U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

**People Saving People**
http://www.nhtsa.dot.gov

**DOT HS 808 502**

**August 1995**

**Final Report**

# Run-Off-Road Collision Avoidance Countermeasures Using IVHS Countermeasures

## TASK 3—*Volume 2*

## Contracting Officer's Technical Representative's Precis

This report provides a basis for disseminating the preliminary contract results on a timely basis resulting in the information being available before the contract final reports are produced. Research performed during the remainder of the contract may support and/or modify the results, therefore, the material contained in this report should not be consider to be final. The current schedule calls for the completion of this research project by the third quarter of 1999.

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No | 3. Recipients's Catalog No |
|---|---|---|
| DOT HS 808 502 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| Run-Off-Road Collision Avoidance Countermeasures Using IVHS Countermeasures<br><br>Task 3 Report - Volume 2 | August 23, 1995 |
| | 6. Performing Organization Code |
| 7. Author(s) L. Tijerina, J.L. Jackson, D.A. Pomerleau, R.A. Romano, A. Perterson | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>Robotics Institute<br>Carnegie Mellon University<br>5000 Forbes Avenue<br>Pittsburgh, PA 15213 | 10. Work Unit No (TRAIS)n code |
| | 11. Contract of Grant No.<br>DTNH22-93-C-07023 |
| 12. Sponsoring Agency Name and Address<br>National Highway Traffic Safety Administration<br>400 Seventh Street, S.W.<br>Washington, DC 20590 | 13. Type of Report and Period Covered<br>Final Report<br>10-93 to 8-95 |
| | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract


The Run-Off-Road Collision Avoidance Using IVHS Countermeasures program is to address the single vehicle crash problem through application of technology to prevent and/or reduce the severity of these crashes.

This report describes the findings of the driving simulator experiments conducted for Task 3. In these experiments, 64 subjects drove a simulated vehicle over a 40-minute course on the Iowa Driving Simulator (IDS), a six degree-of-freedom, moving-base simulator with a wide field-of-view image generation system. For 48 of the subjects, the vehicle was equipped with lateral and longitudinal countermeasures to warn the driver of roadway departure danger. Different subjects experienced a variety of countermeasure algorithms and driver interfaces, including auditory, haptic and combined auditory and haptics displays. There were also 16 subjects who drove the same simulate course, but received no countermeasure support.

Results suggest that the roadway departure countermeasures have potential for preventing crashes. Driver interfaces that provide information about the appopriate driver response appear to have some performance benefit. Either auditory or haptic displays appear promising, but a combination auditory and haptic display appeared to produce driver overload.


| 17. Key Words | 18. Distribution Statement |
|---|---|
| Run-Off-Road Collision Avoidance<br>Single Vehicle Roadway Departure<br>Driving Simulator<br>Auditory Displays/Haptic Displays | Document is available to the public through the National Technical Information Service, Springfield, VA 22161 |

| 19 Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 90 + appendices | $1,217,951 |

**Form DOT F1700.7 (8-72)** **Reproduction of completed page authorized**

## TABLE OF CONTENTS

Page

## Table of Contents (cont.)

**Table of Contents (cont.)**

## List of Tables

## List of Tables (cont.)

## List of Figures

## List of Figures (cont.)

**List of Figures (cont.)**

# ACKNOWLEDGMENTS

The authors would like to thank several individuals who contributed to the research reported here. The authors acknowledge the review comments and suggestions on this research provided by August Burgett and Lloyd Emery of the National Highway Traffic Safety Administration Office of Crash Avoidance Research (NHTSA OCAR). Bala Kumar and Todd Jochem of the Carnegie-Mellon University Robotics Institute contributed to CAS concept generation and algorithm development. From the University of Iowa Center for Computer Aided Design (CCAD), the authors acknowledge several individuals. Andrew Petersen and Daniel McGehee ran the simulator study and carried out the data collection activities. Srinivas Maddhi provided support on data reduction, as did Timothy Brown. Marty Christensen developed the implementation and design of the auditory CAS interface. Tammie Cumming provided extensive support in the area of data analysis. Finally, the authors thank Connie Stephenson of Battelle for manuscript preparation and Jeffery Everson for review of portions of the manuscript. This work could not have been completed without the inputs of these individuals. The authors extend sincere thanks for their contributions.

## EXECUTIVE SUMMARY

This report presents the results of an exploratory study of Collision Avoidance System (CAS) concepts suitable for roadway departure collision avoidance. This work was executed under Phase I, Task 3 of the National Highway Transportation Safety Administration (NHTSA) Roadway Departure Collision Avoidance System Specification Program to develop performance specifications for countermeasures that prevent or reduce the severity of single vehicle roadway departure crashes. According to the 1991 General Estimates System (GES) crash data, this crash type accounts for approximately 20.8% of all crashes, and 37.4% of all fatal crashes in the United States. Countermeasures that could prevent or reduce the severity of even a fraction of these crashes would have a significant benefit to society.

The purpose of the study was to evaluate the following items from a driver-oriented perspective. Sixty-four volunteers (32 males and 32 females between the ages of 25 and 45 years) participated in a study conducted 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 and 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 non-directional), Onset (early CAS onset or late CAS onset), and Algorithm (Time-to-Line-Crossing or TLC versus Time-to-Trajectory Divergence or TTD for lanekeeping and no-pulse vs. pulse braking for approach to a curve.

All participants were assigned to either high or low magnitude hazard conditions based on two collision hazards. 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. The longitudinal or curve disturbance involved approach at highway speed to a curve for which no speed sign was posted; low hazard magnitude was equated to approach to an 800 ft-radius curve and high hazard magnitude was equated to approach to a 250 ft-radius curve. In addition, participant performance was assessed during normal (non-hazard) lanekeeping on a straightaway and during normal (non-hazard) curve negotiation early and late in a simulator session which lasted approximately 40 minutes. Five separate analyses were conducted and the following conclusions were reached for each analysis.

The general conclusions drawn from the general lanekeeping data analysis are the following:

- CAS support is associated with more precise lanekeeping under normal straightaway driving conditions (for both Early and Late driving segments).

- TLC causes relatively more driver workload than TTD (for both Early and Late driving segments).

- Early Onset settings lead to more CAS activations (a potential source of driver irritation) both early and late in the driving segments but it also leads 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.

The pattern of results for the lateral disturbance data was 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.

- 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.

- 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. Directional displays appear to be beneficial in high hazard situations.

- The TLC algorithm appears to be of greater benefit than TTD under high hazard situations.

The general conclusion to be drawn from the results of the data analysis for normal curve negotiation are that CAS support did not significantly alter driving behavior for normal curve negotiation. Drivers were driving close to the design speed for the curve and so the CAS support was generally not needed. At present, this data does not provide any strong evidence of a problem with any CAS support feature. Thus, it is appropriate to move on to an assessment of the impact of CAS on the curve hazard data. Based on the results of the general curve negotiation results, it is recommended that all CAS concepts be retained and other results be used to discriminate among them.

The longitudinal or curve hazard analysis yielded the following results:

- The most obvious conclusion that can be drawn strictly from the data on the longitudinal curve disturbance is that hazard magnitude had a rather strong effect on participants' driving behavior. Participants entered the 250 ft-radius, high hazard, curve at a slower speed than the 800 ft-radius, or low hazard, curve. Participants also exhibited greater maximum and mean decelerations with the 250 ft-radius curve than with the 800 ft-radius curve, and they also traversed the 250 ft-radius curve more slowly. Drivers also exhibited more steering reversals on the 800 ft-radius curve. These results serve as a substantial demonstration that the hazard magnitude manipulation had an effect on driver behavior in this study with respect to curve approach and negotiation.

- None of the CAS support concepts involved an abundance of significant main effects or interactions. However, there are indications that the auditory interface benefits driver behavior in that it led to the shorter brake pedal reaction times (RTs) following a longitudinal alert than either the haptic or the combined interface. Furthermore, the auditory interface, when associated with the no-pulse braking longitudinal algorithm, led to slower curve entrance speeds than it did when combined with the pulse braking algorithm. However, the auditory interface led to slightly, but significantly greater lane deviations than did either the haptic or combined interfaces as drivers traversed the curves.

- Data on the effects of warning onset were equivocal. Late onset led to shorter brake reaction times (RTs) but this may simply reflect the fact that the driver had to begin braking sooner to smoothly negotiate the curve. Thus, no recommendations are offered with respect to this CAS feature.

- Directional warnings offered greater maximum decelerations than did the non-directional counterparts; however, the non-directional warnings led to slightly lesser lane deviations, especially in high hazard curves. With respect to the curve disturbance data, these were the only directionality effects obtained.

The last set of results focussed on subjective assessments by the participants who had some form of CAS support. While there were a number of inconsistencies in the subjective assessment data, the following trends were noted:

- 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) 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).

Based on these results taken as a whole, it appears that the concept of roadway departure CAS has potential, especially in terms of preventing roadway departures on a straightaway due to driver inattention. The longitudinal or curve approach CAS concepts did not demonstrate any superiority over unsupported drivers but this may reflect weaknesses in the methodology used and the difficulty in thwarting the driver's normal information processing. Still, it is worthwhile to continue investigations into the development of better CAS concepts for avoidance roadway departures at curves as well as methods to test such concepts.

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. Early onset is advised for the lateral CAS concept, but a late-onset CAS may be preferred for the longitudinal (curve approach) 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 nonetheless indicates that driver acceptance will need to be a primary 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 factor remains a key element in achieving such gains.

# 1.0 Introduction

## 1.1 Background

The goal of the National Highway Transportation Safety Administration (NHTSA) Roadway Departure Collision Avoidance System Specification Program is to develop performance specifications for countermeasures that prevent or reduce the severity of single vehicle roadway departure colllisions. According to the 1991 General Estimates System (GES) crash data, this collision type accounts for approximately 20.8% of all crashes, and 37.4% of all fatal crashes in the United States. Countermeasures that could prevent or reduce the severity of even a fraction of these crashes would have a significant benefit to society.

Phase I of the roadway departure specification program is divided into four tasks. The tasks and the information flow between them are shown in Figure 1-1.

Task 1 involved analyzing both the GES and National Accident Sampling System Crashworthiness Data System (NASS CDS) databases to characterize typical roadway departure crashes. Through this effort it has been determined that roadway departure 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%).

The Task 1 engineering analysis resulted in a grouping of roadway departure crashes into two broad classes: crashes caused by external factors relating to the road ahead, and those caused by internal factors associated with the condition of the driver. The important external factors include the presence of sharp curves, reduced traction conditions, and obstacles ahead of the vehicle.

The important internal factors include driver distraction (e.g., tuning the radio or reaching for object on the floor) and driver incapacitation (e.g., intoxicated or asleep). Note that due to their low frequency, roadway departure crashes caused by vehicle failure have been excluded from this classification.

Using the crash profiles developed in Task 1, the nearly completed efforts in Task 2 have identified several functional goals for roadway departure countermeasures. The Task 2 time line analyses have determined that for the crashes caused primarily by external factors, intervention must begin prior to the vehicle encountering the hazard directly. Considering the high speeds typically associated with these types of crashes, by the time the vehicle reaches the sharp curve (or ice patch or obstacle in the roadway), it is typically too late to expect appropriate intervention by the driver or by an active countermeasure.

Therefore, the primary functional goals identified for these externally precipitated crashes are first concerned with detecting the potentially dangerous situation several seconds prior to the

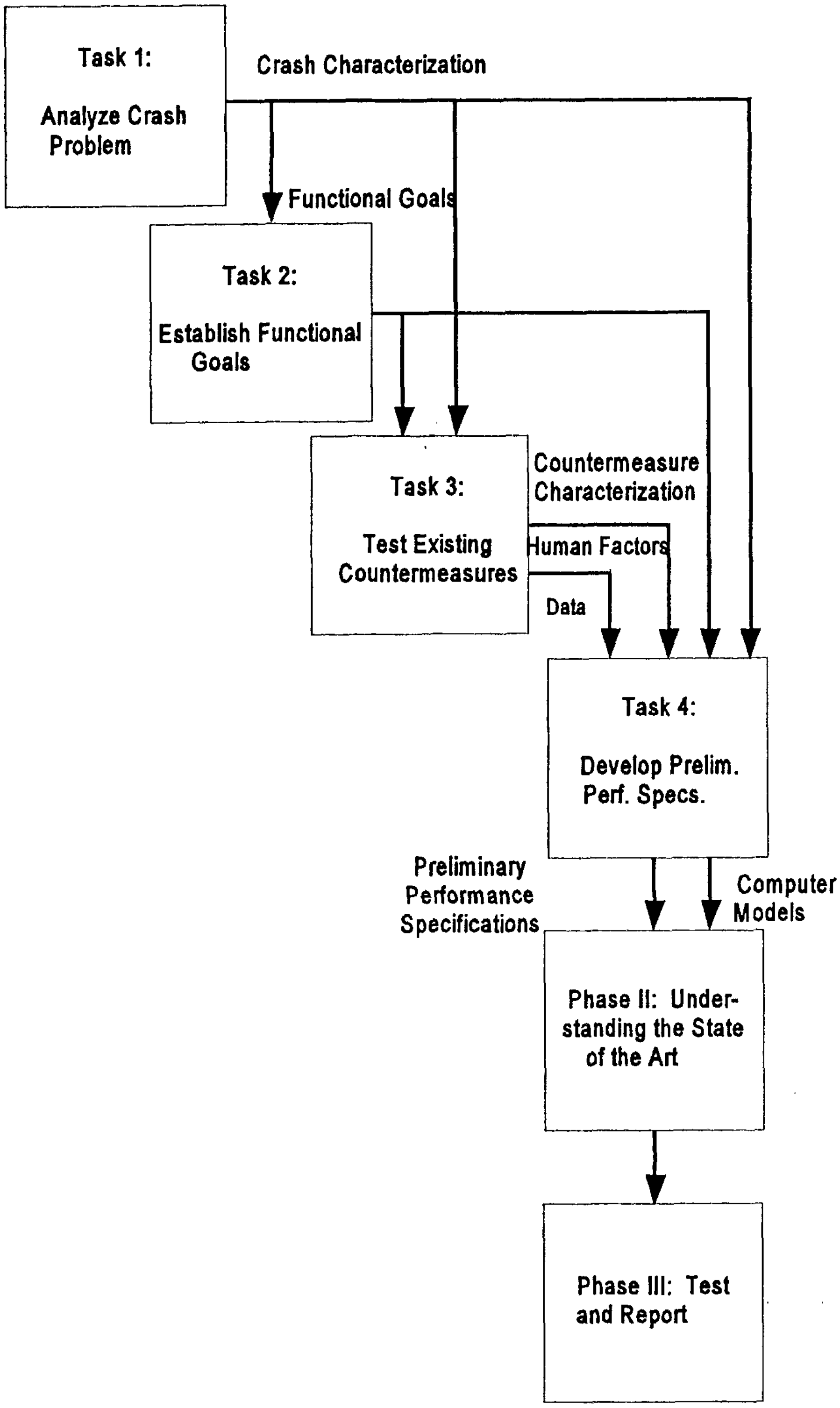



**Figure 1-1 PHASE FLOW DIAGRAM**

vehicle actually encountering the danger. Once detected, the goal is to initially alert the driver of the upcoming hazard with a low intensity stimulus. If the driver does not respond to the alert, a more intense stimulus should be triggered to warn the driver of the upcoming danger. This sequence of "alert - warn " assumes that there is sufficient time to provide a graded driver support. This is a valid premise in the case of roadway departures at curves since the curve is a permanent feature of the route. Furthermore, the "alert-warn" approach assumes that for this level of testing, control intervention measures are not yet invoked. Active control may be an option as a "last chance" maneuver once initial simulation experiments of graded alerting have been properly analyzed.

For crashes caused by internal factors, the Task 2 analyses indicate that the time available between onset of the drift-from-lane to roadway departure itself is somewhat greater. Thus, the intensity of the required intervention is somewhat less than typically required in externally precipitated crashes. Departure angles for driver inattention and driver-relinquishes-steering-control crashes are often relatively shallow. These shallow departure angles can potentially allow for a countermeasure that has built into it enough time to detect vehicle departure as the vehicle moves toward a departure and as the vehicle actually begins to depart the roadway. The countermeasure can warn the driver, and if necessary, provide control intervention through the steering wheel to return the vehicle to the lane center. It is less clear that graded driver support is feasible in the case of internally precipitated drift-out-of-lane situations due the difficulty in unambiguously anticipating the hazard. In the latter case, there may only be sufficient time for warning or warning/control intervention.

In the Task 3 effort, the project team assessed commercially available hardware to test the performance of in-vehicle collision avoidance systems (CAS). This effort is guided by the functional goals identified in Task 2 for preventing crashes caused by external and internal factors. The hardware analysis is reported in Pomerleau, Kumar, Everson, Kopala, and Lazofson (1995).

The term "longitudinal countermeasures" is used for systems designed to prevent roadway departure crashes at curves, since they detect danger ahead of the vehicle on the roadway. The longitudinal countermeasure investigated in Task 3 utilizes a satellite global positioning system (GPS) to determine the vehicle's location on a digital map, and data from weather and pavement monitoring sensors to ascertain the safe travel speed for the upcoming stretch of road. The countermeasure is designed to respond when the driver is traveling too fast for the conditions ahead, such as when approaching a sharp curve or an icy patch of roadway.

The term "lateral countermeasures" is applied to systems designed for the prevention of drift-out-of-lane roadway departure crashes, since they detect when the vehicle starts to drift laterally off the road. The lateral countermeasures investigated employ either a forward or a downward looking optical sensor to detect the vehicle's lateral position on the roadway and the geometry of the road ahead. They are designed to respond when the driver begins to depart from the travel lane due to inattention or incapacitation.

Both of these countermeasures are designed to address four of the six causal factors for roadway departure crashes identified in Task 1: driver inattention (12.66%), driver relinquishes steering control (20.07%), lost directional control (15.96%) and excessive speed (32.00%). The two remaining causal factors are evasive maneuver (15.68%) and vehicle failure (3.64%). Evasive maneuver crashes will be best addressed using obstacle detection sensors under investigation in rear-end collision specifications program. Vehicle failure crashes (3.64%) are a relatively small fraction of the crash population, and are therefore excluded from Phase I of this program.

Prototypes of the sensor technology for both longitudinal and lateral countermeasures are now operational at Carnegie-Mellon University. These sensing systems will undergo refinement and characterization by the project team. However, sensing the situation around the vehicle is just one part of a countermeasure system. The system must also decide when to respond based on a trigger algorithm, and must interact with the driver in carrying out a response. This report details a preliminary investigation of human factors issues associated with CAS design conducted in a high-fidelity motion-base simulator.

### 1.2 Objectives

There were many goals that might have been pursued in an exploratory study. Based on the project team's assessment of priorities together with inputs from NHTSA, the following items were considered in the present study:

a) Multiple system concepts (haptic versus auditory versus combined interfaces; directional versus non-directional driver warnings; alternative lane keeping warning/intervention algorithms; early versus late warning onset thresholds; alternative curve approach warning algorithms). It is important to assess a wide variety of factors early in the program to identify fruitful directions for future research. Thus, assessment of multiple system concepts was deemed critical.

b) Normal driving situations (general lanekeeping on a straightaway, general curve negotiation). It is important to assess the effects of CAS concepts on normal driving.

c) Key collision hazard scenarios (e.g., roadway departure at curves due to excessive speed, roadway departure on straightaway due to driver inattention or incapacitation). These scenarios allow for initial feasibility and effectiveness assessments in the context of key driving conditions associated with roadway departure crashes.

d) Assessments of driver acceptance of various CAS concepts, especially in terms of false or nuisance alarm impacts on driver behavior to support effectiveness estimates. If roadway departure collision avoidance systems are to be viable, they must be acceptable to drivers. Furthermore, they must be used in the manner intended by the system designers. It is worthwhile to begin such assessments early on in the simulator testing.

These goals are in keeping with the scenarios uncovered in Task 1 because they address functional CAS requirements under development in Task 2, and provide data in support of Task 4 and subsequent tasks. In particular, the models of Task 4, suitably enriched with driver performance data under various CAS configurations, will be useful for analytical assessments in later phases of the program.

