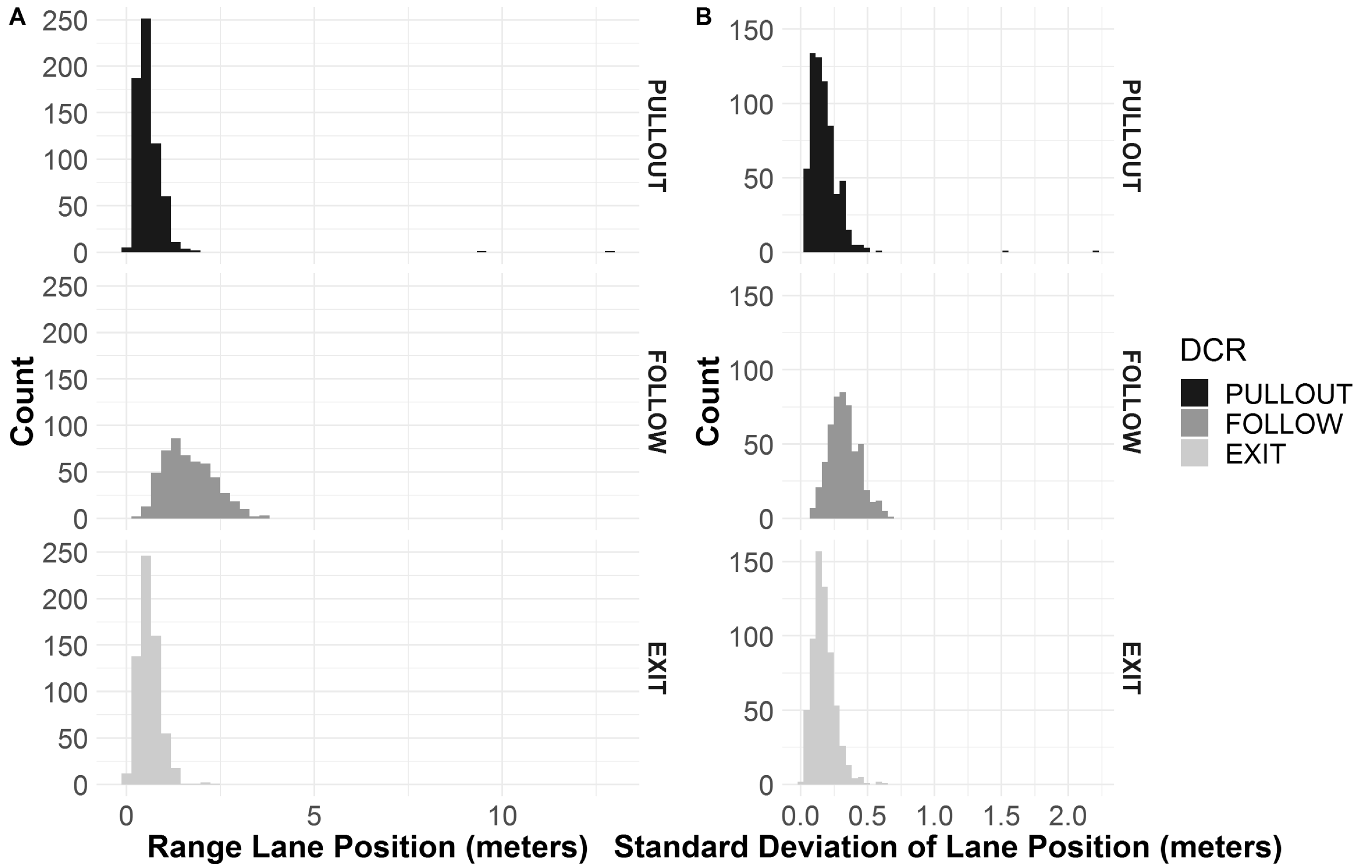

Figure 7.
Panel A: Distribution of range of lane position, Panel B: SDLP across DCR types.

