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Driving Simulator Tests of Lane Departure Collision Avoidance Systems

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ABSTRACT

This report presents the results of a simulator-based exploratory study of Collision Avoidance System (CAS) concepts suitable for roadway departure collision avoidance. Roadway departure crashes account for significant percentages of both the total number of crashes and the number of fatal crashes in the United States. CAS support that could avert or minimize the severity of even a fraction of these crashes would prove beneficial to the driving public.

The purpose of the study was to evaluate the following items from a driver-oriented perspective. Sixty-four volunteers participated at the Iowa Driving Simulator (IDS), a six-degree-of-freedom, moving-base simulator with a wide field-of-view image generation system. Sixteen of the participants were randomly assigned to serve in a control group without CAS support; the remaining 48 participants were randomly assigned to groups of 16 in each of three CAS Interface groups: auditory, haptic, or combined-modality. Within the CAS groups, participants were further assigned to different levels of four factors: directionality of CAS display (directional or nondirectional), Onset (early CAS onset or late CAS onset), and Algorithm (Time-to-Line-Crossing [TLC] versus Time-to-Trajectory Divergence [TTD]) for lanekeeping.

All participants were assigned to either high or low magnitude hazard conditions. The lateral disturbance collision hazard involved a simulated lateral offset (i.e,.wind gust) applied while the driver was engaged in an in-vehicle distractor task; low hazard magnitude was equated to a small lateral offset and high hazard magnitude was equated to a large lateral offset. In addition, participant performance was assessed during normal (non-hazard) lanekeeping early and late in a 40-minute simulator session.

Results suggest that the concept of a roadway departure CAS has potential. Given that a CAS is to be developed. the data indicate that directional displays have some performance advantages and consumer preference. Based on the evidence gathered in this study, auditory and haptic interface types merit further investigation and development. However, a combined-modality display may be a source of information overload to a driver. Early onset is also advised for the lateral CAS concept. While it appears that TLC may be a preferred algorithm for a lateral roadway departure CAS, it is associated with somewhat greater driver steering effort. Furthermore, both TLC and early onset are associated with more CAS activations, a potential source of nuisance alarms. Finally, it must be acknowledged that drivers were, on average, lukewarm to the CAS concepts included in the study. While this is perhaps not surprising given the exploratory nature of the research, it suggests that driver acceptance will need to be a key goal of efforts to bring such Intelligent Transportation System (ITS) concepts to fruition. The potential exists for advanced technology to contribute to enhanced highway safety, but the human factors remain crucial for achieving such gains.

INTRODUCTION

This report presents the results of a simulator-based exploratory study of CAS concepts potentially suitable for roadway departure collision avoidance. According to the 1991 General Estimates System crash data, single vehicle roadway departure crashes account for approximately 20.8% of all crashes, and 37.4% of all fatal crashes in the United States. CAS support that could prevent or reduce the seventy of even a fraction of these crashes would have a significant benefit to society. These crashes are nearly always caused by one or more of the following six factors: driver inattention (12.66%), driver relinquishes steering control (20.07%), lost directional control (15.96%), excessive speed (32.00%), evasive maneuvers (15.68%) and vehicle failure (3.64%) (1). The focus of this article is on roadway departures on straightaways associated with the first two causal factors.

The objective of the study was to evaluate multiple system concepts: haptic versus auditory versus combined-modality interfaces; directional versus nondirectional driver warnings; alternative lane keeping warning algorithms; and early versus late warning onset thresholds. These concepts were assessed under two conditions: normal driving situations involving general lanekeeping on a straightaway; and key collision hazard scenarios involving roadway departures on straightaways due to driver inattention or incapacitation. When considering various CAS driver interface options, the major modalities that can be used are auditory, haptic, and visual. The auditory and haptic modalities were selected over the visual at this time in order to evaluate interfaces that do not impose visual workload at a time when attention to the road scene may be critical (1). Furthermore, the haptic interface was considered based on promising European CAS research (2, 3).

METHOD

Participants

Sixty-four volunteers (32 males and 32 females) were recruited by the University of Iowa for inclusion. All participants had valid U. S. drivers' licenses. Participants' ages ranged from 25 to 45 years of age.

Simuiator

The study was conducted at the IDS. The simulator consists of a sixdegree-of-freedom, moving-base simulator with a wide field-of-view image generation system (1).

CAS Configurations

The study varied interface modality (auditory, haptic, or combined display, and also a control group that had no CAS interface), directionality (directional vs. non-directional displays), Onset (early and late onset), and Algorithm (TLC vs. TTD), and Hazard Magnitude (low vs.

high). Tabie 1 presents descriptions of the various CAS Interface and Directionality configurations. The haptic steering display provided a calibrated directional torque or a non-directional vibration that could be overridden by drivers.

Two warning algorithms with associated early and late onset values were compared. The first, TLC, assesses time until the vehicle crosses a lane line based on the distance between the vehicle and the lane line, and the vehicle's lateral speed (4). For TLC, "early" onset was set to TLC = 0.7 seconds prior to line crossing. "Late" onset was set to TLC = 0.0 seconds, i.e., at the moment of line crossing. The second algorithm, TTD, compares the driver's steering direction with the "optimal" steering direction, defined to be the direction which will return the vehicle to the lane center a fixed distance ahead. If the driver's steering direction differs substantially from the optimal steering direction, the TTD algorithm triggers a response (1). Early onset for the TTD involved a trajectory arc separation of D = 0.55 meters, a Lookahead of 1.2 seconds, and a TTD of 1.13 seconds. Late onset with the TTD algorithm used a value of D = 0.75 meters, the same Lookahead of 1.2 seconds, and a TTD of 1.13 seconds.