## 2.0 A Brief Human Factors Literature Review of CAS Interface Options

### 2.1 CAS Interface Modalities: An Introduction

When considering various CAS interface options, the major modalities that can be used are auditory, haptic, and visual. The auditory and haptic modalities are discussed below. For this initial assessment, no visual displays were used. The reasons for this were threefold. First, distraction of driver visual attention away from the road scene is a major cause of crashes (Tijerina, 1995). There was concern that a visual CAS might inadvertently take the driver's eyes off the road scene at precisely the wrong moment. Second, if the CAS used non-visual means to direct the driver's attention back to the road scene, driver visual processing is usually quite adequate to provide inputs for safe control of the vehicle (Schiff & Arnone, 1995). For example, a visual display that showed an arrow in the direction the driver needed to turn the wheel to avoid a roadway departure on a straightaway, would likely be of little help compared to the driver's direct perception of the road delineation ahead. Third, visual displays might be added at a later time to enhance non-visual displays if preliminary research results indicate a need for or benefit to such augmentation (cf. McGehee, Dingus, & Horowitz, 1994). For these reasons, visual display concepts were not considered in this study.

### 2.2 The Haptic Interface

Gibson (1966) defined the *haptic* system as "the sensibility of the individual to the world adjacent to his body" (p. 97). It comes from the Greek term meaning "able to lay hold of" and operates when an individual feels things with the body or its extremities. One possible display system is a haptic interface that the driver feels rather than sees or hears. A theoretical motivation for such displays is that they contain high stimulus-response (S-R) or ideo-motor compatibility (Wickens, 1992). In this case, the stimulus matches the sensory feedback produced by the response. For example, a steering response might be facilitated by a haptic display that invokes steering wheel motion in the direction the driver needs to turn.

Haptic displays (sometimes also called kinesthetic-tactile or proprioceptive displays) have been used for years in aviation. A common example is the "stick shaker" that alerts a pilot to stall hazards. The earliest automotive example was reported by Fenton (1966). In Fenton's investigation of car following, a joy stick was modified to provide headway information to the driver's hand. If the driver was following too closely, a servo-driven joystick protrusion pushed out from the joystick handle. If the headway was greater than desired, the protrusion recessed into the joystick handle. Both states were detected by the driver's sense of touch. Drivers were able to maintain desired headway separation with the haptic display.

Since Fenton's early design, there have since been other applications of the haptic display to aviation (Gilson & Fenton, 1974) and tracking research (Burke, Gilson & Jagacinski, 1980; Jagacinski, Flach, & Gilson, 1983; Jagacinski, Miller, & Gilson, 1979). In general, haptic displays show promise for various control applications. However, they are likely to be unfamiliar to drivers and may require some practice to achieve useful results.

Recent automotive applications of haptic displays have come from Europe. Janssen (1989) reviewed an earlier study by Panek on the impact of various CAS concepts to rear-end collision avoidance. Panek found that, for car-following warning systems, an auditory alarm kept drivers out of a critical "danger" zone most often when compared to a visual display or a smart accelerator pedal that pushed against the driver's foot when following too closely. Janssen and Nilsson (1990) conducted a simulator study of various rear-end CAS concepts that used two different warning algorithms (a time-to-collision [TTC] algorithm vs. a "worst case" algorithm that assumes the lead vehicle can come to a stop with full braking power at any moment) and auditory, visual (red light), or haptic (active accelerator pedal) driver interfaces. While the systems all reduced the incidence of very short headways, only the active accelerator pedal with the TTC algorithm was not associated with an increase in driving speed, an increase in acceleration and deceleration levels, or an increase in time spent in the left lane (i.e., the opposite traffic lane of a two-lane simulated road). (See also Janssen & Nilsson, 1993, for further discussion of these results).

Janssen and Nilsson's active accelerator pedal provided a constant force whenever the driver was following too closely; no variations in force were applied to indicate variations in close car following. Godthelp (1990), on the other hand, evaluated a servo-controlled accelerator pedal in a driving simulator by presenting a dual-axis tracking task in which the steering wheel and accelerator pedal controlled the horizontal and vertical position of a pointer. Different force-feedback characteristics of the accelerator pedal were used as the main independent variable. Results, though not derived from an actual driving scenario or simulation, nonetheless suggested that the inclusion of force-feedback may strongly improve performance.

Godthelp and Schumann (1991) (see also Godthelp & Schumann, 1993) later evaluated the effects of the active accelerator pedal with error-proportional force feedback on speed control in a driving simulator. Test participants drove a simulated two-lane rural road, executed a lane change, and resumed driving at a requested speed that was perhaps different from the initial speed. Independent variables included the maneuver with or without speedometer information (termed speedometer occlusion) and with accelerator pedal characteristics at four levels: normal (passive) accelerator; speed-error proportional force feedback accelerator; feedback proportional to pedal position (not speed) accelerator; and a vibrating pedal (0.5 s at 10 Hz with 20 N magnitude). Results indicated that the accelerator pedal that provided force feedback proportional to speed error was most effective in reducing speed errors.

Färber, Färber, Godthelp, and Schumann (1991) extended the application of haptic displays from active accelerator pedal to an active steering wheel and conducted psychophysical studies to determine acceptable torque shift. The active steering wheel applies a torque in the direction the driver should turn and for a 0.5 s application, a 1.2 Nm torque shift was recommended, independent of the initial steering torque. This was determined to be noticeable by most test participants.

Färber, Naab, and Schumann (1991) investigated the effectiveness of the active steering and accelerator pedal displays in a series of driving simulator and proving ground studies. The driving simulator scenarios included curve negotiation, overtaking, and car following. For curve driving, the active accelerator pedal reliably reduced speed through the curve but the use of a fixed duration (0.5 s) and fixed amplitude (2 Nm) directional torque shift did not significantly improve lateral control (as measured by lane standard deviation and median time-to-line crossing values). In the overtaking scenario, the CAS warned the driver attempting to pass a slower-moving lead vehicle that there was an oncoming vehicle. Thus, the goal of the CAS was to break up the overtaking maneuver. The CAS support used either a vibrating steering wheel (1.0 s at 10 Hz with 1 Nm amplitude) or a short directional torque steering wheel (0.5 s with torque shirt of 2.5 Nm) was applied along with active accelerator pedal support. Results showed that the directional torque condition was reliably better than either no support or a vibrating steering wheel in terms of maximum lateral position to the left lane achieved prior to the driver canceling the overtaking maneuver. It was speculated that the amplitude of the vibrating steering wheel was too weak to capture the driver's attention, suggesting that the 1.2 Nm value found by Färber, Färber et al. (1991) should be considered an absolute minimum. In the car following scenario, the lead vehicle suddenly braked but the brake lights did not come on. The active accelerator was clearly superior to the condition with no driver support in terms of the number of rear-end crashes avoided. Finally, the discrete directional steering torque (0.8 s with 3 Nm magnitude) was compared to no steering support and to a continuous steering torque that provided directional torque linearly proportional to speed error (up to 3 Nm of torque maximum) on a closed course driven in an instrumented vehicle. In terms of curve negotiation, the two active steering approaches showed no signficant differences in lane standard deviation, steering angle changes, or mean speed through the curve. There was a reliable increase in speed standard deviation for the discrete active steering display relative to the continuous support or no support.

Schumann, Godthelp, Färber, and Wontorra (1993) reported on a fixed base driving simulator study to examine the effectiveness of active steering displays to break up a lane change maneuver. The driver performed a lane change maneuver which was signaled by a short period where the visual scene was occluded. The lane change was then attempted with full vision or with continued visual occlusion. During the lane change maneuver, the haptic display activated to tell the driver to cancel the maneuver because of a vehicle in the adjacent lane. The CAS displays were auditory (0.5 s tone), vibrating steering wheel (0.5 s duration at 10 Hz with 1.2 Nm magnitude), vibrating steering wheel as before but with duration lasting until lateral speed to the right (in the direction of a corrective steering maneuver) was greater than 1 m/s, and a directional torque to the right of fixed duration (0.5 s) and magnitude (2.4 Nm). The lane change maneuver is considered to be open-loop or pre-programmed (McRuer, Allen, Wier, & Klein, 1977) and so should be relatively hard to cancel once it has been initiated. Results indicated no significant effects of display modality on maximum steering wheel angle to the left and to the right, or maximum steering velocity to the left and to the right. However, response times were reliably shorter to the constant torque, directional steering display, and the minimum lateral distance to the center line (lane line) was greatest for the constant torque, directional steering display.

More recently, Schumann, Löwenau, and Naab (in press) have investigated the continuous feedback active steering display driven with alternative control laws. Test participants drove an 80 km stretch on a German freeway in an instrumented vehicle that traveled at approximately 110 km/hr. No driver support was compared with three lanekeeping strategies termed preview compensation, aim-point error, and lateral speed change strategies. Regardless of control strategy, active steering was employed such that an "optimal" steering wheel angle was computed moment to moment. If the driver's input deviated from this optimal steering wheel angle, an additional steering wheel torque was generated proportional to the difference to indicate to the driver how to readjust his or her lanekeeping behavior. Results indicated reliably smaller lane standard deviation with the aim-point error control law relative to the other conditions, but the aim-point error control law induced the most steering effort in terms of the percent of energy in two frequency bands of the power spectrum of steering wheel movements. Thus, there is a tradeoff between performance and effort for lanekeeping.

One logical extension of a haptic interface that displays error-proportional feedback in lanekeeping or speed control is to have an automatic vehicle control system. Limited research has been conducted on this option to date. Nilsson, Alm, and Janssen (1991) evaluated the effects of different levels of automation in collision avoidance systems in a moving-base driving simulator. Three collision avoidance systems for longitudinal, i.e., rear-end, collision avoidance were studied. In one case, a short vibration on the accelerator pedal (0.5 s at 10 Hz with amplitude of 20 N) was applied when a warning algorithm determined the subject vehicle was following too closely. In the second case, the accelerator pedal applied a constant force (30 N, 0.5 s rise time) which also led to an initial slowing of the subject vehicle. The third system presented a vibrating pedal as in the first system, but also applied automatic braking and positioned the subject vehicle (simulated) at a prescribed time headway behind the lead vehicle. Results indicated that the third system provided the most benefits in terms of mean following distances and proportion of time spent in the left lane (including overtaking behavior), but drivers regarded it as most intrusive and most disturbing. This suggests that automatic vehicle control concepts for CAS support will have to be carefully designed and drivers will have to be trained and educated on their potential value. The public's perception of the reliability and risk associated with automatic vehicle control systems may be the single greatest challenge to that class of technology.

Research into haptic displays has shown that there may some opportunity to provide collision avoidance warning information to the driver by means of such displays. Haptic displays hold a special appeal for consideration as CAS support because of the visual workload relief they may offer, and because of the high stimulus-response compatability they are thought to have. To date, however, no study has investigated the efficacy of active steering or active accelerator pedal interfaces on roadway departure collision avoidance. Drift-out-of-lane crashes on a straightaway due to inattention (one common roadway departure scenario) are different from lane changes or overtaking maneuvers. By definition, both of the latter maneuvers are the intent of the driver, while drifting out of lane while momentarily inattentive is unintentional. Thus, there is a need to assess the effects of haptic steering interface concepts for the scenario of roadway departure on a straightaway due to driver inattention. If this can be successful with otherwise normal drivers, then perhaps it may also be extended to drivers who might relinquish control due to drowsiness or intoxication. If the haptic steering concepts do not work with normal drivers, it appears unlikely that they will work with incapacitated (i.e., drowsy, drunk) drivers.

A second roadway departure scenario is departing the roadway at a curve due to excessive speed. A haptic accelerator display might be beneficial in this case. However, it is different from the car following situation because there is no object like a car to provide the driver with visual confirmation of a threat. While the sight of the approaching curve can serve this function, the threat of the curve is likely not to be visible (or apparent) to the driver until much later. Furthermore, since the lead vehicle in car following as also moving, but the curve is fixed in the path ahead, evaluation of the active accelerator pedal--both the speed-error proportional (i.e.,. directional) and vibrating (i.e., non-directional)--is worthwhile.

### 2.3 The Auditory Interface

Reaction times to auditory stimuli are typically faster than reaction times to visual stimuli (Wickens, 1992). This, plus the visual workload relief that an auditory display offers, suggests that an auditory interface might be useful for CAS applications. Indeed, commercially available products like the Eaton-VORAD collision warning system and the SCAN II near-object detection system make use of auditory warnings (along with visual displays). While speech displays are a means of conveying collision avoidance information for the roadway departure scenarios, only non-speech displays were considered in this initial assessment. This decision was motivated by a desire to avoid CAS concepts that "chat" frequently with the driver as well as a concern that synthetic speech may sometimes be difficult to comprehend (Paris, Gilson, Thomas, & Silver, 1995) and serve as a source of distraction.

Non-speech auditory interfaces need not be restricted to provide only non-directional warnings or alerts. Research has demonstrated that auditory display systems can be used for control tasks as well. Vinje and Pitkin (1972) developed an auditory display for use in a single-axis compensatory tracking task. Error magnitude was coded by pitch and error polarity (i.e., direction) was coded by either modulating the tone or by switching the tone between the ears by means of headphones. Tracking results with auditory displays were close to those found with visual displays. A combined auditory-visual display improved tracking only slightly. Mirchandani (1972) studied a single-source auditory display for use in dual axis tracking. The auditory display varied in frequency to indicate direction of error and volume to indicate magnitude of error. Results indicated that the auditory display system supported good tracking performance. More recently, Janiga and Mayne (1977) applied an auditory display system to aid in the control of a computer-simulation (not a driving simulation) of a skidding vehicle. A tone of a fixed frequency appeared to the right ear over headphones if steering to the left was required and the tone became louder with increased error magnitude. Similar rules were applied to the left ear. Results indicated that such an auditory display, as a assist to the visual display, enhanced performance over visual only display conditions.

Results such as these suggest that non-speech auditory displays can provide substantial information for collision avoidance. They also provide visual workload relief, can prompt fast reactions, and do not depend on where the driver is looking for their effectiveness. In a normal automobile, it is harder to make auditory displays directional, but it is nominally possible. Non-directional displays are frequently found. Thus, there is the potential for auditory displays to be quite effective for roadway departure collision avoidance. To date, no literature was found that applied auditory warnings to driving situations like the lane departure on a straightaway or departure at a curve.

## 3.0 General Approach

The project team was directed by NHTSA to make use of an advanced driving simulator to conduct the study. The University of Iowa driving simulator was chosen for this purpose. An approach was developed for a single simulator session to generate data sufficient to conduct five separate analyses to assess the impact of CAS support concepts on:

- normal lanekeeping on a straightaway;
- normal curve negotiation on an 800 ft-radius curve;
- collision avoidance in a lateral disturbance on a straightaway;
- collision avoidance in a longitudinal disturbance on approach to a curve; and
- driver subjective impressions of the CAS support concepts.

This section describes the general method used in the data collection.

### 3.1 Method

#### 3.1.1 Participants

Sixty-four volunteer participants (32 males and 32 females) were recruited by the University of Iowa for inclusion in this study. All participants had valid U. S. drivers' licenses. Participant ages ranged from 25 to 45 years of age and all were screened for predisposing medical conditions that were incompatible with University of Iowa Driving Simulator (IDS) guidelines for test participant selection.

#### 3.1.2 Apparatus

The apparatus used for this study included the IDS and special purpose equipment used to emulate various CAS concepts. These are described below.

##### 3.1.2.1 *Iowa Driving Simulator*

The University of Iowa Driving Simulator (IDS) was used in this study. The IDS is a motion-base simulator with a wide-field visual display. The visual system used an Evans and Sutherland ESIG 2000 Image Generator that provided a 190° forward field of view, and 60° rear field of view. Three color projection units generated the forward field of view. A 1990 Ford Taurus buck was mounted in a large payload, six-degree-of-freedom motion base driven by a vehicle dynamics model that reproduces many of the motion cues experienced while driving.

### 3.1.2.1 *Collision Avoidance System (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 (Time-to-Line Crossing or TLC vs. Time-to-Trajectory Divergence or TTD for the lateral roadway departure case; pulse braking vs. no pulse braking for the curve roadway departure case), as well as Hazard Magnitude (low magnitude vs. high magnitude). Table 3-1 presents descriptions of the various CAS Interface and Directionality configurations for the lateral warning system. Table 3-2 presents descriptions of the various CAS Interface by Directionality configurations for the longitudinal or curve approach warning system. The haptic steering display was implemented by means of a servo motor connected to the steering column by a drive chain and it provided a calibrated directional torque or a non-directional vibration. The haptic accelerator pedal display was implemented by means of a servo motor connected to the accelerator pedal to provide either a graded counterforce or a vibration, as needed. In both cases, the system was designed so that the driver could apply additional force or torque to override the servo motor outputs.

Algorithm and Onset require some elaboration. Algorithms addressed both lateral warning and longitudinal control warning. Two lateral warning algorithms were compared. One alternative recently proposed is the Time-to-Line-Crossing (TLC) algorithm (Godthelp, 1984). TLC is calculated by:

$$TLC = \frac{D}{V}$$

where D = distance to lane line in meters (m), and V = lateral velocity in m/s.

For TLC, early onset was set by pre-pilot testing to TLC = 0.7 s or 700 ms prior to line crossing. Late onset was set to TLC = 0.0 s, i.e., at the moment of line crossing.

A second algorithm proposed by the project team for lateral warning is referred to hereafter as Time-to-Trajectory Divergence (TTD) algorithm. The TTD algorithm 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. See Appendix A for details. Early onset for the TTD with a trajectory arc separation of D = 0.55 m, a Lookahead of 1.2 s, and a TTD of 1.13 s. Late onset with the TTD algorithm used a value of D = 0.75 m, the same Lookahead of 1.2 s, and a TTD of 1.13 s.

For the longitudinal warning algorithm, a "slowing distance" approach was used. This algorithm provides a time delay budget to accommodate driver and machine delays, and then

## Table 3-1
## Interface Type and Directionality for the Lateral Warning System

| Interface Type | Non-Directional Condition | Directional Condition |
|---|---|---|
| Auditory Display | Alert: None (Insufficient time) | Alert: None (Insufficient time) |
| | Warn: 2000 Hz complex tone presented for 0.5 s duration in front of seated participant at a comfortable loudness relative to ambient cab noise. The tone was adjusted by the test participant at the beginning of the simulator run. | Warn: 2000 Hz complex tone for 0.5 s presented at the right of participant if vehicle departed toward right, or presented at 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 volume was adjusted by the test participant at the beginning of the simulator run. See notes below. |
| Haptic Display | Alert: None (Insufficient time) | Alert: None (Insufficient time) |
| | Warn: Vibrated steering wheel for 0.5 s with square wave at 10 Hz and 1.5 Nm magnitude. | Warn: 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 s. Torque was applied in the direction needed for recovery. For example, if the vehicle was departing the roadway 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. |

Notes:

For the auditory interface, 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.