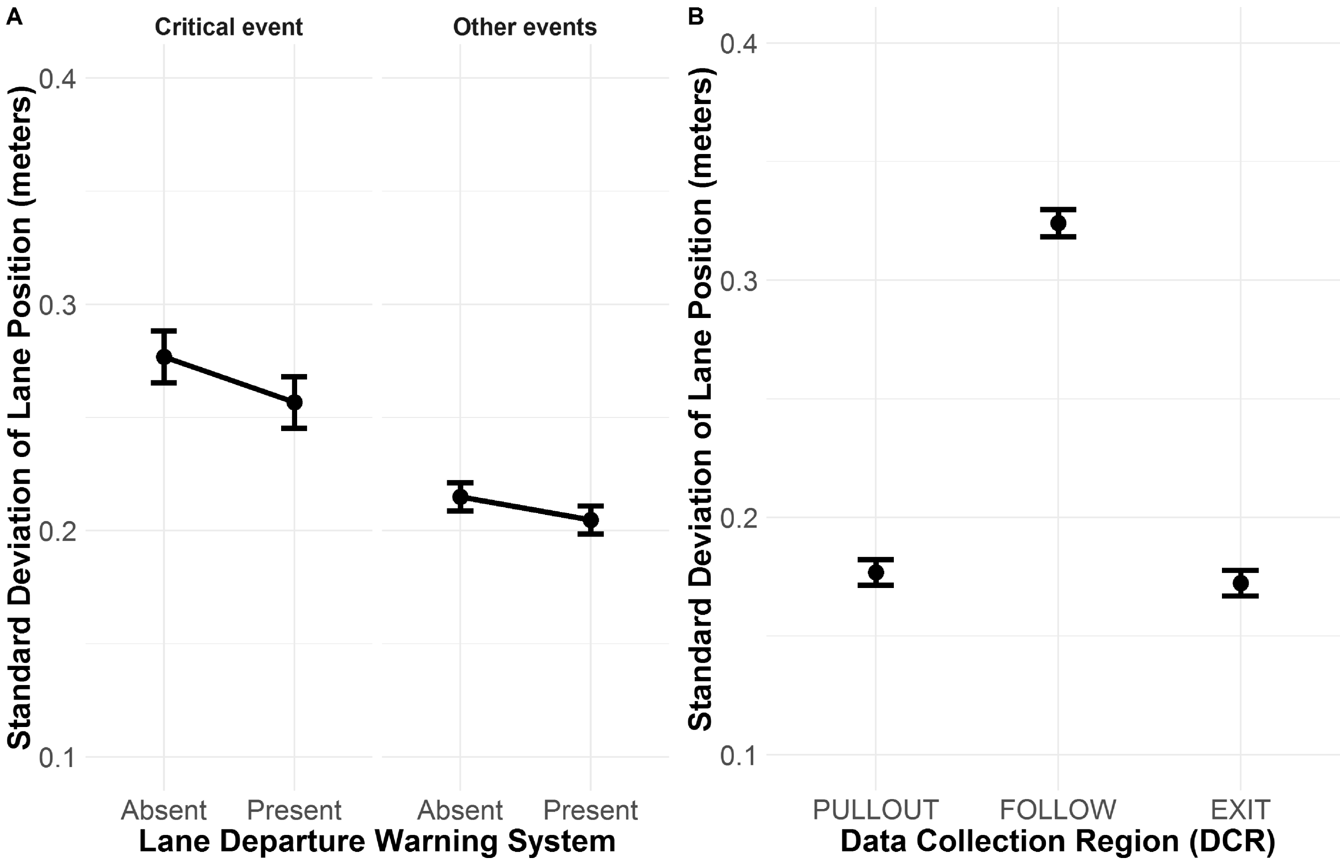

Figure 8.

Panel A: Main effect of critical event. Panel B: Effect of DCR type on SDLP (meters). Error bars represent +/− 1 standard error.

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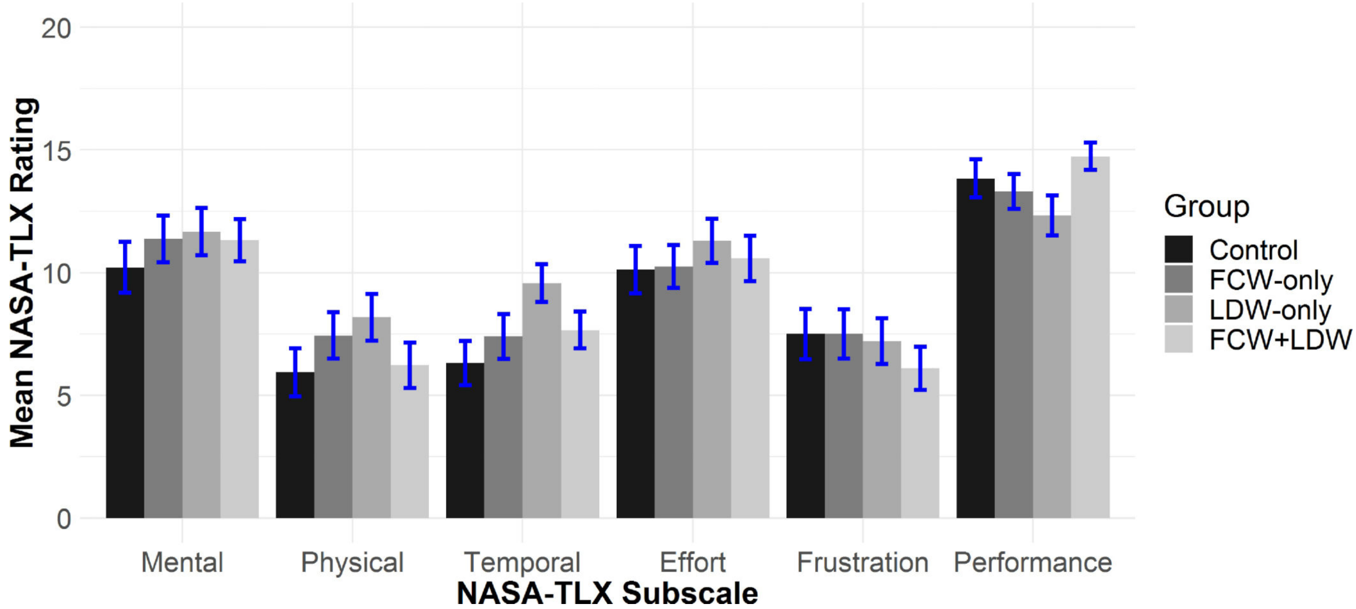

Figure 9.