The remaining independent variable was Hazard Magnitude. The low magnitude disturbance was accomplished by initiating an equivalent steering wheel angle offset of 19.35° clockwise (i.e., to the right) for 1.0 second to simulate a light wind gust. The high magnitude lateral disturbance was initiated by a 38.7" steering wheel angle offset for 1.0 second to simulate a heavy wind gust. These disturbances were initiated by the in-vehicle experimenter who rode in the backseat during the session.

Experimental Design

The independent variables manipulated in this study are presented in Table 2. Sixteen of the participants were randomly assigned to serve in a control group without CAS support; the remaining 48 participants were randomly assigned to groups of 16 in each of three CAS Interface groups: auditory, haptic, or combined-modality. Within the CAS groups, participants were further assigned to different levels of three CAS factors: directionality of CAS display (directional or nondirectional), Onset (early CAS onset or late CAS onset), and Algorithm (TLC versus TTD). All participants were assigned to either high or low magnitude hazard conditions. The lateral disturbance collision hazard involved a simulated lateral offset (i.e,. wind gust) applied while the driver was engaged in an in-vehicle distractor task; low hazard magnitude was equated to a small lateral offset and high hazard magnitude was equated to a large lateral offset. In addition, participant performance was assessed during 3-minute segments of normal (non-hazard) lanekeeping on a straightaway, both early and late in the simulator session which lasted approximately 40 minutes. Thus, CAS impacts under both normal and hazard conditions were assessed.

Procedure

Upon arrival, participants completed intake information. The in-vehicle experimenter accompanied participants to the IDS, where they were instructed to drive at highway speeds (obeying posted speed signs) over a course that contained a mix of straightaways, 1000-ft radius, 800-ft radius, and 250-ft radius curves. A distractor task was employed that required participants, during the drive, to turn around and look over their right shoulders to count the number of horizontal bars printed on an index card. Participants responded verbally as quickly as possible while continuing to drive. The distractor task was presented after drivers passed the curve exit line on each curve. After completing the fourth curve, the distractor task was implemented in conjunction with the lateral disturbance (simulated side wind gust). Following the drive, participants were debriefed, during which time they responded to a series of subjective assessments about the drive, paid, and released.

RESULTS: GENERAL LANEKEEPING

The results are presented in two sections, the first of which deals with normal driving on a straightaway with no lateral disturbances introduced. The second section considers driver-vehicle performance with respect to the introduction on the two levels of lateral disturbance described before. Analysis of Variance (ANOVA) methods were applied using the Statistical Analysis System (SAS) General Linear Models (GLM) procedure (5). The model included the following fixed main effects and their two-way interactions:

- Interface type (auditory, haptic, or both),
- Directionality (non-directional or directional display),
- Onset (early or late), and
- Algorithm (TLC or TTD).

The alpha level for statistical significance was set at 0.05.

In addition to the ANOVA results, planned, pairwise comparisons were conducted to compare the control group of participants that had no CAS support with those who did have CAS support. To minimize the experimentwise Type I error rate, a per-test significance level of .0025 was selected (1).

To address normal lanekeeping, data were collected during 3 minutes of driving on a straightaway both early and late in the simulator session. The following dependent measures were recorded and analyzed:

- Lane Standard Deviation (as a measure of modified driving precision), inches:
- Mean Lane Position (as a measure of bias in lane keeping), inches from lane center;

- Number of steering reversais in the 3-minute period (as a measure of driving effort), defined as steering movement of 2 degrees or more in angle after steering velocity has passed through zero (or a zero deadband), count
- Number of CAS lateral activations in the 3-minute period (as a measure of potential nuisance alarms), count
- Number of Lane exceedences to the left (as a measure of lanekeeping), count of the number of times any part of the vehicle crossed the left lane boundary;
- Number of Lane exceedences to the right (as a measure of lanekeeping), count of the number of times any part of the vehicle crossed the right lane boundary.

Lanekeeping Early in the Session

Consider first the Early driving segment data. There was a significant main effect of Algorithm ($F(1,31) = 9.67, p < .004$) for number of steering reversals (see Figure 1-A). The TLC algorithm led to an average of 137.1 steering reversals over the 3-minute driving segment and the TTD algorithm led to an average of 105.9 steering reversals over the 3-minute driving segment. All else being equal, these results provide evidence that the TLC algorithm was associated with greater steering efforts than the TTD algorithm. As a point of reference, the control group of participants Without CAS support averaged 114.5 steering reversals over the 3-minute driving segment. There were no significant differences among pair-comparisons of each algorithm mean with the control group mean.

There was a significant main effect of Onset on number of CAS activations, $F(1,31) = 4.76, p < .037$. As indicated in Figure 1-B, Early onset, averaged over all other conditions, led to more CAS activations than late onset (mean (M) = 13.5 for Early onset, and $M = 7.8$ for Late onset). There was a significant main effect of Onset on the number of lane exceedences to the left (i.e., centerline), $F(1, 31) = 4.58$. $p < .041$, there being fewer for Early than Late onset (means of 2.4 and 5.7 exceedences. respectively). These data illustrate the increase in activations with Early onset relative to Late onset as well as the benefits that accrue. For reference. participants without CAS support averaged 10.67 lane exceedences to the left (see Figure 1-C).