## Table 3-2
## Interface Type and Directionality for the Longitudinal Warning System

| Display Type | Non-Directional Condition | Directional Condition |
|---|---|---|
| Auditory Display | Alert: At $D_{alert}$, 1000 Hz complex tone was presented for 0.5 s, centered in front of seated participant. | Alert: At $D_{alert}$, 1000 Hz complex tone was presented for 0.5 s, centered in front of seated participant. |
| | Warn: At $D_{warn}$, 1000 Hz complex tone, 0.5 s duration at a comfortable loudness relative to ambient cab noise, centered in front of seated participant until speed error ≤ 0. See Notes below. | Warn: At $D_{warn}$, 1000 Hz complex tone with repetition rate proportional to speed error in both pitch and frequency was presented at a comfortable loudness relative to ambient cab noise. The repetition rate was between 1 Hz and 25 Hz at 40 ms/cycle, 50% cycle time, 10 dB/ms onset rate from 0 dB to 80+ dB. Tone sounded with varying repetition until speed error ≤ 0. See Notes below. |
| Haptic Display | Alert: Vibrated accelerator pedal for 0.5 s with 10 Hz sine wave at 40 N magnitude. | Alert: Vibrated accelerator pedal with 10 Hz sine wave at 40 N for 0.5 s. |
| | Warn: Vibrated accelerator pedal for 0.5 s with 10 Hz sine wave of 40 N magnitude. | Warn: Generated accelerator pedal counterforce between 20 N and 250 N proportional to speed error. (See notes below). |
| Auditory-Haptic Combined | Both of the above concurrently. | Both of the above concurrently. |

Notes:

- In the directional warning case, the repetition rate of the auditory warnings was varied from 1 Hz to 25 Hz based on:

$$Repetition\ Rate\ (Hz) = 1 + 2\,\frac{(V_{current} - V_{design})}{V_{design}}$$

The on-time remained constant at 40 ms and only the off-time varied as the frequency went from 1 Hz to 25 Hz. For the auditory interface:

- Fundamental wave type: Sine
- Secondary wave type: Square
- Fundamental wave frequency: 1000 Hz

## TABLE 3-2 (Continued)

- Secondary wave frequency: 1200 Hz
- Amplitude of the fundamental wave was 6 dB above the secondary wave.
- Frequency range of the fundamental wave in the directional condition was from 1000 Hz to 2000 Hz. The tone frequency for the directional condition was calculated by:

$$Tone\ Frequency\ (Hz) = 10^{3.0\ +\ (.0120412) Repetition\ Rate}$$

- When the system was in neither warning nor alert mode, the following force equation was used on the accelerator pedal:

$$Force\ (N) = 10 + 60(position)$$

where accelerator position runs from 0 to 1.

When the system was in warning mode, an additional force was applied, so that total force is the sum of basic force plus the additional force. The additional force was calculated by:

$$Additional\ Force\ (N) = .25 + 9\ \frac{(V_{current} - V_{design})}{V_{design}}$$

- In the longitudinal case, Algorithm A is described in Appendix B. Algorithm B was identical except that, in addition, at the beginning of the warning, 0.5 s of pulse braking was applied equal to 10% of the push down in the brake pedal position.

determines the slowing distance required to achieve the desired speed for safe curve negotiation. See Appendix B for further details about the slowing distance algorithm and how it has been extended to provide driver support throughout a curve of non-constant curvature. For Early onset, the longitudinal or curve approach algorithm used an assumed deceleration level of $a_x = 0.17$ g while the Late onset assumed a deceleration level of $a_x = 0.3$ g. For both, the driver time delay budget was fixed at 2.5 s, a commonly used traffic engineering value (Pline, 1992).

The remaining independent variable was Hazard Magnitude. For the lateral disturbance on a straightaway, 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 s to simulate a light wind gust. The high magnitude lateral disturbance was initiated by a 38.7° steering wheel angle offset for 1.0 s to simulate a heavy wind gust. These disturbances were initiated by the in-vehicle experimenter who pressed a button as soon as the test participant turned away from the road scene to attend to the distractor task. For the longitudinal or curve departure hazard, the low magnitude hazard was accomplished by removing the speed sign ahead of an 800 ft-radius curve. The high hazard magnitude curve departure hazard was a 250 ft-radius curve whose speed sign had been removed.

### 3.1.3 Driving Simulator Scenarios

The project team developed a test scenario database sufficient to allow data collection for the five analyses presented earlier. The test scenario provided an orientation and practice segment followed by a course that takes approximately 35-40 min to drive if traveling at approximately 55 mph. The course simulates a two-lane rural undivided highway with approximately 10-ft wide lanes and light intermittent traffic. The course was made up of straightaway segments along with curves to the left and curves to the right of various radii. Three different curve radii are used: 1000, 800, and 250 ft-radius curves. Each curve segment or tile is designed as an elbow with a straight segment on either side of a quarter-circle of the designated radius. The virtual (invisible) line that joins the entering straightaway segment with the beginning of the quarter-circle curve is hereafter referred to as the *curve entrance line*. The virtual (invisible) line that joins the end of the quarter-circle curve with the exit straightaway segment is hereafter referred to as the *curve exit line*. Appendix C provides schematics of the test course and component tiles.

Participants began with an orientation and practice segment that allowed the test participant to get accustomed to the IDS and also to experience the CAS concepts, as appropriate (see Procedure section for details). Upon leaving the practice segment of the course, the formal part of the data collection began. The remaining portion of the course included normal driving segments as well as special hazard scenarios. The normal driving segments consisted of driving on a straightaway early and late in the scenario. Normal driving segments also include negotiating 1000 ft-radius and 800 ft-radius curves marked with posted speed and "curve ahead" warning signs early and late in the session. From these, data were collected to assess the impact of CAS support on normal lanekeeping and curve negotiation.

Beyond the normal driving segments, collision hazard scenarios were also included in the study. Muto and Wierwille (1982) found that repeated emergency response trials of the same type during an extended driving simulator session led to faster reaction times with each successive emergency. In order to avoid this "thrill a minute" effect, the simulator session was designed to support a one-trial-per-test participant test. Part of this "thrill a minute" effect is countermanded by the fact that each test participant received one and only one lateral roadway departure hazard and one and only one longitudinal (curve approach) roadway departure hazard. These scenarios were sufficiently different from one another that inclusion of both in a single data collection session was considered inconsequential. The hazards were also separated in time to minimize any cross-contamination. These roadway departure hazards are described next.

In the longitudinal or curve approach roadway departure hazard, the intent is to create a situation where the test participant approaches the curve at excessive speed. A standard simulator protocol of instructing a participant to maintain a specific speed (e.g., 55 mph) was used. This condition resulted in the participants approaching curves at speeds greater than those necessary to safely navigate the curve, which in this study, were rated for varying speeds ranging as low as 25 mph. It was anticipated, based upon previous experience in the simulator, that the participants would decelerate at varying rates due to entering curves at speeds above the safe rating for the curve. Excessive entry speed into a curve, therefore, initiated a countermeasure response from the system. While normal curves were preceded by curve warning signs and posted speed limits, the curve roadway departure hazards were not; i.e., it was as though the signs had been knocked down. In the "high hazard magnitude" case, the test participant came upon an unsigned 250 ft-radius curve. In the "low hazard magnitude" case, the test participant came upon an unsigned 800 ft-radius curve. In each case, the test participant had to successfully traverse the curve without exiting the roadway. As necessary, after the event was over, the participant was asked to return to 55 mph. Long, straight sections of road between curves further encouraged the participant to return to the 55 mph suggested speed.

The lateral roadway departure scenario involved driving along straight portions of the roadway while the participant performed an in-vehicle distractor task (see Procedure for description of the distractor task). The purpose of this distractor task was to force the driver to avert his/her visual attention from the road scene. The distractor task was presented after the test participant passed the curve exit line on each curve through the simulator course. This introduced the distractor task to the test participant. During one implementation of the distractor task, a vehicle lateral offset (simulating a gust of wind) was generated so that the simulator vehicle laterally deviated from the roadway. A high roadway departure hazard was associated with a high-magnitude lateral offset while a low roadway departure hazard magnitude was associated with a low-magnitude lateral offset. It was anticipated that the subject vehicle would be more apt to deviate from the roadway during these "wind gusts" when distracted, than when the participants' full attention was devoted to driving. Thus, a countermeasure response was expected that would serve to alert the driver.

Both scenarios gauged the effectiveness of the countermeasures in preventing run-off-road crashes. The first scenario pertained to the effectiveness of successfully navigating curves of various speed ratings, while the second scenario ranked countermeasures' effectiveness in maintaining a safe lane position on the roadway.

During the experimental drives, the IDS was configured to allow for drivers to cut the center lines during curve negotiation. The curve cutting logic operated the same for both TLC and TTD. The "optimal" steering direction was computed and compared with the driver's steering direction. If the driver was cutting the curve by steering more sharply than the optimal trajectory, but in the appropriate direction (i.e., left vs. right), responses from both the TLC and TTD algorithms were suppressed. This suppression allowed for a limited degree of drift toward the inside of curves without triggering a countermeasure response. However, if the vehicle drifted too far toward the inside of the curve, the sign of the optimal trajectory changed (i.e., instead of steering left to follow the curve, the optimal trajectory indicated that the driver should steer right to return to the lane center). At this point, the curve cutting logic was overridden, and a response from the CAS countermeasure was triggered.

### 3.1.4 Procedure

Upon arrival at the University of Iowa Driving Simulator, participants read an information summary sheet (see Appendix D) followed by the informed consent form (see Appendix E). Participants were then presented with audio taped descriptions of the study. These tapes provided information on how the warning system (if any, depending upon the participants' random assignment to experimental conditions) operated. They are included in Appendix F. Participants' questions were answered by the research host following the completion of the taped summary. Participants then completed a general demographic survey.

Upon completion of the initial briefing and consent form, participants were escorted to the Iowa Driving Simulator. The specific scripts for the in-vehicle instructions used for each condition are included in Appendix G. The experimenter sat in the backseat behind the front passenger's seat. A video monitor was present in the back seat with the experimenter and it displayed the participant's face during the simulator session. Once inside the vehicle, participants were shown the various vehicle controls and their operation. The experimenter then reviewed the warning systems (if any) that would be in use. Participants were also given an opportunity to become familiar with the distractor task. The distractor task required the participant, during the drive, to turn around and look over their right shoulder to count the number of horizontal bars printed on an index card. There were between 4 and 7 horizontal bars on each card. The bars themselves were 9.2 cm by 1.2 cm and were printed in black ink on 4 in by 6 in white index cards. The participant responded verbally as quickly as possible while continuing to drive. The distractor task was presented after the driver passed the curve exit line on each curve, not just when the lateral offset was presented. The distractor task's purpose was to force participants to avert their attention from the roadway so that a brief lateral disturbance (simulated side wind gust) could be introduced.

Participants were informed that the first section of the drive would be used as practice so that they could become familiar with the vehicle and its warning systems (if present). When the simulator was readied, participants were told to begin the drive. Participants were instructed to make deviations (swerves) to the left and right so they could get better acquainted with the vehicle's steering dynamics and with the lateral warning system. Following the first (100 ft-radius) curve, the distractor task was first employed. At the end of the practice portion of the drive, participants were asked about how comfortable they were with the vehicle and how well they understood the warning systems. At this point, the experimenter told participants that the practice component was completed and that they were to continue driving.

Participants continued driving the Carmel database or course. During the experimental drive, conversation between participants and the in-simulator experimenter was kept to a minimum. As explained earlier, following each curve, the distractor task was employed. (If participants did not have the vehicle in sufficient control coming out of the curve, the distractor task was not employed. However, this was rare.)

After completing the fourth curve, the distractor task was employed. It was at this time that the experimenter activated the lateral disturbance by depressing a button concealed in the backseat. Once participants regained complete control of the vehicle, the experimenter again depressed the button in order to mark the end of the event in the data file.

The roadway departure hazard at a curve was presented toward the end of the simulator session. The high hazard magnitude, 250 ft-radius, curve was the last curve encountered since it was believed this curve might lead to roadway departures. The low hazard magnitude, 800 ft-radius curve was presented as the next-to-last 800 ft-curve location.

If a roadway departure crash occurred, this event was recorded. The experimenter then reset the simulator to a restart point prior to the hazard location and the simulation began again. This procedure was followed in order to insure that data would be available for analysis of successful collision avoidance maneuvers as well as a tally of collision occurrences.

Upon completion of the simulator session, participants who had some form of CAS support were given a debrief that included a subjective assessment questionnaire, the contents of which are presented in Appendix H. In addition, all participants answered a set of University of Iowa Driving Simulator Facility questions. These additional questions address issues of perceived simulator fidelity, motion sickness, and other general points not specific to this particular study. These items were administered at IDS, but will not be discussed further in this report as they are not germane to the CAS concept evaluations that were undertaken in this study. Participants were thanked for their participation, paid, and released.

### 3.1.5 Independent Variables and Experimental Design Strategy

The independent variables manipulated in this study are presented in Table 3-3. The design matrix for this study is provided in Appendix I. This matrix defines the assignment of participants to experimental conditions. The control group of 16 participants who did not have CAS support (but did experience either high or low magnitude lateral and curve approach roadway departure hazards) can be identified by the assignments with no auditory and no haptic display. Note that while these participant assignments have codes for the factors Directionality, Onset, and Algorithm, they have no meaning. On the other hand, for the remaining 48 participants who have some form of CAS support, all independent factors or variables have meaning. Additional details of the experimental design are provided in the Results sections for each analysis. For the sake of clarity, dependent measures appropriate to each analysis are described in the Results section for each analysis.

**Table 3-3**
**Table of Independent Factors for Task 3 Driving Simulator Study**

| Factor | Code | |
|---|---|---|
| | - | + |
| 1. Auditory Display System | NO | YES |
| 2. Haptic Display System | NO | YES |
| 3 Hazard Magnitude | LOW (equivalent steering wheel angle offset of 19.35° clockwise for 1.0 s to simulate light wind gust for lateral scenario; 800 ft.-radius curve for longitudinal scenario) | HIGH (equivalent steering wheel angle offset of 38.7° clockwise for 1.0 s to simulate heavy wind gust for lateral scenario; 250 ft.-radius curve for longitudinal scenario) |
| 4 Directionality | NON-DIRECTIONAL | DIRECTIONAL |
| 5 Warning Onset | EARLY (TTD = 1.13 s, with D = 0.75 m, lookahead of 1.2 s and 0.7 s TLC for lateral scenario; 0.17 g assumed deceleration and 2.5 s driver time delay budget for longitudinal scenario) | LATE (TTD = 1.13 s, with D = 0.55 m, lookahead of 1.2 s and 0.0s TLC for lateral scenario; 0.3 g assumed deceleration and 2.5 s driver time delay budget for longitudinal scenario) |
| 6 Algorithm | "A" (TLC for lateral scenario; no pulse "wake up" braking for longitudinal scenario) | "B" (TTD for lateral scenario; pulse "wake up" braking for 0.5 s at 10% of pedal pressure for longitudinal scenario |

## 4.0 Results -- General Lane Keeping Early and Late in the Session

It is important to determine the effects of CAS support on normal driving. Ideally, a CAS should not introduce excessive driver workload or promote unsafe or imprecise driving. To address these issues for lanekeeping on a straightaway, data were collected in the following conditions during the simulator run, termed "Early" and "Late":

Early: Approximately middle 3 minutes of driving on the first straightaway after the 1000-ft curve that indicates the end of orientation driving;

Late: Approximately middle 3 minutes of driving on the last straightaway segment prior to entering the last 250 ft curve.

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 reversals 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.

The dependent measures described above were analyzed using several inferential statistical methods. Analysis of Variance (ANOVA) methods were applied using the Statistical Analysis System (SAS) General Linear Models (GLM) procedure and Ryan-Einot-Gabriel-Welsh post-hoc comparisons (SAS Institute, 1992). The model included the following 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, t-tests were conducted to compare the control group of participants who had no CAS support with those that did have CAS support. These t-tests used the approximate t statistic with Satterwaite's approximation for the degrees of freedom when the variances were unequal. Given the large number of tests that can be conducted (39 per dependent measure), there is an increased risk of Type I errors (i.e., declaring significant differences by chance). This Type I error risk is managed by adjusting the per-comparison criterion for significance but most procedures result in an increase in Type II error risk (i.e., declaring no differences when real differences exist) (Keppel, 1991). To balance off these competing error types, a per-test significance level of .0025 was selected. While somewhat arbitrarily chosen, this significance level roughly corresponds to the simplest form of Bonferroni correction for experiment-wise error where the desired alpha level is increased to .10 (to improve the power of the tests and reduce Type II error) and then divided by the number of tests per dependent measure (39), i.e., 0.10/39 = .0025.

### 4.1 Early Lanekeeping Results

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 4-1, Early segment). 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 (cf. MacDonald and Hoffmann, 1980). 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 4-2, 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 4-3).

A note on lane exceedences to the left is in order. The Iowa Driving Simulator 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.