NASA-TLX Ratings by Group. Error bars represent +/− 1 standard error.

Table 1.

Breakdown of attrition by experimental group.

Phase	Total Drops	*Drop Counts by Group*				*Count Female*	*Mean Age*
		Control	*FCW-only*	*LDW-only*	*FCW+LDW*		
Familiarization drive	7	2	1	3	1	6	77
Primary task	5	0	4	1	0	3	75

Table 2.

Descriptive Statistics by Group

	Age & Gender			
	Control	**FCW-Only**	**LDW-Only**	**FCW+LDW**
N	32	32	33	31
# Female	17	20	15	12
Mean Age	74.5	76.2	74.5	74.5
SD Age	4.68	6.47	5.28	5.77
Minimum Age	67.4	66.9	67.6	66.7
Maximum Age	84.0	97.9	87.9	87.2

Note: Gender was not found to significantly differ by group (χ^2 (3) = 3.98, p = .264), nor did age (F(3, 124) = .716, p = .54). There was one outlier concerning age (age 98), but removing this participant from the analyses led to no significant changes in the results.

Table 3.

FCW System Parameters

Level	Warning Characteristics	TTC
1	Centered red rectangle taking up 6% x 3% of screen	4.0s-3.5s
2	Centered red rectangle taking up 8% x 4% of screen	3.5s-3.0s
3	Centered red rectangle taking up 10% x 5% of screen	3.0s-2.5s
4	Centered red rectangle taking up 12% x 6% of screen	2.5s-2.0s
5	Auditory warning & centered red rectangle taking up 12% x 6% of screen	<2.0s

Note: TTC uses the relative speed of the lead and following vehicles to calculate the number of seconds until they would collide without intervention.

Table 4.

LDW System Parameters

Level	Warning Characteristics	Deviation from Lane Center
1	LDW graphic at 60% opacity	0.6m – 0.7m
2	LDW graphic at 75% opacity	0.7m – 0.9m
3	LDW graphic at 90% opacity	0.9m – 1.2m
4	LDW graphic at 100% opacity	1.2m – 1.5m
5	Auditory Warning & LDW graphic at 100% opacity	> 1.5m

Note: Measurements represent the absolute value of deviation from lane center (0) in meters.

Table 5.

Proportion of Drive Spent within Alert Range

System	Alert Type	Percentage of Drive Active
LDW	No Alert	84.0%
	Visual	15.8%
	Auditory	0.21%
FCW	No Alert	99.8%
	Visual	0.16%
	Auditory	0.02%

Percentages reflect the amount of time drivers across all conditions were within the range to receive LDW and FCW alerts.

Table 6.

Fixed effects descriptives, parameter estimates, and *p*-values, for model predicting log-transformed median time-to-collision.

Term	Estimate	Std. Error (*SE*)	*T*-Statistic	*P*-value
(Intercept)	3.15	0.092	34.1	< 0.001
DCR.order.n	−0.026	0.022	−1.16	0.246
DCRFOLLOW	0.785	0.056	13.9	< 0.001
DCRPULLOUT	0.824	0.054	15.2	< 0.001
FCW	0.017	0.091	0.182	0.856
critical	0.294	0.103	2.85	0.004
FCW:critical	0.280	0.125	2.25	0.025

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Table 7.

Fixed effects descriptives, parameter estimates, and p-values, for model predicting median headway distance.

Term	Estimate	Std. Error (*SE*)	*T*-Statistic	*P*-value
(Intercept)	81.6	3.67	22.2	< 0.001
DCR.order.n	−9.89	0.638	−15.5	< 0.001
DCRFOLLOW	14.5	1.56	9.26	< 0.001
DCRPULLOUT	15.2	1.44	10.5	< 0.001
FCW	−4.82	4.54	−1.06	0.291
Critical	21.4	3.00	7.13	< 0.001
FCW:critical	−0.012	3.69	−0.003	0.997

Table 8.

Fixed effects descriptives, parameter estimates, and *p*-values, for model predicting SDLP.

Term	Estimate	Std. Error (*SE*)	*T*-Statistic	*P*-value
(Intercept)	0.239	0.009	27.0	< 0.001
DCR.order.n	−0.025	0.002	−11.1	< 0.001
DCRFOLLOW	0.152	0.006	24.3	< 0.001
DCRPULLOUT	0.005	0.006	0.790	0.430
LDW	−0.010	0.009	−1.19	0.236
critical	0.062	0.011	5.46	< 0.001
LDW:critical1	−0.010	0.014	−0.731	0.46