A note on lane exceedences to the left is in order. The IDS scenario was configured as a two-lane undivided roadway with a narrow berm and a ditch on the right hand side (i.e., passenger side) of the road. There was very little opposite direction traffic during the scenario. It appears that drivers tended to drive "left of center" because of the apparently greater maneuvering room on the left. not because of CAS effects per se. However, given that all drivers experienced the same simulator scenario, lane exceedences to the left is a reasonable response measure for comparison purposes. It is also interesting to note that drivers in the simulator apparently adhered to the CAS activations, and more activations did not lead drivers to ignore the warnings. The validity of such results to real-world driving is unknown at this time.

Multiple pairwise comparisons with the control group of participants without **CAS** support were assessed. Lane standard deviation was statistically significantly ($p < .0008$) smaller with the TTD algorithm than with no driver support. The TTD algorithm was associated with **a** mean lane position standard deviation of **5.28** inches while the unsupported drivers averaged **7.45** inches. This difference of approximately **2.2** inches does not appear to be of any practical significance.

Of all the other pair comparisons with the control group of unsupported drivers, only the number of lane exceedences to the left were significantly affected with $p < .0025$. The mean number of exceedences to the left for the conditions below were found to be significantly different when compared to an control group mean of 10.67 exceedences to the left (note that each condition indicated is averaged over independent factors not explicitly mentioned):

- Auditory CAS (means of 3.53 exceedences to the left)
- Auditory+Directional **CAS** (mean of **2.12** exceedences to the left)
- Haptic + Non-directional **CAS** (mean of **1.25** exceedences to the left)
- Auditory + Early onset **CAS** (mean of **2.75** exceedences to the left)
- Auditory + Late onset **CAS** (mean of **1.75** exceedences to the left)
- Haptic + Early onset **CAS** (mean of **1.57** exceedences to the left)
- Auditory + TLC algorithm (mean of **2.62** exceedences to the left)
- Auditory + TTD algorithm support (mean of **2.87** exceedences to the left)

The average number of exceedences to the left is uniformly lower with **CAS** support than without. This is taken as evidence that the presence of a lanekeeping **CAS,** in general, can reliably improve driving performance.

Lanekeeping Late in the Session

Consider next the Late straightaway driving segment data. Analysis of Variance procedures were applied to each dependent measure to assess the effects of interface type (auditory, haptic, or both), directionality (non-directional or directional display), onset (early or late), and algorithm (TLC or TTD). Results again indicated a significant main effect of Algorithm on the number of steering reversals, $F(1, 33) = 10.31, p < .0029$. As can be seen in Figure 1-A, while the overall number of steering reversals over **3** minutes of driving on **a** straightaway dropped (indicating drivers were becoming accustomed to the scenario and simulator), there were still significantly more steering reversals, on average, for the TLC algorithm ($M = 87.7$) than for the TTD algorithm ($M = 57.9$). These data suggest that, with exposure to the **CAS,** the driving effort with TLC is greater than with TTD, that TLC is no worse than with no driver support, and that TTD may actually ease lanekeeping effort relative to unsupported driving. For unsupported drivers, the mean number of steering reversals in the late segment was $M = 82.0$. There were no significant pairwise differences among comparisons of each algorithm mean with the control group mean.

There was again a significant main effect of Onset on the number of **CAS** activations, $F(1, 33) = 4.17$, $p < .05$. Figure 1-B shows that there were, on average, more **CAS** activations associated with the early onset than with the late onset (means of **4.16** and 1.37, respectively). It appeared that while the overall number of activations dropped with driving practice. early onset continued to lead to more **CAS** activations.

There was also a significant main effect of Directionality on the number of lane exceedences to the left, $F(1, 33) = 5.52$, $p < .025$. The mean number of lane exceedences to the left for the non-directional **CAS** was $M = 0.708$, while the mean for the directional **CAS** was $M = 0.125$. The small means reflect the greater precision in driving attained during the later driving segment for both directional and non-directional **CAS.** The difference is interpreted to reflect some small benefit of directionality on staying within one's lane with experience using the **CAS.** There were no other significant **ANOVA** results for other dependent measures included in this analysis.

As with the Early segment data, pair comparisons With the control group of drivers that had no driver support were carried out for each dependent measure. A per-test significance level of .0025 was again used. There was a significant difference between auditory **CAS** group and the control **group** in mean lane position (means of -0.96 and -7.9 inches, respectively, from lane center, where the negative sign indicates left of lane center). Thus, auditory **CAS** support promoted tighter lane keeping to lane center, possibly because the drivers as a whole did not want to hear the tones.

The number of steering reversals were significantly different between the mean of the control group ($M = 82.0$) and the mean of the **CAS** group that used the **TTD** algorithm and non-directional display ($M = 43.33$). Note that, while not statistically significant, TTD was associated with lower numbers of steering reversals relative to the control group in the Early driving segment as well. The reasons for this are unknown and merit further research to determine if the effect of lower steering activity with TTD holds under other test conditions and with other test participants.