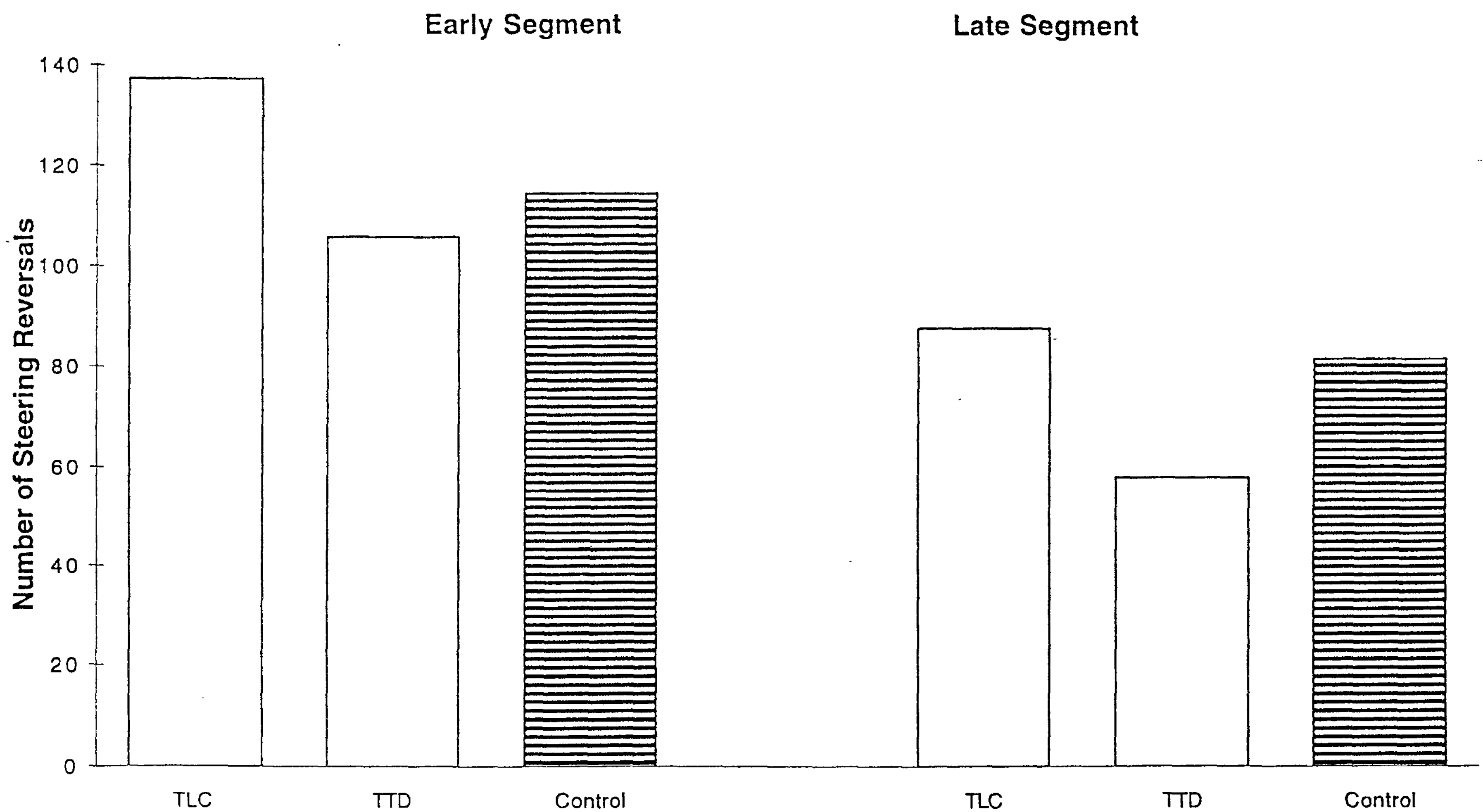



**Figure 4-1 MEAN NUMBER OF STEERING REVERSALS OVER 3-MINUTE STRAIGHTAWAY DRIVING SEGMENTS, EARLY AND LATE**

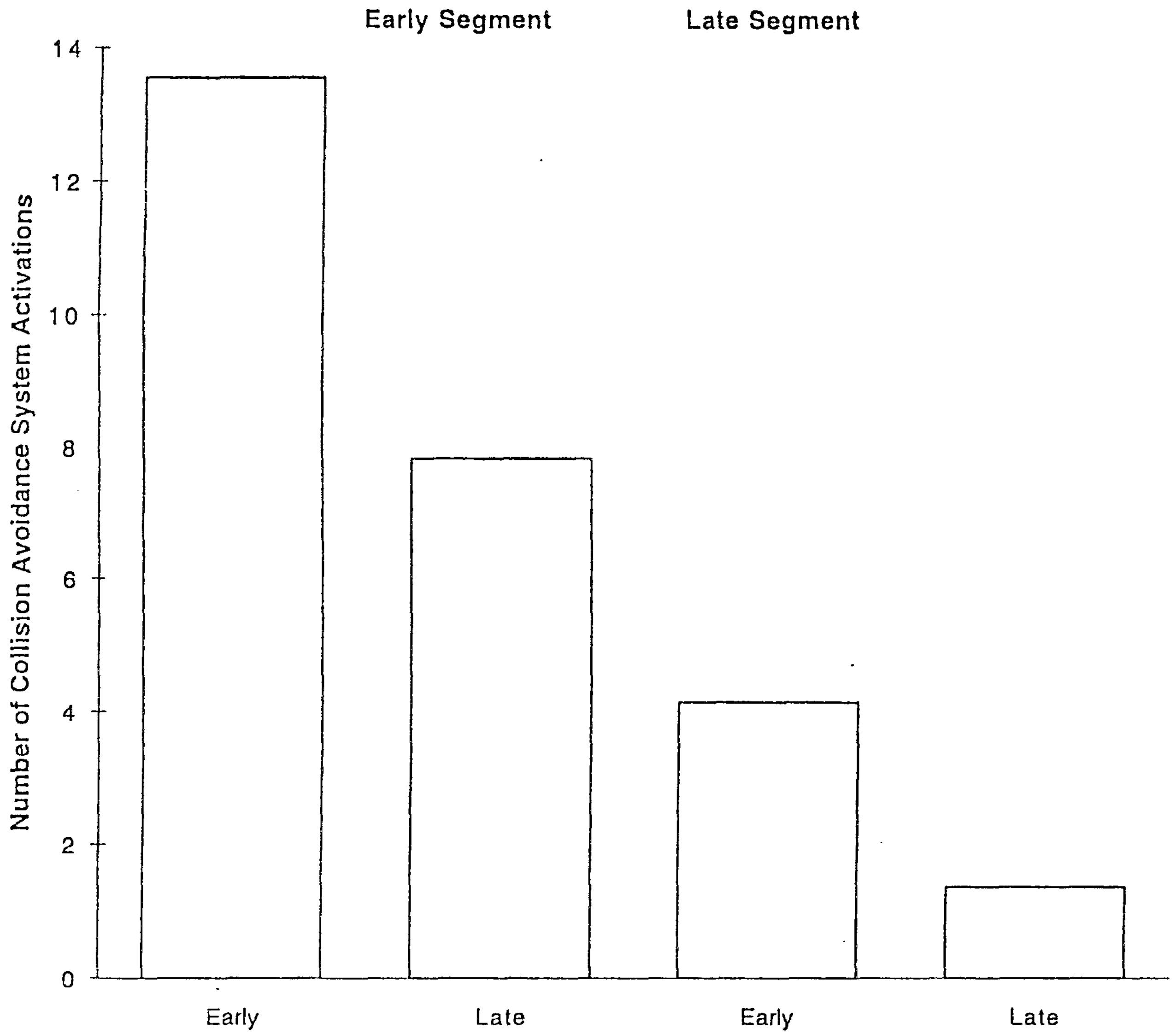



**Figure 4-2 MEAN NUMBER OF CAS ACTIVATIONS AS A FUNCTION OF CAS ONSET, EARLY AND LATE STRAIGHTAWAY DRIVING SEGMENTS**

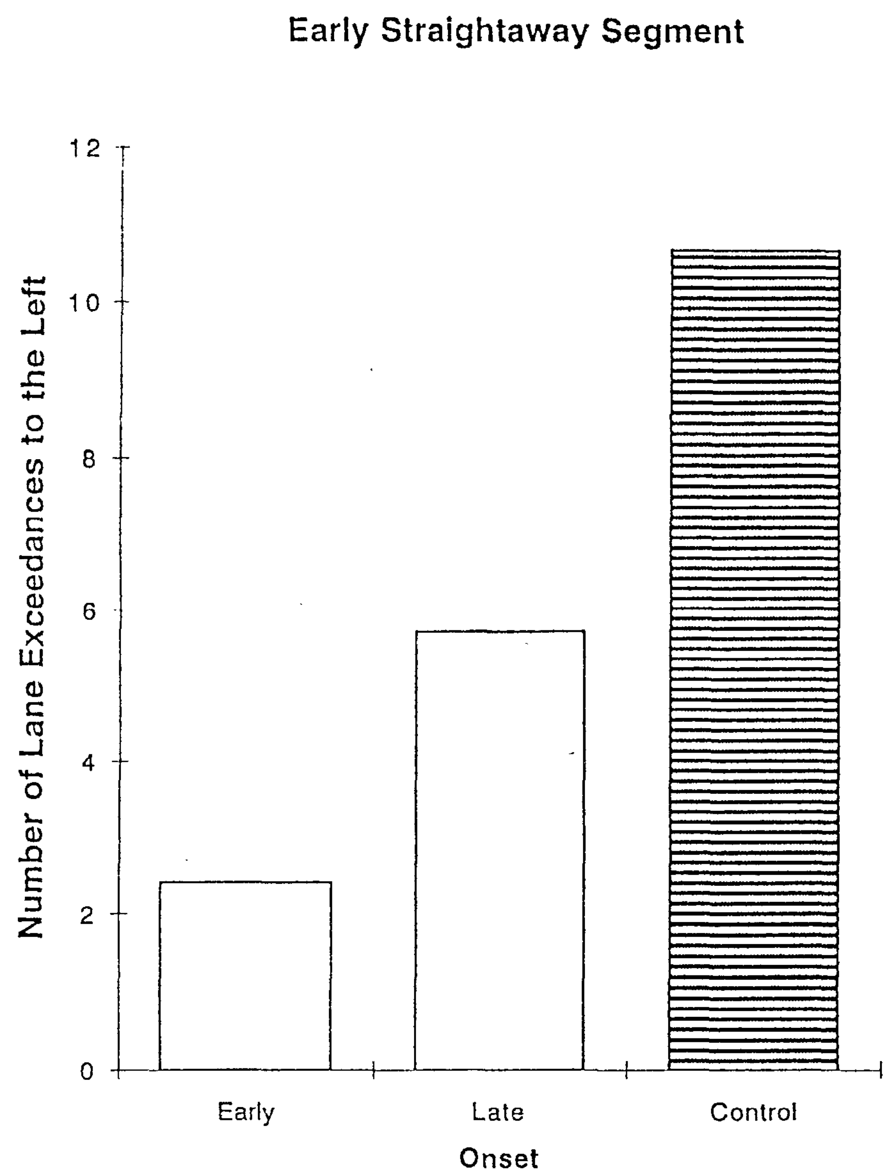



**Figure 4-3** **MEAN NUMBER OF LANE EXCEEDENCES TO THE LEFT AS A FUNCTION OF CAS ONSET, EARLY STRAIGHTAWAY SEGMENTS**

ANOVA results indicated no other significant effects for the Early straightaway driving segment.

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.

### 4.2 Late Lanekeeping Results

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 4-1, 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 4-2 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.

### 4.3 Conclusions and Recommendations based on General Lanekeeping Results

The general conclusions drawn from the general lanekeeping data analysis are the following:

- CAS support is associated with more precise lanekeeping under normal straightaway driving conditions (for both Early and Late driving segments).

- TLC causes relatively more driver workload than TTD (for both Early and Late driving segments).

- Early Onset settings lead to more CAS activations (a potential source of driver irritation) both early and late in the driving segments but it also leads 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.

Based on this pattern of results only, it is recommended that the following concepts be retained for further consideration in roadway departure collision countermeasures:

- CAS;

- TTD;

- Early Onset;

- Directional Displays;

- Consider Auditory Interface and Haptic Interface options further. A combination of the two does not appear beneficial.

## 5.0 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 (a lateral offset of either low or high magnitude) while the test participant was engaged in an in-vehicle distractor task (see Section 3-1 Methods Section.) 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 initial lane deviation to the right (how far over the vehicle got before its lateral motion was stopped), in
    - 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), ms
    - Steering RT after disturbance onset (indicator of delay in initiating evasive steering), ms
    - Max initial lane deviation to the left, i.e., in direction of initial recovery maneuver (to indicate stability of maneuver, in particular overshoot potential), in
    - 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), in

- **General Measure of Merit: Proportion of Crashes Avoided**

The dependent measures described above were analyzed using several inferential statistical methods. Analysis of Variance (ANOVA) methods were applied using the Statistical Analysis System (SAS) General Linear Models (GLM) procedure and Ryan-Einot-Gabriel-Welsh post-hoc comparisons (SAS Institute, 1992). The model included the following main effects and their two-way interactions:

- Interface type (auditory, haptic, or combined),
- Hazard magnitude (low or high),
- 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, t-tests were conducted to compare the control group of participants who had no CAS support with those that did have CAS support. These t-tests used the approximate statistic with Satterwaite's approximation for the degrees of freedom when the variances were unequal. Given the large number of tests that can be conducted (39 per dependent measure), there is an increased risk of Type I errors (i.e., declaring significant differences by chance). This Type I error risk is managed by adjusting the per-comparison criterion for significance but most procedures result in an increase in Type II error risk (i.e., declaring no differences when real differences exist) (Keppel, 1991). To balance off these competing error types, a per-test significance level of .0025 was selected.

## 5.1. Results: Initial Movement Based on the Disturbance

Consider first the initial movement after the lateral disturbance onset. 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 31.9 and 62.7 in 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 5-1). 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.

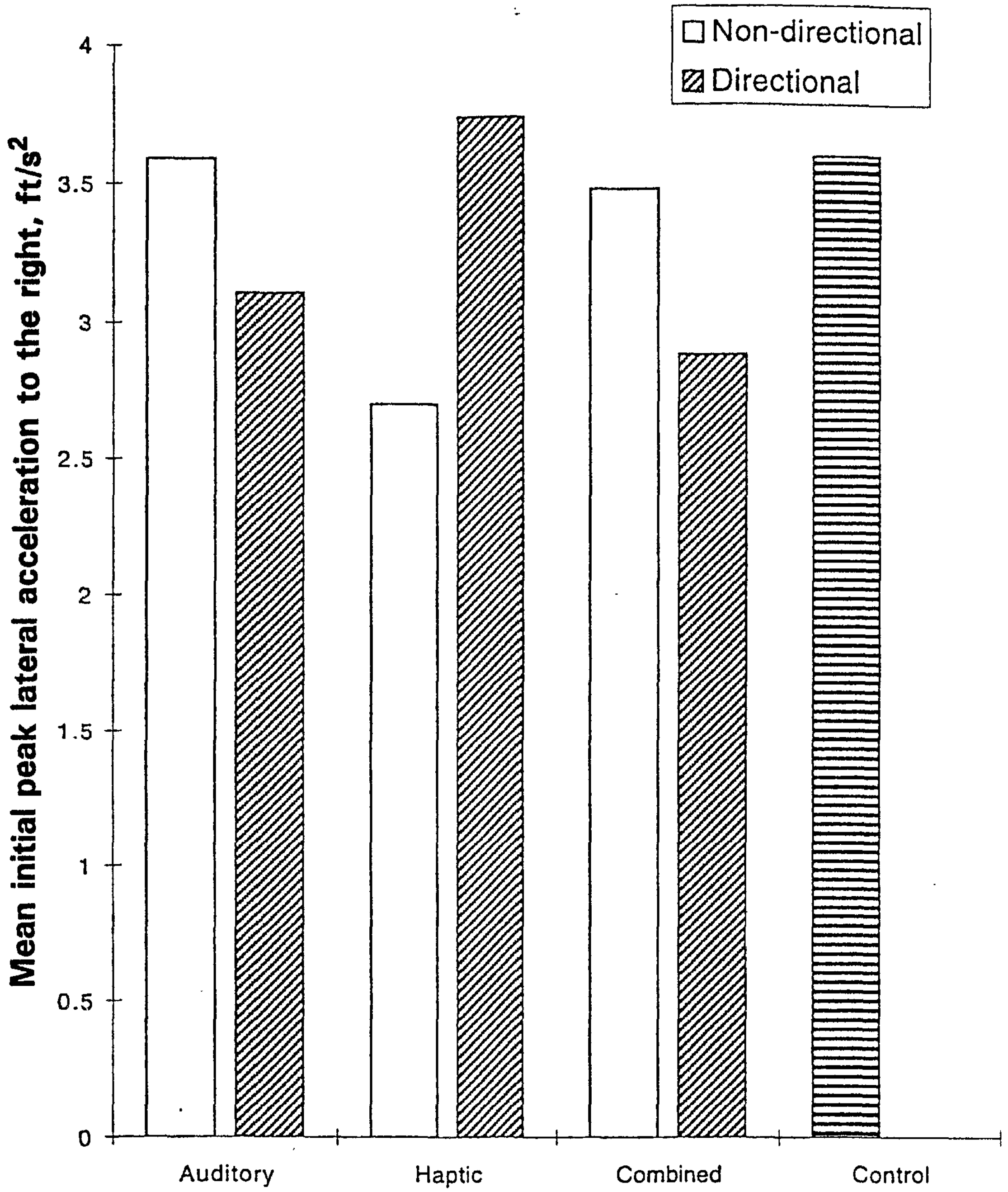



**Figure 5-1 MEAN INITIAL PEAK LATERAL ACCELERATION TO THE RIGHT ($FT/S^2$) AS A FUNCTION OF BOTH INTERFACE TYPE AND DIRECTIONALITY**

### 5.2. Results: 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 5-2, 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 5-3, 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 5-4). Steering reaction times are earlier for the non-directional 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

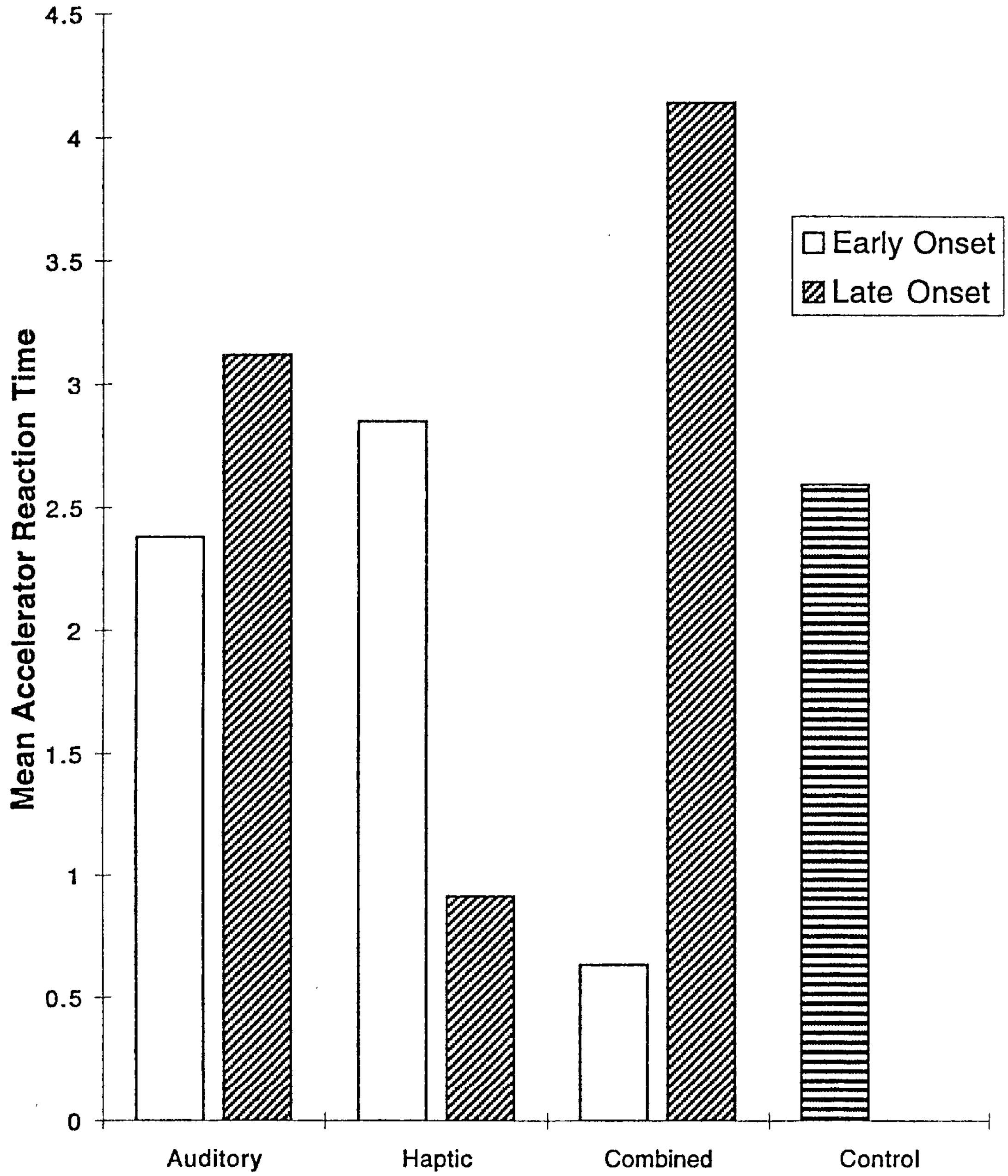



**Figure 5-2** **MEAN ACCELERATOR REACTION TIME (RT) (SEC AFTER DISTURBANCE ONSET) AS A FUNCTION OF BOTH INTERFACE TYPE AND ONSET**

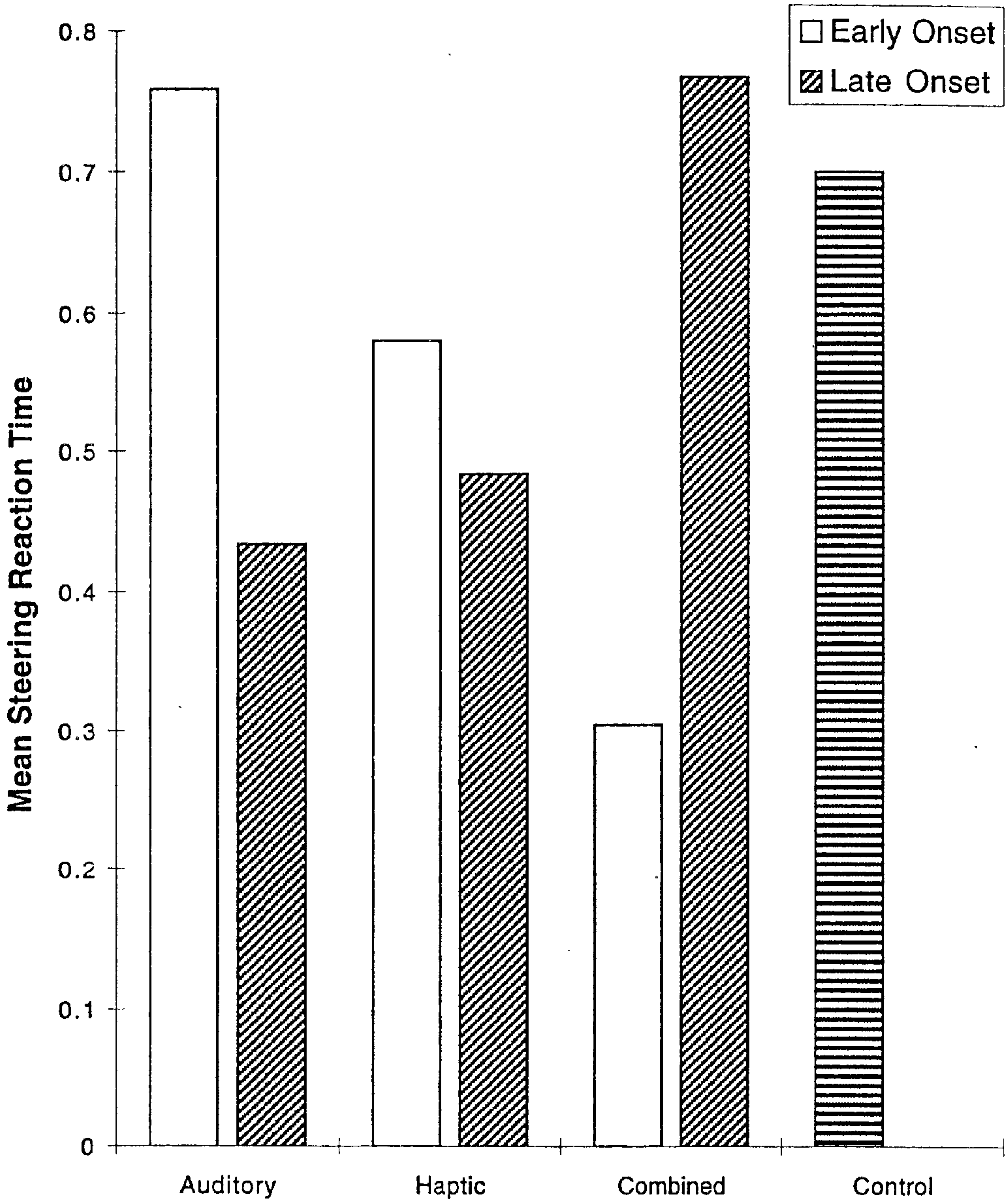



**Figure 5-3 MEAN STEERING REACTION TIME (RT) (SEC AFTER DISTURBANCE ONSET) AS A FUNCTION OF BOTH INTERFACE TYPE AND ONSET**