RESULTS: LATERAL DISTURBANCE ON A STRAIGHTAWAY

The effectiveness of **CAS** for roadway departure on a straightaway was assessed while the driver was momentarily distracted. The experiment was designed such that each test participant experienced one lateral disturbance (see Table 2) while he/she was engaged in an in-vehicle distractor task. To address **CAS** effects, the following dependent measures were collected in each of several phases of this disturbance:

- Initial Movement Based on the Disturbance: This included response measures indicative of how "bad" the roadway departure got before the driver was able to stop the departure motions:

- Max initiai lane deviation to the right (how far over the vehicle got before its lateral motion **was** stopped), inches
- Initial Peak lateral acceleration to the right (how much acceleration **had** increased before lateral motion was stopped), ft/s^2

- Initial Reaction to the Disturbance: This segment included response measures indicating the driver's latency and aggressiveness of initial evasive maneuvers.
  - Accelerator Reaction Time (RT) after disturbance onset (indicator of driver awareness of the **CAS** activation or hazard onset or both), milliseconds
  - Steering RT after disturbance onset (indicator **of** delay in initiating evasive steering), milliseconds
  - **Max** initial lane deviation to the left, **i.e.,** in direction of initial recovery maneuver (to indicate stability of maneuver, in particular overshoot potential), inches
  - Peak lateral acceleration to the left (indicative of aggressiveness of initial lateral recovery maneuver), ft/s^2

- Corrections to Resume Lane Keeping: **This** segment included response measures that looked at indicators of the subsequent stability of the evasive maneuver.
  - Number of Right-Hand-Side (RHS) Lane exceedences (indicator of control of evasive maneuver), count
  - Number of Left-Hand-Side (LHS) Lane exceedences (indicator of control of evasive maneuver), count
  - Lane standard deviation after steering RT until the point where the experimenter judged the participant had resumed normal lanekeeping (general indicator of collision avoidance maneuver stability), inches

- General Measure of Merit: Proportion of Crashes Avoided

Initial Movement Based on the Disturbance

Results indicated a significant main effect of Hazard magnitude on the maximum initial lane deviation to the right, $F(1, 27) = 6.96$, $p < .014$, with means of **3**1.9 and 62.7 inches for the low and **high** disturbances, respectively. Hazard magnitude had a significant main effect for initial peak lateral acceleration to the right, $F(1, 27) = 47.27$, $p < .0001$, With means of 2.28 and 4.22 ft/s^2, respectively. Finally, there was an Interface **x** Directionality interaction that was significant for initial peak lateral acceleration to the right. $F(2, 27) = 3.49$, $p < .05$. For the auditory and combined displays, directional warning reduced the peak lateral acceleration, while higher peak lateral accelerations were associated with directional haptic displays (see Figure 2-, **A).** In absolute terms. the best combination appears to be the haptic, non-directional display, followed by the combined, directional display. Note. however, that none of the CAS means were significantly different from the mean for the control group of drivers without **CAS** support.

Initial Reactions to Lateral Disturbance

Next consider dependent measures that more directly gauge the initial reaction of the driver to the lateral disturbance. The **ANOVA** procedures described earlier were applied to each of the dependent measures intended to provide further insights into the initial driver reaction to the disturbance. The Interface x Onset interaction was significant for accelerator RT, $F(2, 27) = 4.14$, $p < .03$. As can be seen in Figure 2-B, the fastest accelerator RT was associated with the combined (i.e., auditory and haptic), early onset display system. Pairwise comparisons with the control group of drivers without CAS support indicated this condition was not significantly different from the other group means. The reason for the reversal in accelerator RT latency as a function of onset for the haptic display is unknown.

There was a significant interaction between Interface and Onset, $F(2, 27) = 4.81$, $p < .017$ for the steering RT measure. The means are provided in Figure 2-C, along with the Control group mean for reference. With early onset, the auditory and haptic display systems are associated with longer, not shorter steering RTs. Perhaps this might be attributed to the early onset alerting the driver such that a steering correction was less urgent (because the lateral disturbance had not developed to as high a magnitude than with Late onset). While this may be a plausible explanation for the pattern of auditory and haptic data, the reversal for the combined display system does not lend itself to ready interpretation. Pair comparisons between with the control group of drivers without CAS support indicated that the other conditions were not significantly different from the unsupported driver mean.

There was a significant interaction between Hazard magnitude and Directionality, $F(1, 27) = 4.90$, $p < .036$, for the Steering RT measure (see Figure 2-D). Steering reaction times are earlier for the nondirectional warnings with the low hazard magnitudes but are greater with the high hazard magnitude. It is possible that for the low magnitude hazard, the directional warning provides drivers with extra information that allows for a later, more measured, response. On the other hand, the high hazard magnitude disturbance must be reacted to relatively more quickly and here directional displays are beneficial. Some evidence that high magnitude lateral disturbances prompted faster steering RTs comes from the mean values for the control groups who did not have CAS support but nevertheless encountered a lateral disturbance (half the controls experienced the low magnitude disturbance and half of the controls experienced the high magnitude disturbance). Since earlier responses (provided they are controlled) seem to offer no drawbacks relative to later responses, it appears that directional CAS sometimes has a performance benefit.

There was a significant main effect for Algorithm on the initial maximum lane deviation to the left (i.e., in the direction of recovery), $F(1, 27) = 10.32$, $p < .004$. Averaged over all other conditions, the TLC algorithm was associated with an initial maximum lane deviation to the left of 72.9 inches versus a mean of 91.5 inches for the TTD algorithm. As a point of reference, the average initial lane deviation to the left was 90.2 inches for the control group. The observed

difference is taken as an indication that. on average, there may be a decrease in probability of an initial recovery maneuver overshoot with TLC.

There were several effects that significantly varied on the response measure of initial peak lateral acceleration to the left (i.e., in the direction of the recovery maneuver). Hazard magnitude was significant, $F(1, 27) = 23.86, p < .0001$, With means of 3.04 ft/s^2 and 6.79 ft/s for low and high magnitude lateral disturbances, respectively. There was a significant main effect for Directionality, $F(1, 27) = 7.31, p < .012$, with means of 3.88 ft/s^2 and 5.96 ft/s^2 for the non-directional and directional displays, respectively. These data imply that directional displays may have promoted more aggressive recovery maneuvers, on average. Why this would be is unclear but might be attributed to a tendency among drivers to react strongly to the directional displays. There was a significant main effect for Algorithm, $F(1, 27) = 6.63, p < .016$, with means of 3.93 ft/s^2 and 5.91 ft/s^2 for TLC and TTD, respectively. It appears that TLC supported less aggressive lateral recovery maneuvers than TTD, perhaps because it apparently was more "sensitive", than TTD. For reference, the mean of the control group of participants with CAS support was 6.3 ft/s^2. Subjective impressions of several members of the project team during pre-pilot testing suggested that TTD might alarm less frequently or perhaps allow the driver more latitude in lane position before activation. There was a significant Hazard magnitude x Algorithm interaction, $F(1, 27) = 10.12, p < .004$ (see Figure 3-A). While the different algorithms appear to have no substantial effect at the low hazard magnitude level, TLC appears superior to TTD at the high hazard magnitude, in terms of keeping lateral accelerations low for the recovery maneuver. This suggests that TLC may be more effective for extreme lateral disturbances.

Corrections to Resume Lanekeeping

There was a significant Hazard Magnitude x Algorithm interaction on the number of lane exceedences to the right, $F(1, 27) = 6.04, p < .021$ (see Figure 3-B). At low hazard magnitudes, it appears that while TLC was associated with more lane exceedences to the right than TTD, yet the TLC algorithm was associated with better corrective lanekeeping than TTD with the hazard magnitude was high.

There was also a significant main effect of Hazard magnitude on lane standard deviation as measured from initial recovery steering input until the driver resumed normal lanekeeping, $F(1, 27) = 5.79$, $p < .024$, with means of 13.63 inches and 21.58 inches for the low and high magnitude disturbances, respectively. These data indicate that the high magnitude lateral disturbance did indeed lead to more disrupted lanekeeping. No other significant ANOVA effects were found.

In addition to the ANOVA results, t-tests were conducted to compare the control group of drivers who had no CAS support with those that did have CAS support. At a .0025 level of significance. no statistically reliable differences were found. The comparisons with the control group of unsupported drivers might be interpreted to indicate that no CAS concept provided

benefits over unaided driving. It may also be interpreted to indicate that the **CAS** concepts tested did not degrade collision avoidance either.

Crashes **Avoided**

The last analysis of results examines the number of crashes that occurred in the simulator while the driver **was** distracted. The control participants **had** a greater number of crashes **(5** crashes out of **16** participants) than any of the **CAS groups** (see Figure 3-C). **Pair** comparisons of the control group **with** each of the **CAS groups** indicates that the differences between the control group collision incidence **and** the **CAS** groups that had **only** 1 collision out of 16 (i.e., the auditory interface **CAS group** and the haptic interface **CAS** group) is $p < .087$ by a one-tailed Fisher exact test. While this does not technically achieve statistical significance given **an** .05 criterion level, it does indicate a trend that **CAS** support like that provided in the simulator study is associated with greater collision avoidance than no **CAS** support. Given the exploratory **nature** of the research, this trend merits attention and **further** research.

Subjective **Assessments**

Based on assessments made after the simulator session by the 48 participants who had **CAS** support, the following points are highlighted.

- The subjective **data** are rather clear-cut with respect to directionality. Based on subjective impressions, directional presentation of warnings should be implemented instead of their non-directional analogs.
- The indications from the subjective assessments are that either the haptic or auditory interface **as** currently configured should be selected over the combined interface.
- On the bases of subjective impressions and personal preference, the late warning onset configuration should **be** adopted over the early configuration, **as** treated in the current study.
- The overall degree of variability associated with algorithm (that is. the paucity of significant algorithm effects within the subjective data) suggests that further research needs to be conducted to evaluate a suitable **CAS algorithm.**
- Generally speaking, test participants were lukewarm toward the **CAS** concepts. This is reflected in part by the wide range of **amounts** of money that they would be willing to pay for **CAS** technologies (from an average low of $62.50 to **an** average high of $542.50).

DISCUSSION

On the basis of the general lanekeeping data, it appeared that **CAS** support was associated with more precise lanekeeping under normal straightaway driving conditions (for both Early and Late driving segments). Furthermore, TLC caused relatively more driver workload than **TTD** (for both Early **and** Late driving segments). Early Onset settings led to more **CAS** activations (a potential source of driver irritation) both early and late in the driving segments but it also led to

fewer lane exceedences (to the left) for the Early driving segment. In the Late driving segment. directional **CAS was** reliably better than non-directional **CAS** in reducing the incidence of lane exceedences to the left, though the effect was small because the incidence of exceedences to the left was small. The auditory **CAS** shows evidence of promoting better lanekeeping (as evidenced by mean lane position) than unsupported driving. The auditory **CAS** and the haptic **CAS** promoted better lanekeeping (as evidenced by lane exceedences to the left) than unsupported driving. No evidence was found that a combined system that includes both auditory and haptic **CAS** displays in the vehicle was particularly beneficial.

With respect to lanekeeping following a lateral disturbance, the pattern of results is less consistent than that found for the general lanekeeping data.. Nonetheless, the following general conclusions can be drawn from the lateral disturbance data analysis for the simulation, test participants, procedures, and dependent measures used. **CAS** support to drivers did not statistically differ from the no support control drivers. This is taken as evidence that **CAS** support neither aided nor degraded collision avoidance maneuvers relative to drivers without **CAS** support. However, trends in the data. though not statistically significant at the selected criteria, suggest that **CAS** may provide benefits in terms of earlier response, reduced roadway departure extent and acceleration, and more controlled evasive steering maneuvers and improved crash avoidance. Based on the performance of participants with **CAS** support, combined and haptic displays appear promising. Early onset has generally beneficial effects on the collision avoidance maneuver. Directional displays exhibited complex interactions with interface modality, and hazard magnitude. The data suggest that directional displays may be beneficial in high hazard situations. Lastly, the TLC algorithm appears to be of greater benefit than TTD under high hazard situations.