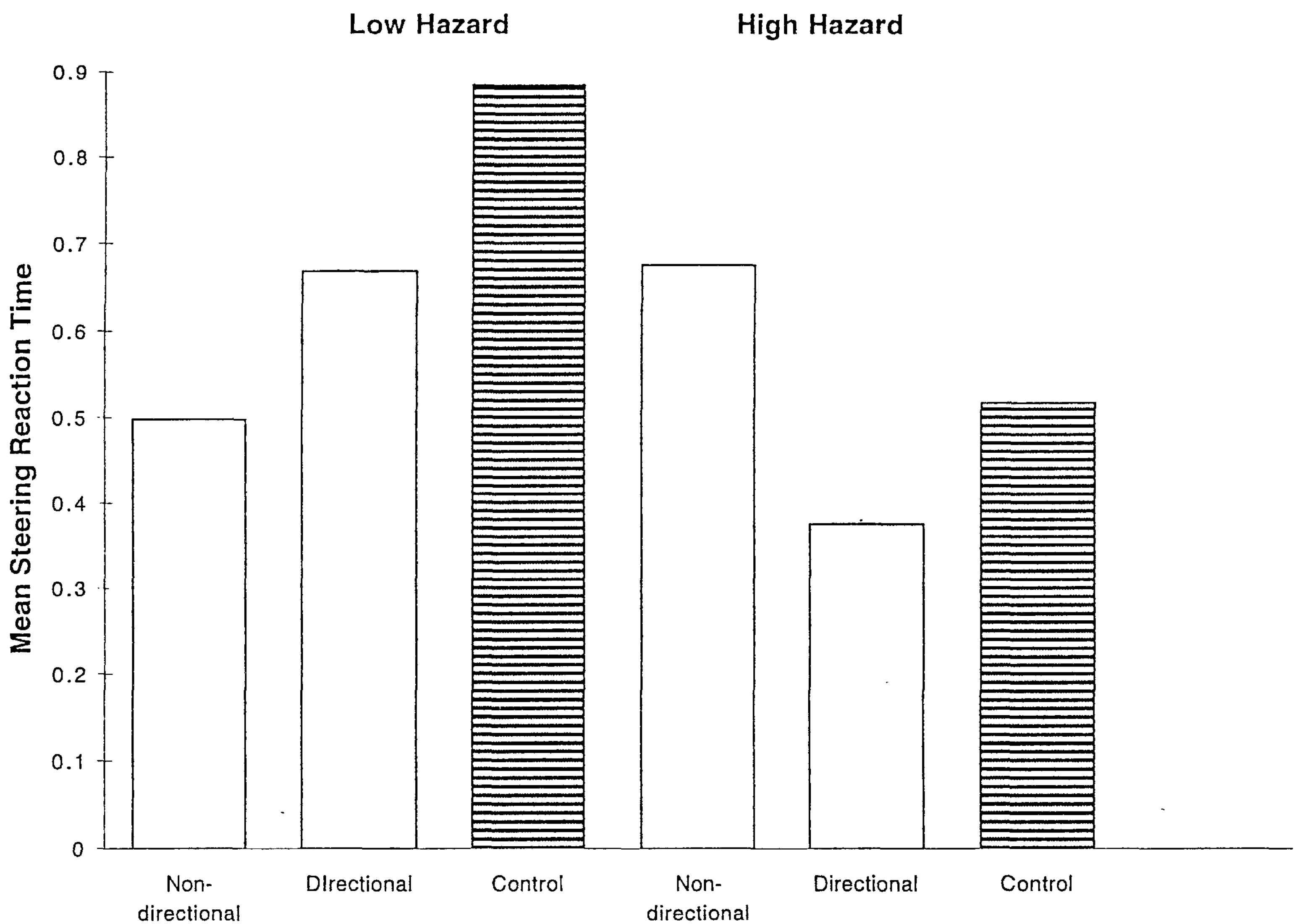



**Figure 5-4** **MEAN STEERING REACTION TIME (RT) (SEC AFTER DISTURBANCE ONSET) AS A FUNCTION OF BOTH HAZARD MAGNITUDE AND DIRECTIONALITY**

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. This data implies 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 5-5). 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.

### 5.3. Results: 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 5-6). 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. This data indicates 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. Some of these pairwise comparisons were reported on earlier. 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

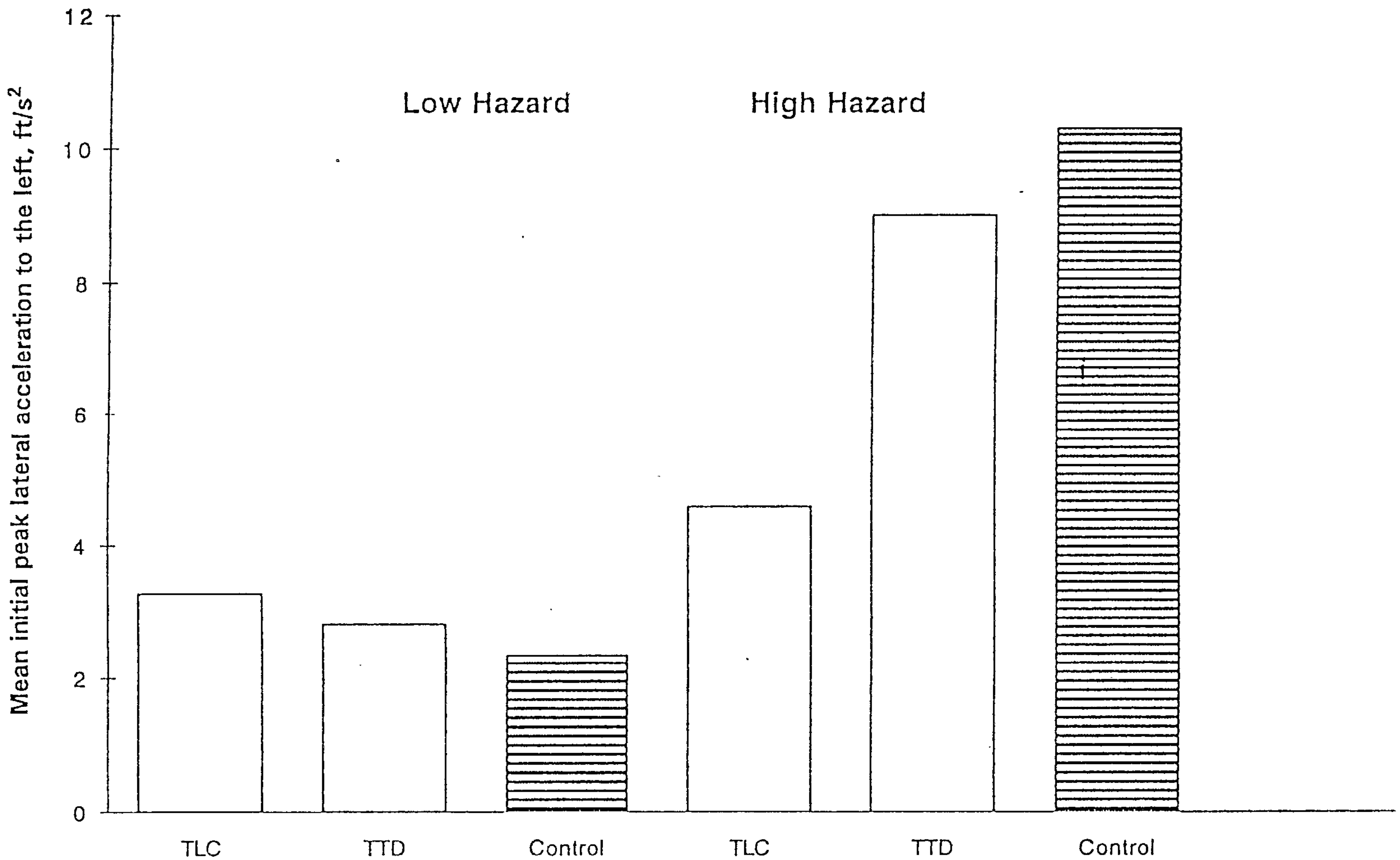



**Figure 5-5** **MEAN INITIAL PEAK LATERAL ACCELERATION TO THE LEFT, FT/S , AS A FUNCTION OF HAZARD MAGNITUDE AND ALGORITHM, WITH CONTROL GROUP DATA INCLUDED FOR REFERENCE**

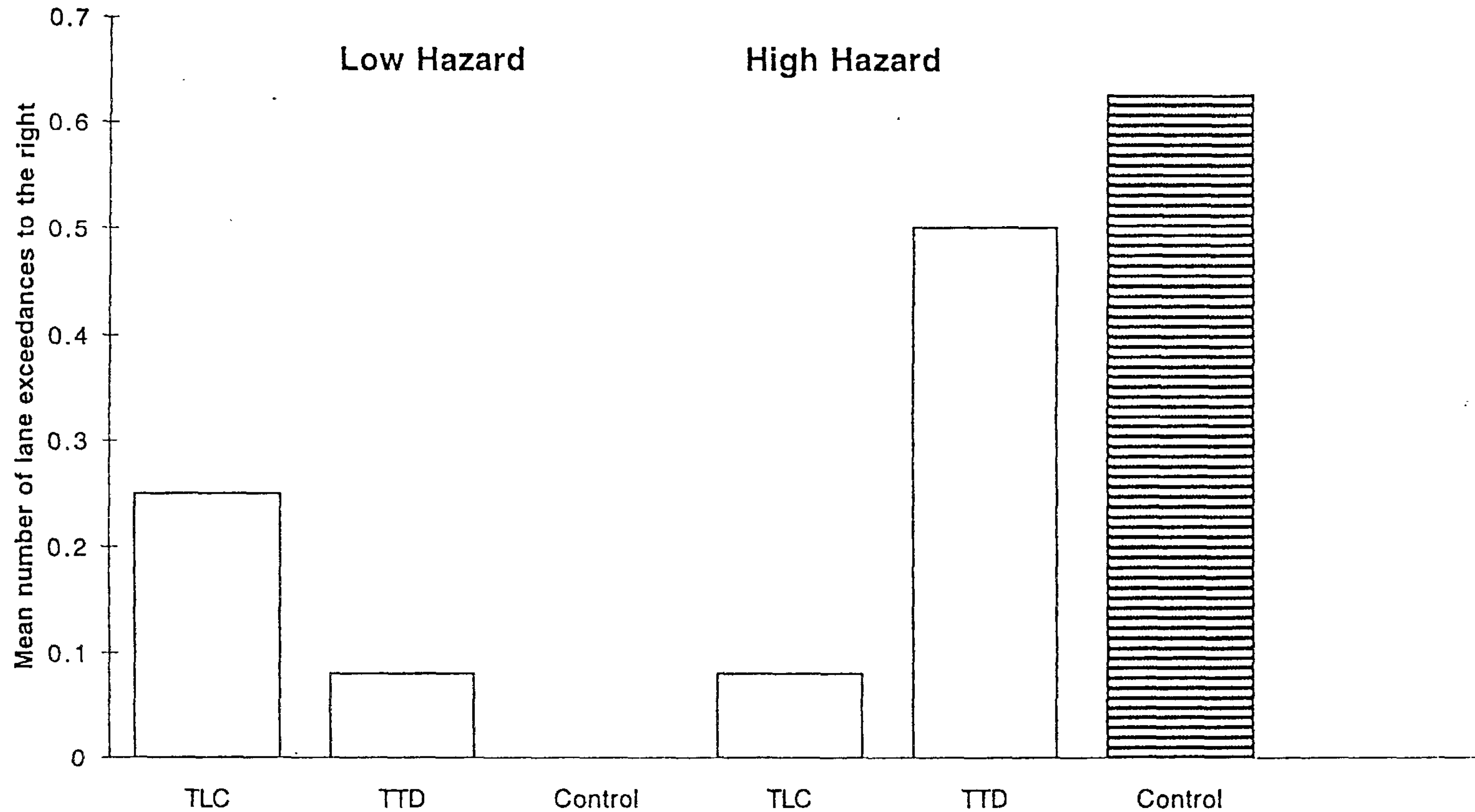



**Figure 5-6 MEAN NUMBER OF LANE EXCEEDENCES TO THE RIGHT AS A FUNCTION OF HAZARD MAGNITUDE AND ALGORITHM, WITH CONTROL GROUP RESULTS INCLUDED FOR REFERENCE**

may also be interpreted to indicate that the CAS concepts tested did not degrade collision avoidance either.

### 5.4 Results: Crashes Avoided

The last analysis of results examines the number of crashes that occurred in the simulator while the driver was distracted. Figure 5-7 indicates the number of crashes and non-crashes out of 16 test participants in each of the Interface groups and the control group of drivers without CAS support. As can be seen in the figure, the control participants had a greater number of crashes than any of the CAS groups. 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 the previously stated .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.

### 5.5 Conclusions and Recommendations Based on Lateral Disturbance Results

The pattern of results for the lateral disturbance data 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.

- 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.

- 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. Directional displays appear to be beneficial in high hazard situations.

- The TLC algorithm appears to be of greater benefit than TTD under high hazard situations.

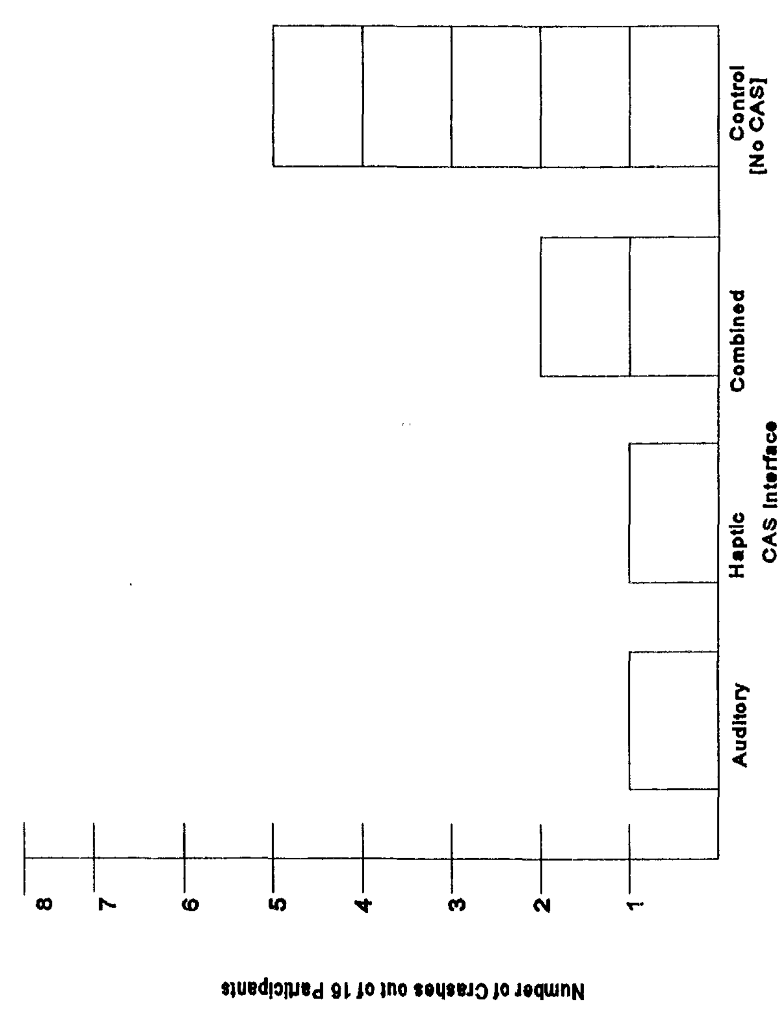



**Figure 5-7 NUMBER OF CRASHES WHILE THE TEST PARTICIPANT WAS DISTRACTED**

Based on this pattern of results, it is recommended that the following CAS concepts be retained for further consideration as roadway departure collision countermeasures:

- CAS (as opposed to no driver support);
- TLC (for terminus condition collision avoidance);
- Early onset;
- Directional displays, with combined displays;
- Consider haptic and the combined (auditory+haptic) Interface options further.

## 6.0 Results -- General Curve Negotiation Early and Late in the Session

It is important to determine the effects of CAS support on normal driving. Ideally, a CAS should not introduce excessive driver workload or promote unsafe or imprecise driving. To address these issues for curve negotiation, data were collected in the following conditions during the simulator run, termed "Early" and "Late":

Early: The first 800-ft radius curve encountered after the training segment;

Late: The last 800-ft radius curve prior to the end of the experiment;

The following measures were recorded and analyzed:

### Curve Approach

- Curve Entrance Speed, measured at curve entrance line, i.e., the beginning of the quarter-circle portion of each curve after the straight line approach, ft/s
- Max deceleration approaching curve, measured over a distance of 1250 ft before the curve entrance line, $ft/s^2$
- Mean deceleration approaching curve, measured over a distance of 1250 ft before the curve entrance line, $ft/s^2$
- Accelerator pedal RT after D_alert (if presented), ms
- Brake RT after D_alert (if presented), ms
- Accelerator pedal RT, after D_warn (if presented), ms
- Brake pedal RT, after D_warn (if presented), ms

### Curve Traversal (measures taken after curve entrance line and until curve exit line)

- Mean speed through curve, ft/s
- Lane Position Standard Deviation, in
- Steering reversals of 2 degrees or greater through curve, count

The dependent measures described above were analyzed using several inferential statistical methods. Analysis of Variance (ANOVA) methods were applied using the Statistical Analysis System (SAS) General Linear Models (GLM) procedure and Ryan-Einot-Gabriel-Welsh post-hoc comparisons (SAS Institute, 1992). The model included the following main effects and their two-way interactions:

- Interface type (auditory, haptic, or combined),
- 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, t-tests were conducted to compare the control group of participants who had no CAS support with those that did have CAS support. These t-tests used the approximate t statistic with Satterwaite's approximation for the degrees of freedom when the variances were unequal. Given the large number of tests that can be conducted (39 per dependent measure), there is an increased risk of Type I errors (i.e., declaring significant differences by chance). This Type I error risk is managed by adjusting the per-comparison criterion for significance but most procedures result in an increase in Type II error risk (i.e., declaring no differences when real differences exist) (Keppel, 1991). In an attempt to balance off these competing error types, a per-test significance level of .0025 was selected.

At the outset it should be noted that, with very few exceptions, drivers did not brake or change their accelerator pedal angle sufficient to be recorded as a reaction for this normal driving scenario. This occurred because the drivers approached the curve in an acceptable manner. This was true for both Early and Late curves. Thus, no differences in various CAS conditions are reported with regard to brake or accelerator reaction times.

While curve traversal made use of the same algorithms as were used for lanekeeping (TLC and TTD), there were modifications made to allow for "cut-in" or lane exceedences, as described in Section 3.0. Since lane line exceedences are common in normal driver curve negotiation strategies they should not be considered unplanned lane exceedences. Thus, lane exceedences are omitted from consideration in this report.