Based on these results taken as a whole, it appears that the concept of roadway departure **CAS** has potential in terms of preventing roadway departures on a straightaway due to driver inattention. Given that a **CAS** is to be developed, the data indicate that directional displays have some performance advantages and consumer preference. Based on the evidence gathered in this study, auditory and haptic interface types merit further investigation and development. It appears that a combined-modality display may be a source of information overload to a driver. Driver-vehicle performance indicates that early onset is advised for the lateral **CAS** concept; however, subjective preference was for late-onset **CAS** thresholds (perhaps to minimize the number of **CAS** activations). While it appears that TLC may be a preferred algorithm for a lateral roadway departure **CAS,** it is associated with somewhat greater driver steering effort. Furthermore, both TLC and early onset are associated with more **CAS** activations, a potential source of nuisance alarms. Finally, it must be acknowledged that drivers were, on average, lukewarm to the **CAS** concepts included in the study. While this may not be surprising given the exploratory nature of this study, it nonetheless indicates that driver acceptance will need to be a **primary** goal of efforts to bring ITS concepts to fruition. The potential exists for advanced technology to contribute to enhanced **highway** safety, but the human factor remains a key element in achieving those ends.

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The views expressed in this article are solely the responsibilities of the authors and are not intended to reflect the official positions of NHTSA OCAR, Battelle, Carnegie-Mellon University, ITT Automotive, or the University of Iowa.

ENDNOTES

1. L. Tijerina, J. L. Jackson, D. A. Pomerleau, R. A. Romano, A. D. Petersen, "Run-Off-Road Collision Avoidance Using IVHS Countermeasures Task 3--Volume II," Contract No. DTNH22-93-C-07023 (Pittsburgh, PA: Carnegie-Mellon University, 1995).
2. B. Färber, B. A. Färber, H. Godthelp, and J. Schumann, J, "State of the art and recommendations for characteristics of speed and steering support systems," Deliverable Report DRIVE V 1041/GIDS-CON01 (Haren, The Netherlands: Traffic Research Centre, University of Groningen, 1991).
3. W. H. Janssen, W. H. and L. Nilsson, L., "Behaviourai effects of driver support," in Driving Future Vehicles (London: Taylor and Francis, 1993) pp. 147-155.
4. H. Godthelp, Studies of human vehicle control (Soesterburg, The Netherlands: TNO Institute for Perception, 1984).
5. SAS Institute, SAS/STAT User's Guide, Version 6 (4th ed.) (Carey, NC: Author, 1992).

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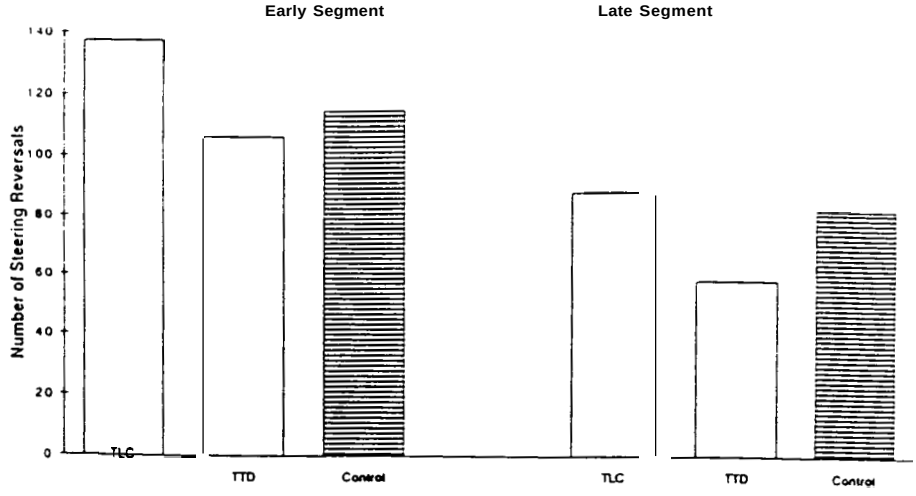
Driver Interface Type	Non-Directional Warning Condition	Directional Warning Condition
Auditory Display (Note: the fundamental wave frequency was 2000 Hz. The secondary wave had a frequency of 2119 Hz. The amplitude of the fundamental wave was 6 dB above that of the secondary wave.)	2000 Hz complex tone presented for 0.5 seconds duration in front of seated participant at a comfortable loudness relative to ambient cab noise. The tone was adjusted by the participant at the beginning of the simulator run.	2000 Hz complex tone presented for 0.5 seconds to the right of the participant if vehicle departed toward right, or presented to the left of the participant if the vehicle departed toward the left. Warnings were presented at a comfortable loudness relative to ambient cab noise. The tone was adjusted by the participant at the beginning of the simulator run.
Haptic Display	Vibrated steering wheei for 0.5 seconds with square wave at 10 Hzand 1.5 Nm magnitude.	A constant torque was applied by means of a single triangle wave at 2.0 Nm of force. The half-period of the triangle wave was 0.5 seconds. Torque was applied in the direction needed for recovery, e.g., if the vehicle was departing to the right, the steering wheel torque shift was to the left.
Combined (Auditory+Haptic)	Both of the above concurrently.	Both of the above concurrently.