### 6.1 Early 800 ft-radius Normal Curve Negotiation Results

Consider first the Early 800 ft-radius curve negotiation data. In the Early 800 ft-radius curve negotiation, only two significant differences were found among the various CAS support conditions. Lane standard deviation was statistically significantly different as a function of algorithm, $F(1,33) = 4.21, p < .049$. As indicated in Figure 6-1, the TLC algorithm was associated with slightly larger lane standard deviations, on average, than the TTD algorithm (means of 8.75 inches and 7.33 inches, respectively). This difference, however, does not appear to be of any practical significance. For reference, the control group of participants without CAS support had a mean lane standard deviation of 10.21 inches. While substantially larger than either algorithm condition, pairwise comparisons with this control revealed no significant differences.

In terms of steering reversals through the curve, a significant interaction was found between Interface and Algorithm, $F(2, 33) = 3.36, p < .048$. Figure 6-2 presents the means of the interaction. An auditory interface with the TTD algorithm produced, on average, the smallest number of steering reversals, while the differences among the remaining combinations were small. The reason for this pattern of results is unknown. For reference, the number of steering reversals, on average, generated by the control group of drivers without CAS support was 17.9. Pairwise comparisons of each CAS support group condition with the control condition were not

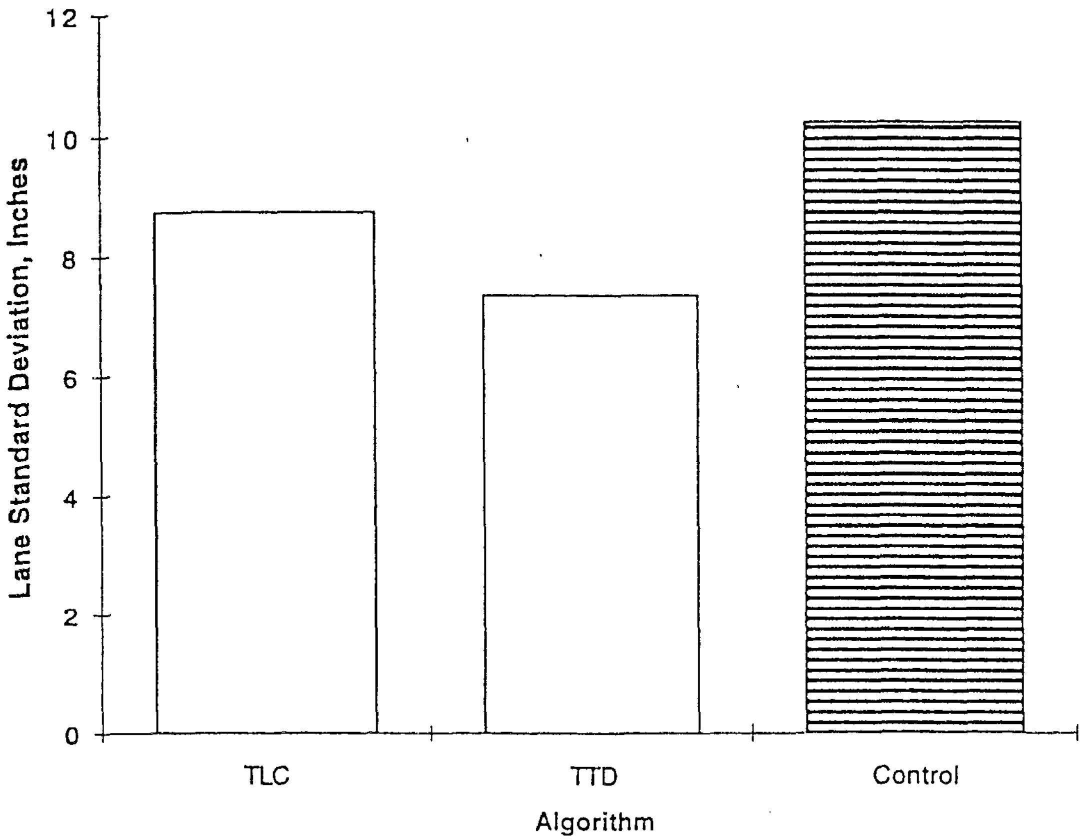



**Figure 6-1** **MEAN LANE STANDARD DEVIATION THROUGH EARLY 800 FT-RADIUS CURVE AS A FUNCTION OF CAS ALGORITHM**

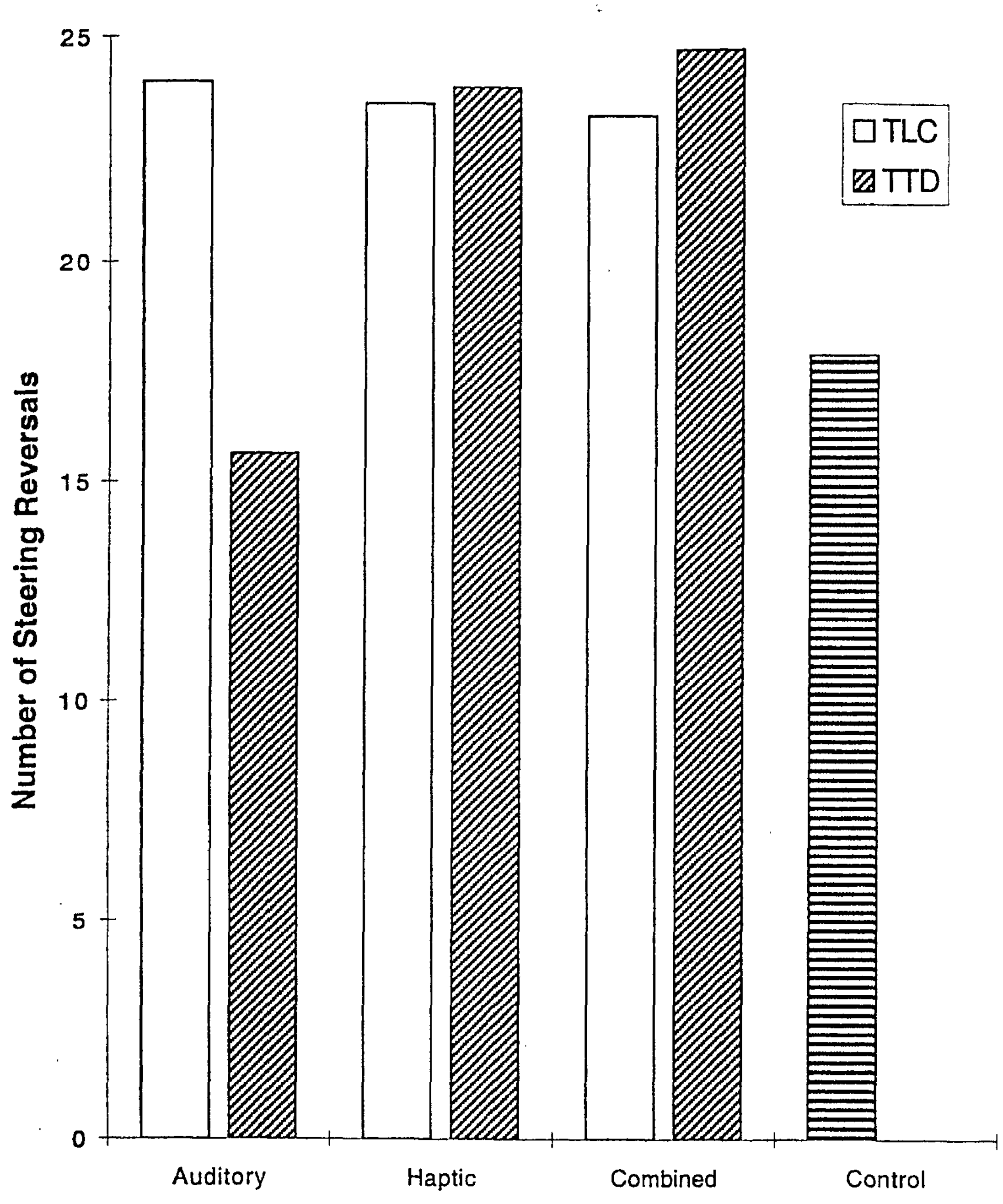



**Figure 6-2** **MEAN NUMBER OF STEERING REVERSALS WHILE DURING THROUGH EARLY 800 FT-RADIUS CURVE AS A FUNCTION OF CAS INTERFACE TYPE AND ALGORITHM TYPE**

statistically significant at a per-comparison significance level of .0025 or beyond (see earlier discussion of comparisons with control). No other significant ANOVA effects were found.

For the Early 800 ft curve negotiation data, pair comparisons of the various CAS support conditions 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 used. At this significance level, only two significant differences were found. The mean number of steering reversals was greater with the haptic, non-directional CAS than with the control group (means of 27.6 and 17.9, respectively). The mean number of steering reversals was also reliably greater with the Non-directional, early onset CAS than with the control group (means of 25.3 and 17.9, respectively). Collectively, this is taken as evidence that the CAS support conditions had no substantial impact on driving in the Early curve negotiation other than some increased steering activity during the traversal through the curve itself.

### 6.2 Late 800 ft-radius Normal Curve Negotiation Results

ANOVA procedures were applied to the dependent measures collected during the Late 800 ft-radius curve negotiation and statistically significant effects were found for mean deceleration approaching the curve entrance line. Interface had a significant effect, $F(2,33) = 3.51, p < .042$, with mean decelerations of 1.18, 1.47, and 1.13 ft/s$^2$ for the auditory, haptic, and combined interfaces, respectively (see Figure 6-3). These differences appear to be of no practical significance. For reference, the mean deceleration of the control group of drivers without CAS support was $M = 1.10$ ft/s$^2$ and was not significantly different from any of the CAS group means at a per-test significance level of .0025.

There was a significant Directionality x Onset interaction, $F(1, 33) = 4{,}40, p < .044$ on mean deceleration levels. Figure 6-4 shows the means for this interaction. Again, these differences are small and appear to be of no practical significance.

In the late curve negotiation segment, there was also a significant Interface x Directionality interaction on number of steering reversals, $F(2, 33) = 3.31, p < .05$. Figure 6-5 presents the mean number of steering reversals for this interaction. The differences, while reliable are considered small except for the combined interface, non-directional display system which had fewer steering reversals, on average, and so may involve less steering workload. On the other hand, if the combined interface was more confusing or provided information overload, research literature (MacDonald & Hoffman, 1980) suggests that when in-vehicle demand increases, the number of steering reversals decreases as the driver attempts to cope with the overload and is distracted from the lanekeeping task. This hypothetical interpretation should be the focus of further research and is offered as a tentative explanation pending more information. Note that there were no statistically significant differences among pairwise comparisons of CAS support means with the mean of the control group of drivers without CAS support. No other ANOVA results were significant for the Late 800 ft curve negotiation.

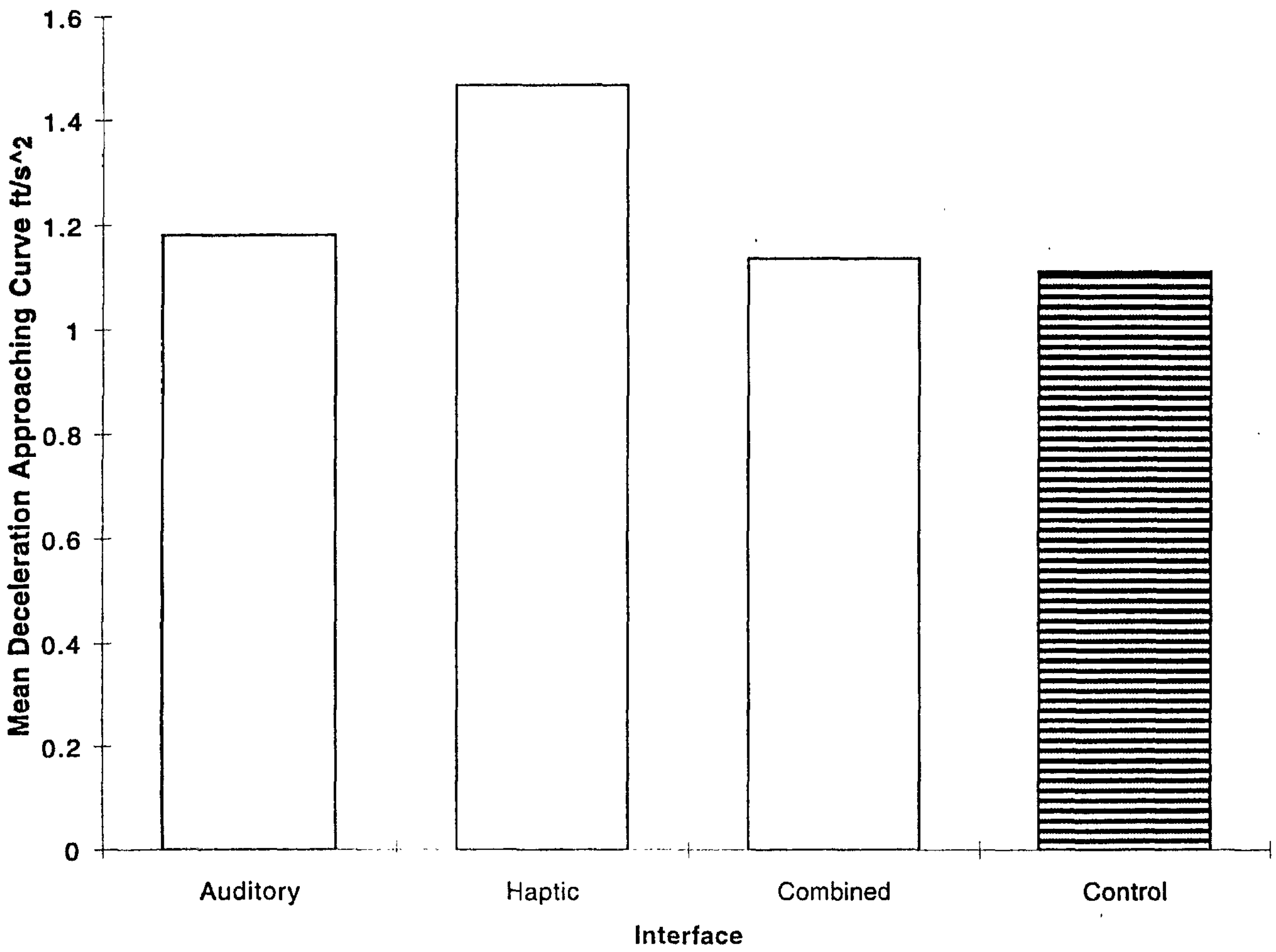



**Figure 6-3 AVERAGE MEAN DECELERATION APPROACHING LATE 800 FT-RADIUS CURVE AS A FUNCTION OF CAS INTERFACE TYPE**

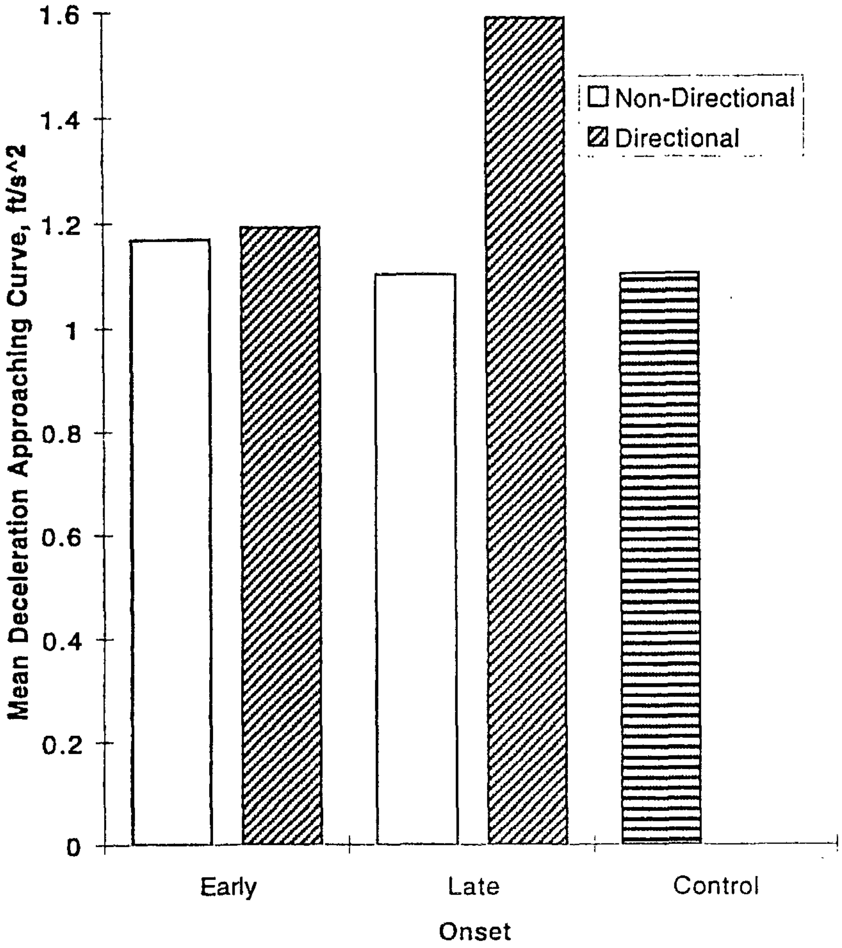



**Figure 6-4** **AVERAGE MEAN DECELERATION APPROACHING LATE 800 FT-RADIUS CURVE AS A FUNCTION OF CAS ONSET AND DIRECTIONALITY**

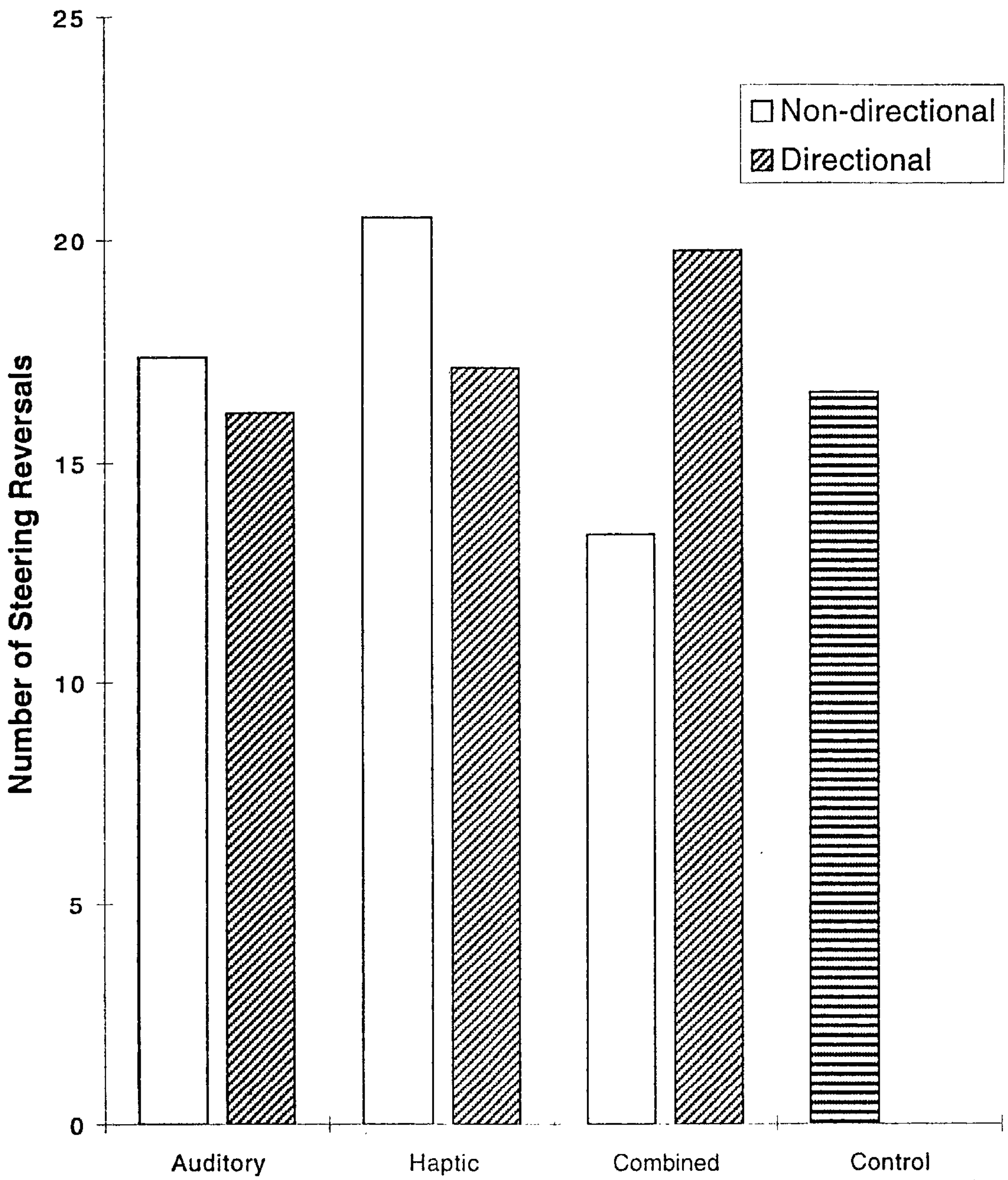



**Figure 6-5** **MEAN NUMBER OF STEERING REVERSALS THROUGH LATE 800 FT-RADIUS CURVE AS A FUNCTION OF CAS INTERFACE TYPE AND DIRECTIONALITY**

As with the Early 800 ft curve negotiation data, pair comparisons of the various CAS support conditions 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. No sigificant differences were found.