Table 1. Interface type and directionality for the CAS.

Independent Factor	Code	
	-	+
Auditory Display System	NO	YES
Haptic Display System	NO	YES
Hazard Magnitude	LOW (equivalent steering wheel angle offset of 19.35° clockwise for 1.0 second to simulate light wind gust)	**HIGH** (equivalent steering wheel angle offset of 38.7° clockwise for 1.0 second to simulate heavy wind gust)
Directionality	Non-Directional	Directional
Warning Onset	EARLY (TTD = 1.13 seconds, with D = 0.75 meters, lookahead of 1.2 seconds; and TLC = 0.7 seconds)	**LATE** (TTD = 1.13 seconds, with D = 0.55 meters, lookahead of 1.2 seconds: and TLC = 0.0 seconds)
Algorithm	TLC	TTD

Table 2. Table of independent factors.



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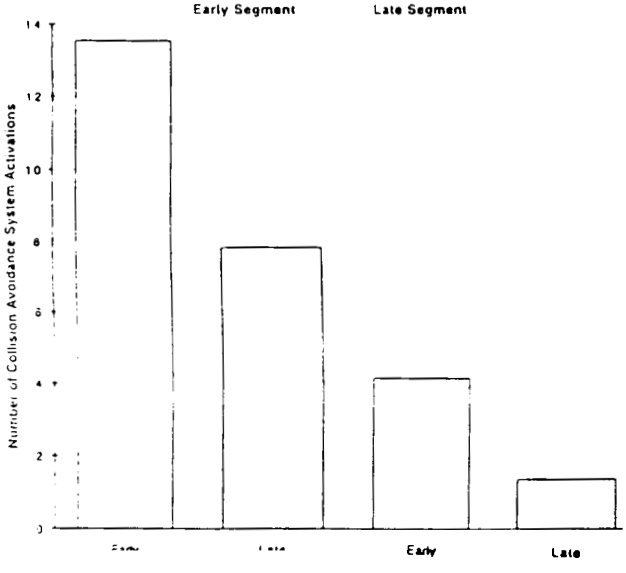

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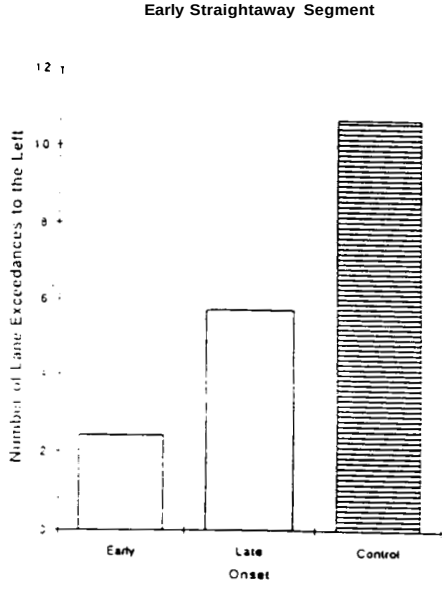


(C)

Figure 1. Driver-vehicle performance on straightaway driving: **(A)** Mean number of steering reversal over the 3-minute straightaway driving segments, early and late: (B) Mean number of **CAS** activations as a function of **CAS** onset. early and late straightaway driving segments; (C) Mean number of lane exceedences to the left as a function of **CAS** onset. early straightaway segments