### 6.3 Conclusions and Recommendations based on General Curve Negotiation Results

The general conclusion to be drawn from the results presented here is that CAS support did not significantly alter driving behavior for normal curve negotiation associated with an 800 ft-radius curve either early or late in the simulator session. Drivers were driving close to the design speed for the curve and so the CAS support was generally not needed. At present, these data do not provide any strong evidence of a problem with any CAS support feature. Thus, it is appropriate to move on to an assessment of the impact of CAS on the curve hazard data. Based on the results of the general curve negotiation results, it is recommended that all CAS concepts be retained and other results be used to discriminate among them.

## 7.0 Results--Longitudinal Curve Disturbance

A signficant proportion of roadway departure crashes are roadway departures at curves due to excessive speed with respect to road surface conditions and/or roadway geometry. In an attempt to assess CAS concepts for collision avoidance at curves, the simulator session included, per test participant, one longitudinal or curve disturbance. This collision hazard was created by eliminating the speed sign before the hazard curve. The intent was to promote a curve approach at highway (excessive) speeds and then examine the effects of CAS concepts (and the performance of a control group of participants who did not have CAS support) on curve negotiation and collision avoidance.

The following measures were recorded and analyzed:

**Curve Approach**

- Curve Entrance Speed, measured at curve entrance line, i.e., the beginning of the quarter-circle portion of each curve after the straight line approach, ft/s
- max deceleration approaching curve, measured over a distance of 1250 ft before the curve entrance line, $ft/s^2$
- Mean deceleration approaching curve, measured over a distance of 1250 ft before the curve entrance line, $ft/s^2$
- Accelerator pedal RT after D_alert (if presented), ms
- Brake RT after D_alert (if presented), ms
- Accelerator pedal RT, after D_warn (if presented), ms
- Brake pedal RT, after D_warn (if presented), ms

**Curve Traversal (measures taken after curve entrance line and until curve exit line)**

- Mean speed through curve, ft/s
- Lane Position Standard Deviation, in
- Steering reversals of 2 degrees or greater through curve, count

The dependent measures described above were analyzed using several inferential statistical methods. Analysis of Variance (ANOVA) methods were applied using the Statistical Analysis System (SAS) General Linear Models (GLM) procedure and Ryan-Einot-Gabriel-Welsh post-hoc comparisons (SAS Institute, 1992). The model included the following main effects and their two-way interactions:

- Interface type (auditory, haptic, or both),
- Hazard Magnitude (low: 800 ft-radius curve or high: 250 ft-radius curve)
- 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, t-tests were conducted to compare the control group of participants who had no CAS support with those that did have CAS support. These t-tests used the approximate t statistic with Satterwaite's approximation for the degrees of freedom when the variances were unequal. Given the large number of tests that can be conducted (39 per dependent measure), there is an increased risk of Type I errors (i.e., declaring significant differences by chance). This Type I error risk is managed by adjusting the per-comparison criterion for significance but most procedures result in an increase in Type II error risk (i.e., declaring no differences when real differences exist) (Keppel, 1991). In an attempt to balance off these competing error types, a per-test significance level of .0025 was selected.

### 7.1 Curve Approach Results

Consider first the dependent measure of curve entrance speed. There was a main effect for Hazard Magnitude, with $F(1, 26) = 81.42, p < .0001$. For the high magnitude longitudinal hazard (i.e., 250 ft-radius curve), mean curve entrance speed was 43.719 ft/s. This is reliably slower than mean curve entrance speed for the low magnitude longitudinal hazard (i.e., 800 ft-radius curve), which was 66.520 ft/s. This provides evidence that the hazard magnitude manipulation was effective in altering driver behavior.

There were two significant interactions for this curve entrance speed. The first of which was Interface X Algorithm, with $F(2, 26) = 4.13, p < .028$. The means associated with this interaction are presented in Figure 7-1. This interacton revealed a significant difference in curve entrance speeds with respect to the pulse braking algorithm for the auditory interface only. Both the haptic and the combined interfaces were associated with relatively more similar mean curve entrance speeds for pulse and no pulse braking. Pairwise comparisons with the control group of participants who did not have CAS support revealed no differences at the .0025 significance level. The reason for this pattern of results is unknown.

There was also a significant Directionality X Algorithm interaction. For this interaction, $F(1, 26) = 4.80, p < .038$. The cell means for this interaction are plotted in Figure 7-2. This interaction indicates that when the non-directional (i.e., vibrating) accelerator pedal was applied, it resulted in a greater reduction in curve entrance speed when it was not accompanied by pulse braking. Again, the reason for this pattern of results is unclear.

There were two main effects for maximum deceleration approaching the curve. This value involved the maximum deceleration between the point at which the speed sign, had it been posted, would have been visible and the beginning of the curve. For the 800 ft (low magnitude) radius curve, this meant a distance of 1250 ft, and for the 250 ft radius curve, it meant a distance of 600 ft. For Hazard Magnitude, $F(1, 26) = 16.16, p < .0004$. Maximum deceleration as participants approached the curve was greater for the high magnitude hazard, the 250 ft radius curve ($M = 17.103$ ft/s$^2$) than for the low magnitude hazard, the 800 ft radius curve ($M = 9.680$

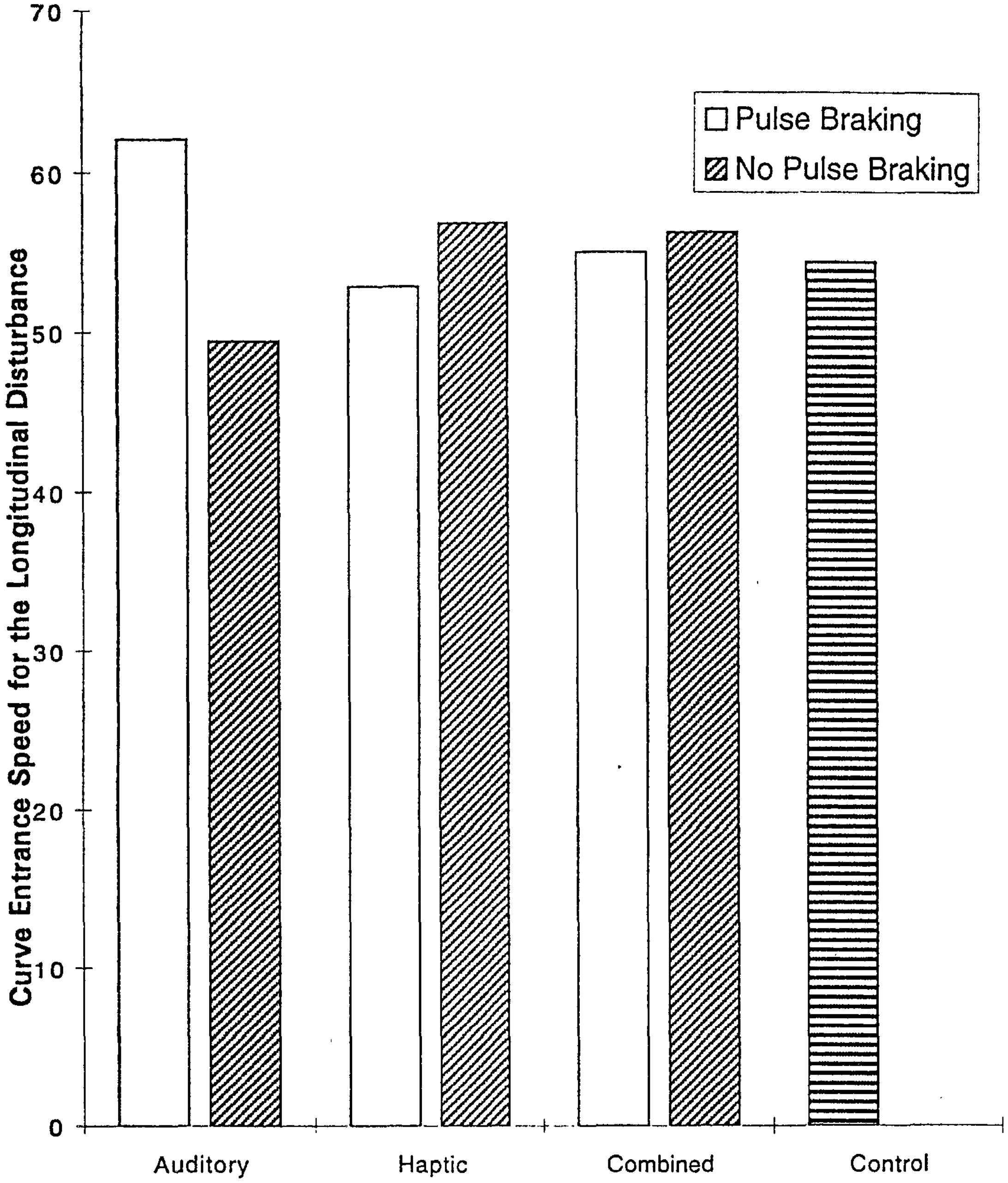



**Figure 7-1** **CELL MEANS FOR THE INTERFACE X ALGORITHM INTERACTION FOR CURVE ENTRANCE SPEED FOR THE LONGITUDINAL DISTURBANCE**

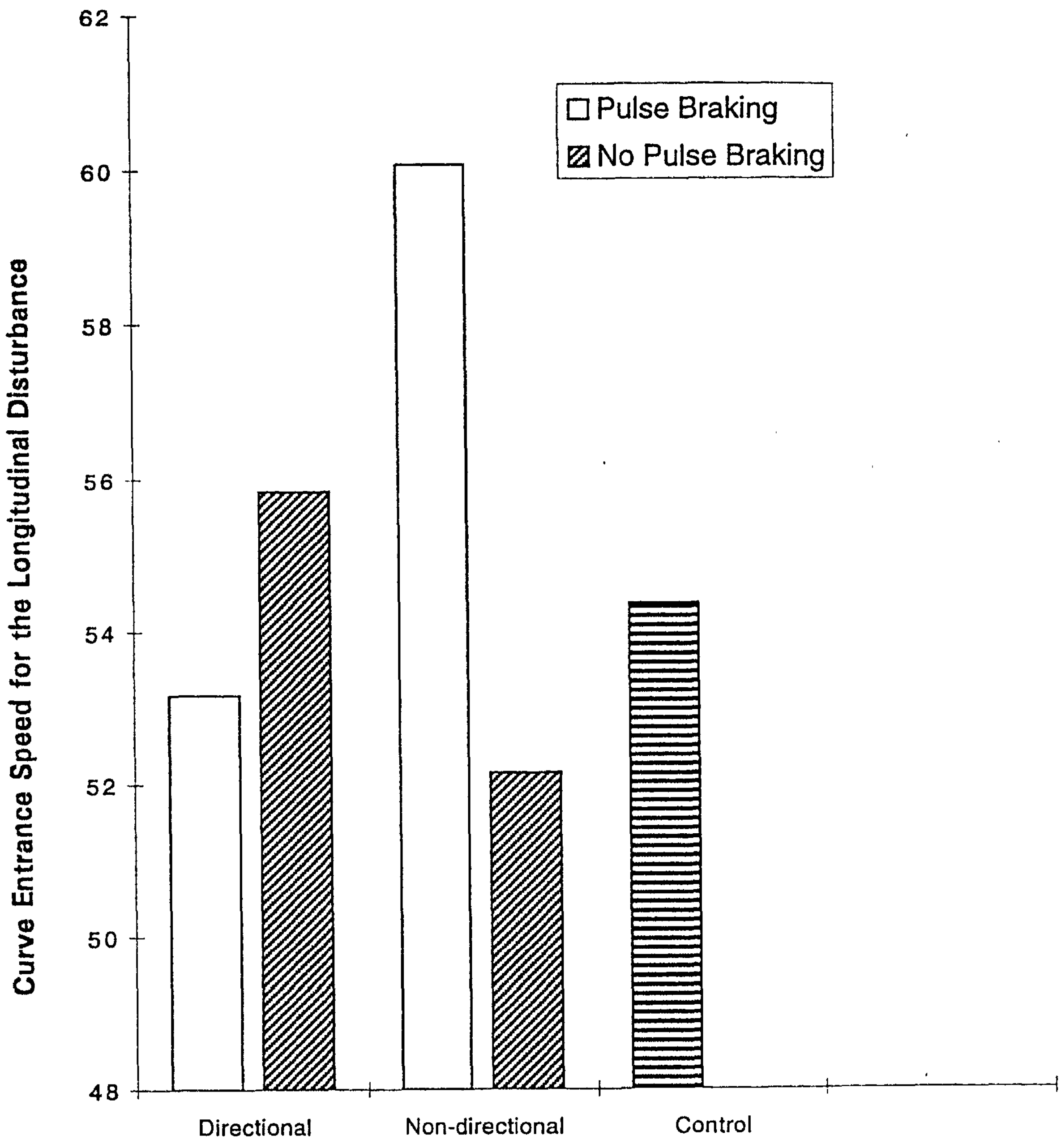



**Figure 7-2** **CELL MEANS FOR THE DIRECTIONALITY X ALGORITHM INTERACTION FOR CURVE ENTRANCE SPEED FOR THE LONGITUDINAL DISTURBANCE**

ft/s$^2$). This indicates that the 250 ft radius curve demanded, overall, greater deceleration from the driver-vehicle system than did the 800 ft radius curve.

The second main effect for maximum deceleration approaching the curve involved Directionality, with $F(1, 26) = 23.66, p < .0001$. As indicated in Figure 7-3, participants' maximum deceleration, as defined here, was greater under conditions of directional warning presentation ($M = 17.589$ ft/s$^2$) than under conditions of non-directional warning presentation ($M = 8.849$ ft/s$^2$). As a point of reference, the mean for the control group was $M = 15.76$ ft/s$^2$. This is an indication that the directional CAS involving accelerator pedal counterforce was affecting driver decelerations relative to non-directional CAS and was somewhat, but not signficantly, greater than that for the control group.

The was one significant main effect for mean deceleration between where the speed sign should have been posted and the beginning of the curve. Mean decelerations were differentiated only on the basis of hazard magnitude. For Hazard Magnitude, $F(1, 26) = 94.83, p < .0001$. There was greater mean deceleration between the speed sign and the beginning of the curve when the high magnitude curve was approached ($M = 4.672$ ft/s$^2$) than when the low magnitude curve was approached ($M = 2.124$ ft/s$^2$).

Significant main effects for Interface and for alert Onset were revealed by the ANOVA on brake pedal reaction time (RT) after an occurrence of a longitudinal alert. For Interface, $F(2, 26) = 3.58, p < .042$. Figure 7-4 indicates that brake RT was shortest when the auditory interface was used ($M = 1570.8$ ms) than when the haptic interface was used ($M = 3314.6$ ms). The combined interface did not significantly differ from either of the other two interfaces with respect to brake pedal RT after a longitudinal alert was presented to participants.

There was also a signficant main effect for alert Onset, $F(1, 26) = 10.08, p < .004$. Figure 7-5 illustrates that late alart onset yielded significantly shorter brake pedal RT after the longitudinal alert was introduced ($M = 1572.2$ ms) than did the early alert onset ($M = 3323.2$ ms). This may be due to the fact that drivers, though alerted chose to begin deceleration later than what the CAS indicated.

A single main effect for Onset of Warning was obtained for brake pedal RT after the longitudinal warning was initiated. ANOVA revealed an $F(1, 26) = 6.55, p < .017$. Brake pedal RT after the longitudinal warning was significantly shorter for late warning onset ($M = 362.5$ ms) than for early warning onset ($M = 1202.9$ ms). The late warning onset was based on the presentation of a warning when it would require 0.3 g deceleration and a 2.5 s driver time delay budget to reduce speed to match the design speed of the curve. This onset of warning effect indicates that drivers were sensitive to the need to apply their brakes more quickly with a late warning. No other significant ANOVA effects for curve approaches dependent variables were found.