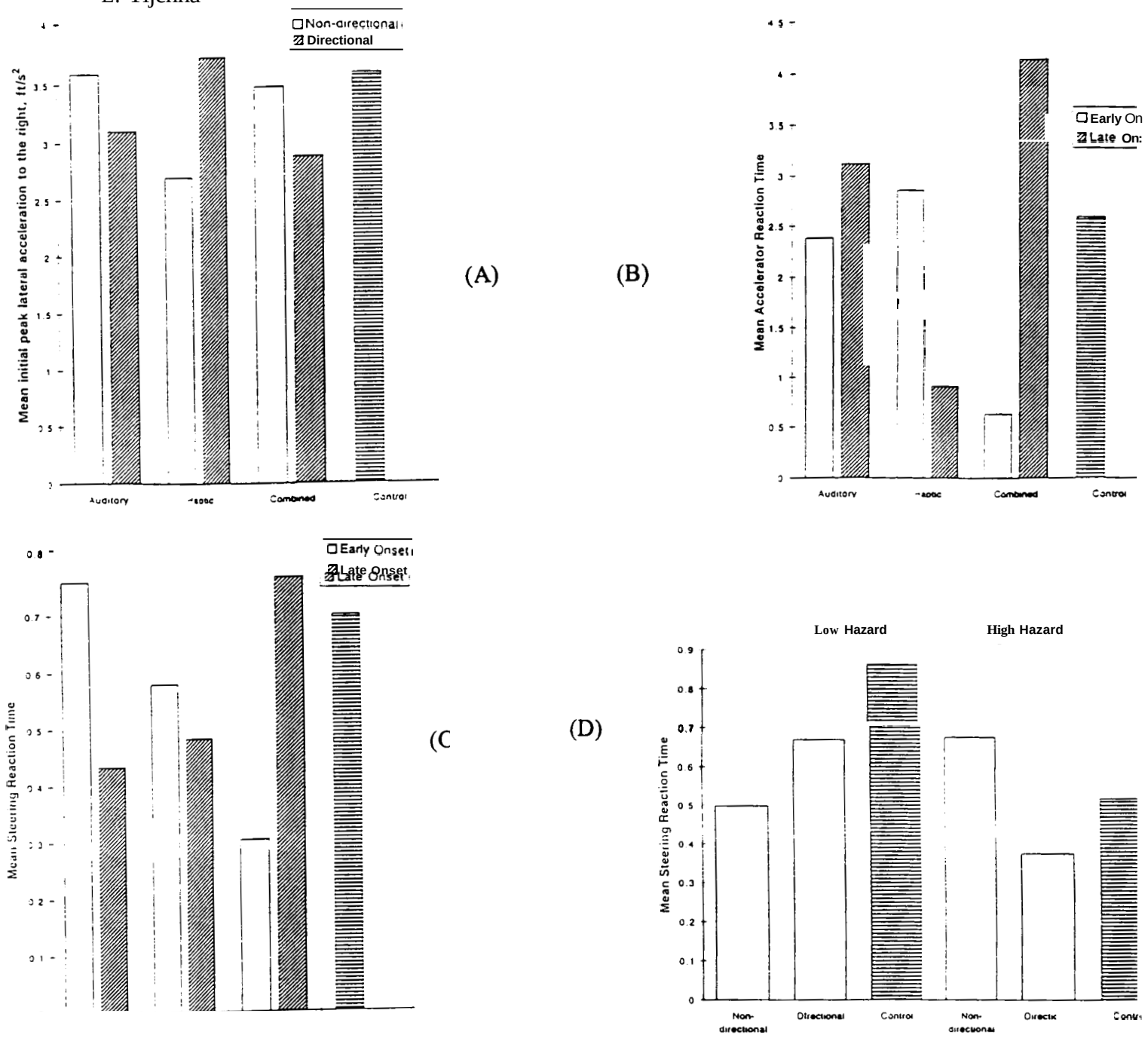
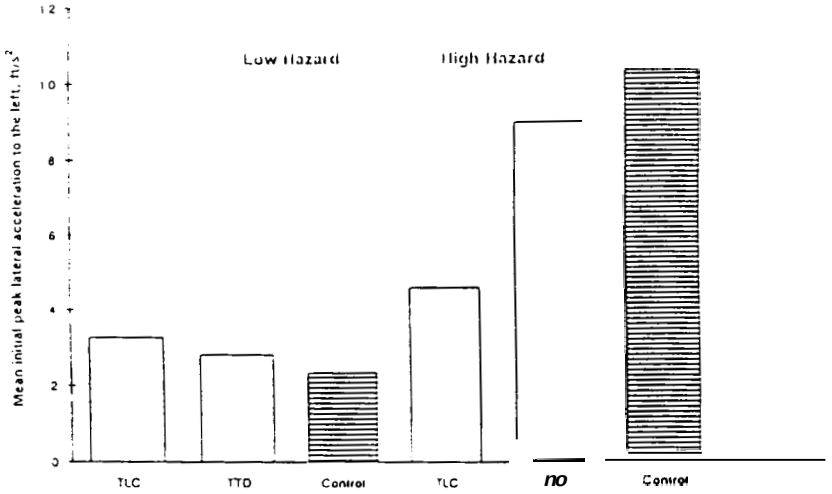
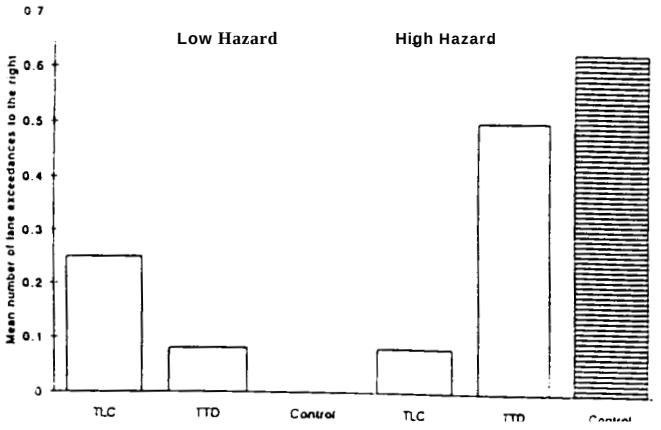


Figure 2. Driver-vehicle performance for initial movement and reaction to the lateral disturbance: **(A)** Mean initial peak lateral acceleration to the right (ft/s^2) as a function of both interface type and directionality; (B) Mean accelerator reaction time (RT) (Sec after disturbance onset) as a function of both interface type and onset; (C) Mean steering reaction time (RT) (Sec after disturbance onset) as a function of both interface type and onset; (D) Mean steering reaction time (RT) (Sec after disturbance onset) as **a** function of both hazard magnitude and directionality



(A)



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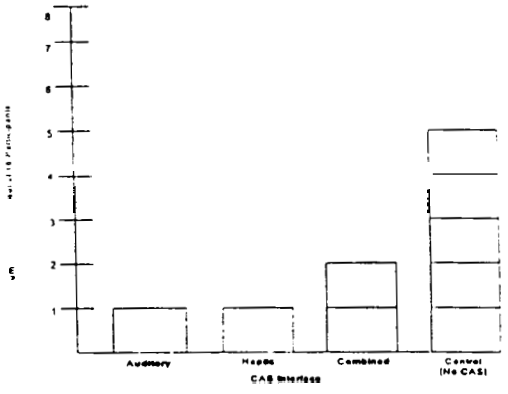

(C)

Figure 3. Driver-vehicle performance following the lateral disturbance: **(A)** Mean initial peak lateral acceleration to the left, ft/s^2, as a function of hazard magnitude and algorithm, with control group data included for reference: (B) Mean number of lane exceedences to the right as a function of hazard magnitude and algorithm, with control group results included for reference: (C) Number of crashes while the test participant was distracted