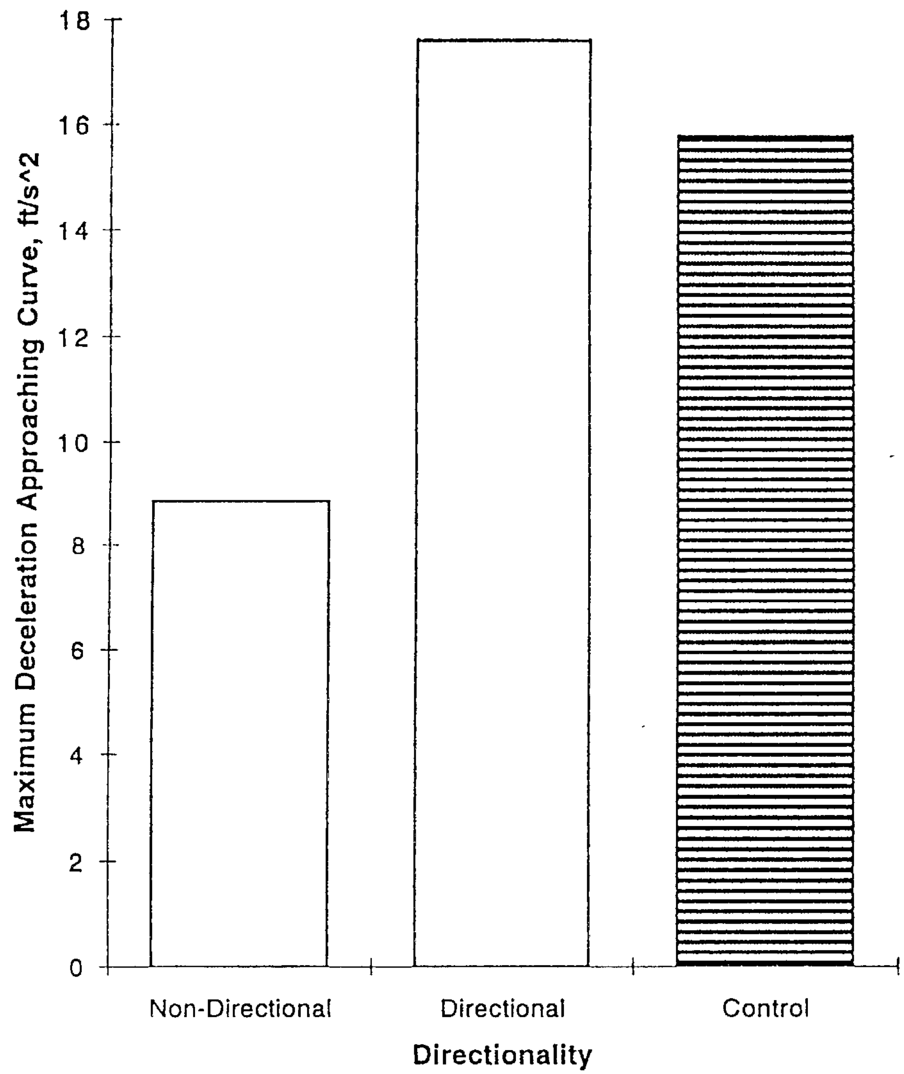



**Figure 7-3 MAXIMUM DECELERATION APPROACHING CURVE AS A FUNCTION OF DIRECTIONALITY**

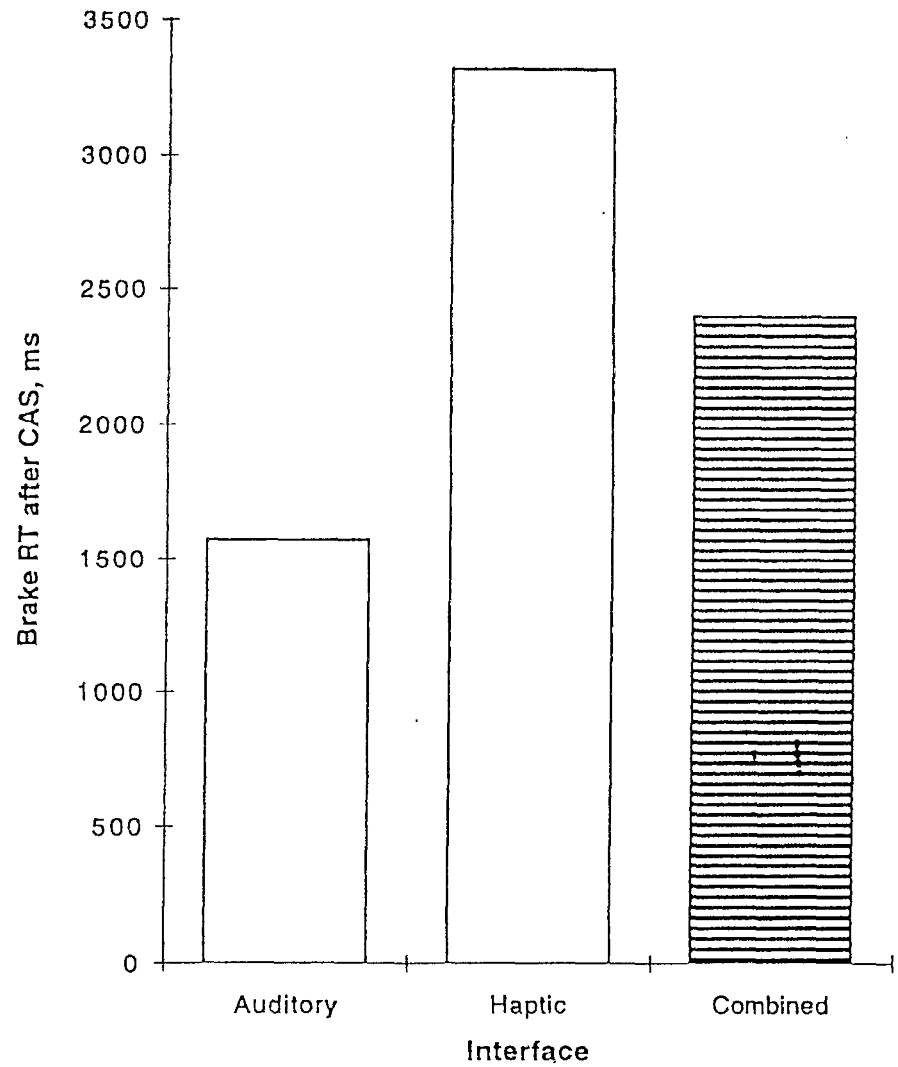



**Figure 7-4 BRAKE REACTION TIME (RT) AFTER CAS AS A FUNCTION OF INTERFACE**

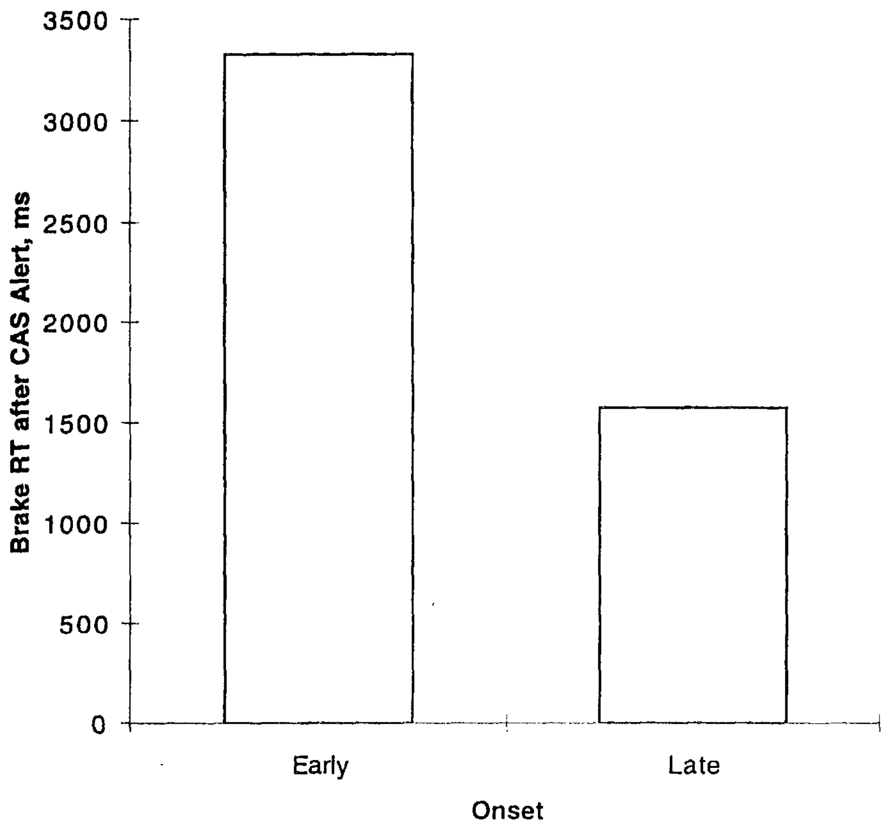



**Figure 7-5 BRAKE REACTION TIME AFTER CAS ALERT AS A FUNCTION OF ONSET**

## 7.2 Curve Traversal Results

Hazard Magnitude had a reliable effect on mean speed through the curve. $F(1, 26) = 120.75$, $p$ >0001. Mean speed through the curve was slower on the 250 ft radius curve ($M$ = 39.150 ft/s) than on the 800 ft radius curve ($M$ = 60.757 ft/s). This is as expected given the difficulty of the 250 ft radius curve. As a point of reference, the control group of participants without CAS support who traversed the high hazard curve (250 ft-radius curve) averaged 42.03 ft/s and the control group who traversed the low hazard curve (800 ft-radius curve) averaged 63.69 ft/s.

Three significant effects were obtained using ANOVA on lane standard deviation through the curve. For Interface, $F(2, 26) = 4.94$, $p < .015$ (see Figure 7-6). The standard deviation of lane position was greater when warnings were presented with the auditory interface ($M$ = 9.393 in) than with either of the other two interfaces (for haptic, $M$ = 6.448 in and for combined, $M$ = 6.809 in). This indicates that the haptic and the combined interfaces allowed drivers more precise lateral control of the vehicle during curve negotiation than did the auditory interface. As a point of reference, the control group of participants without CAS support had an average lane standard deviation of 9.419 inches. While lane standard deviation with CAS support is, on average, less than or about equal to that of unsupported drivers, the largest difference is rather small (less than 3 in) and so may be of only minor practical significance.

There was also a main effect for Directionality on lane standard deviation through the curve, with $F(1, 26) = 6.39$, $p < .018$. As indicated in Figure 7-7, the standard deviation of lane deviations was greater for directional than for non-directional warnings (means of 8.560 in and 6.528 in, respectively). The small differences obtained here appear to lack practical significance.

The Directionality X Hazard Magnitude interaction also reached statistical significance, with $F(1, 26) = 4.35$, $p < .047$. The cell means for this interaction are presented in Figure 7-8. There are reliable differences revealed by this significant interaction; the non-directional CAS displays, on average, had the lowest lane standard deviation, especially under the high hazard magnitude condition. However, the magnitudes of the differences noted seem to have only minor practical significance.

For the number of steering reversals that drivers exhibited as they drove through the curve, only a main effect for Hazard Magnitude was obtained. For this factor, $F(1, 26) = 43.80$, $p < .0001$. During the more severe, 250 ft radius curve, there were fewer steering reversals ($M$ = 8. 696 reversals) than during the 800 ft radius curve ($M$ = 17.708 reversals). This may be taken to mean that participants made more steering reversals in the 800 ft radius curve because a longer curve allows for more steering maneuverability during negotiation. No other significant ANOVA effects were found. Furthermore, no significant differences were found in pairwise comparisons of various CAS conditions with the control group means.

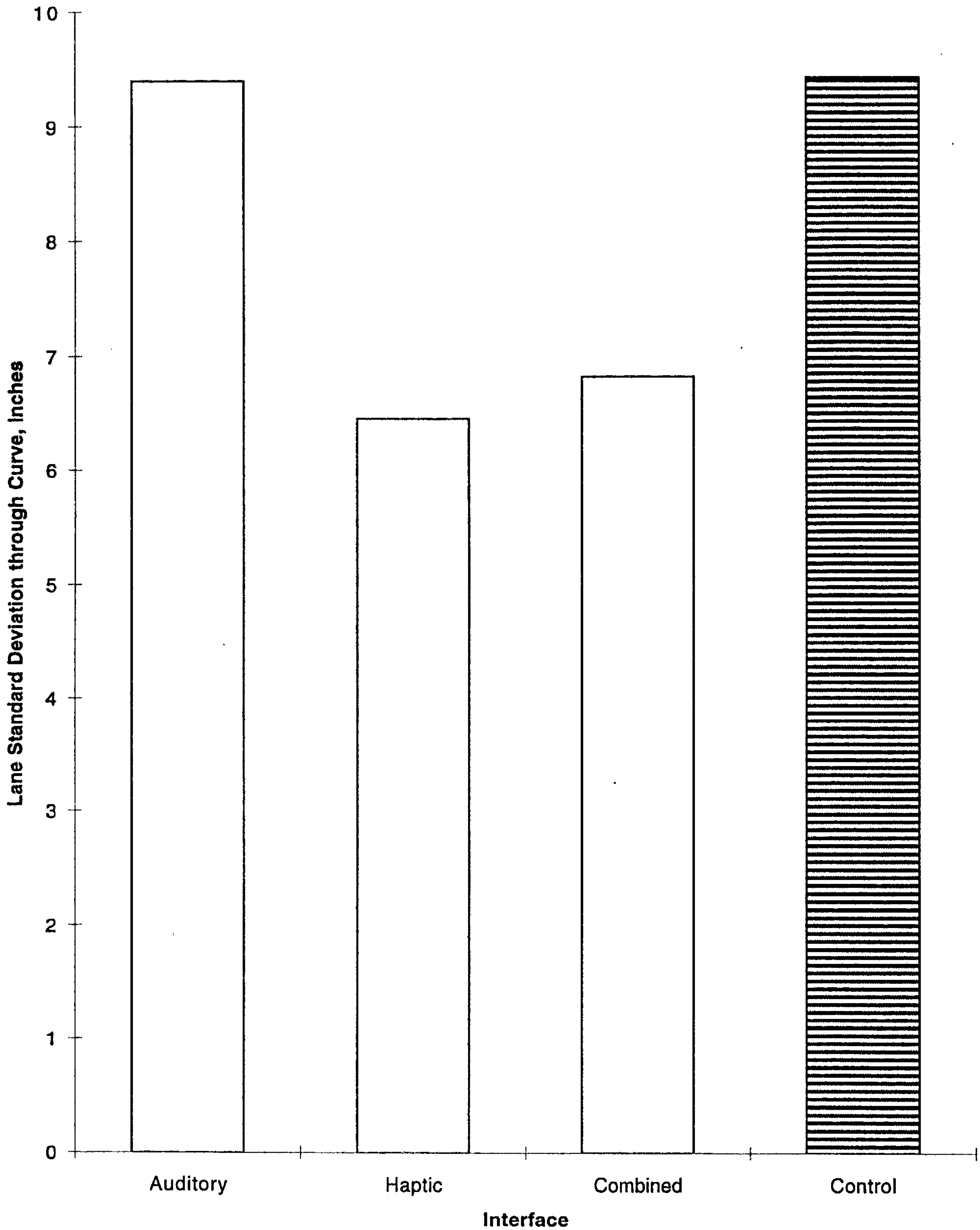



**Figure 7-6 LANE STANDARD DEVIATION THROUGH CURVE AS A FUNCTION OF INTERFACE**

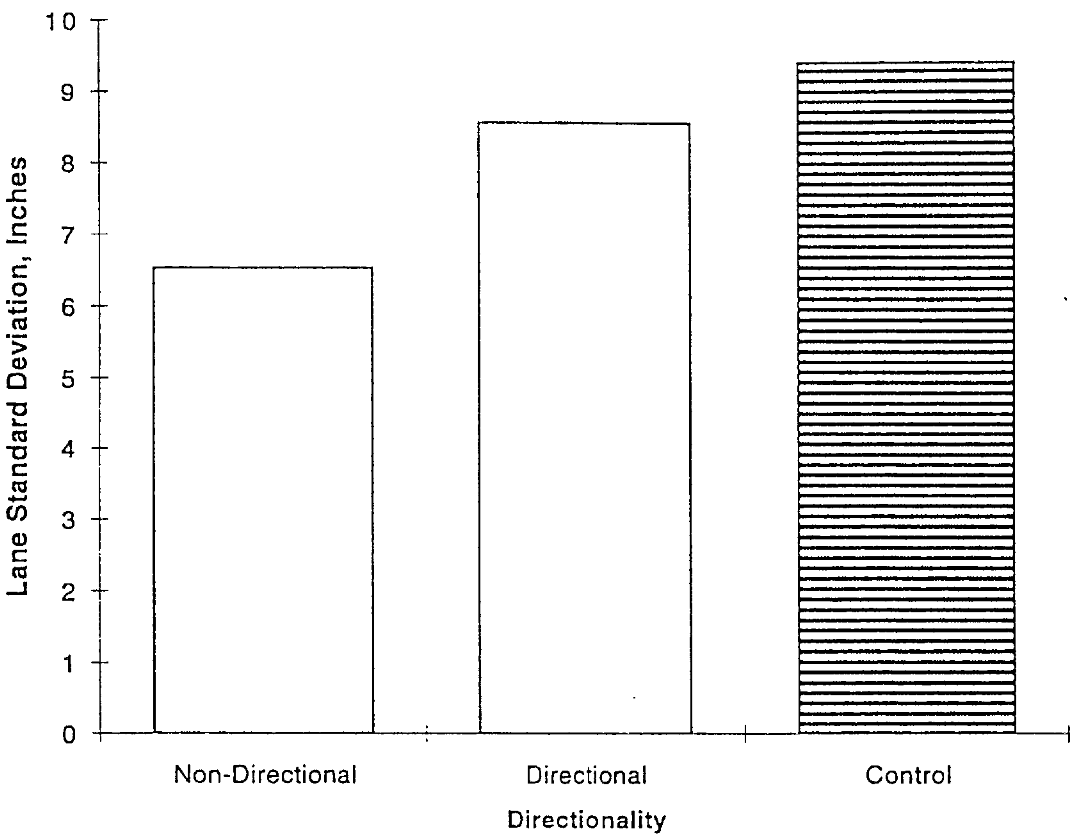



**Figure 7-7 LANE STANDARD DEVIATION THROUGH CURVE AS A FUNCTION OF CAS DIRECTIONALITY**

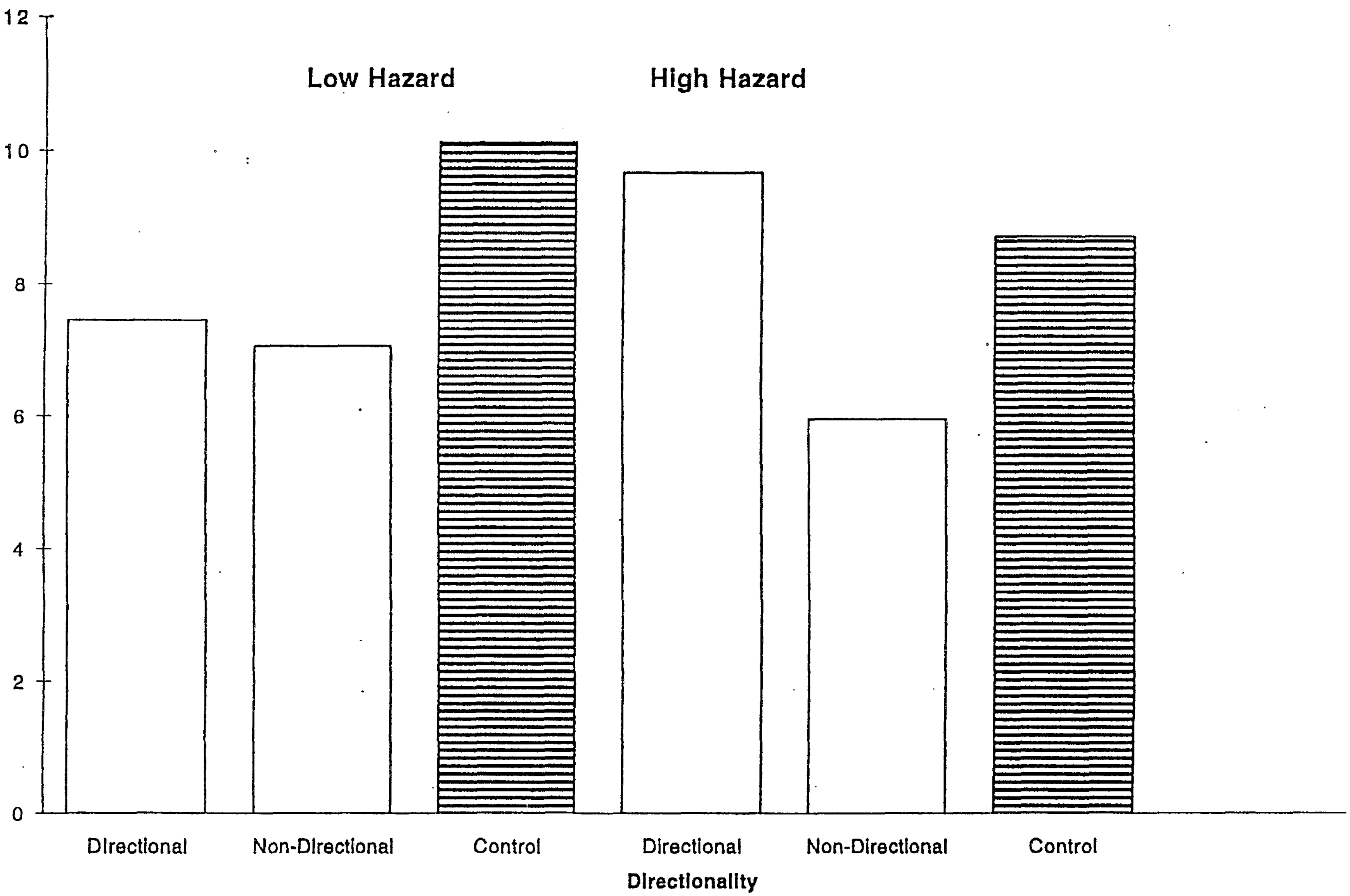



**Figure 7-8** LANE STANDARD DEVIATION THROUGH CURVE AS A FUNCTION OF CAS DIRECTIONALITY AND HAZARD MAGNITUDE

### 7.3 Conclusions and Recommendations based on Longitudinal Curve Disturbance Results

The most obvious conclusion that can be drawn strictly from the data on the longitudinal curve disturbance is that hazard magnitude had a rather strong effect on participants' driving behavior. Participants entered the 250 ft-radius, high hazard curve at a slower speed than the 800 ft-radius, low hazard curve. Participants exhibited greater maximum and mean decelerations with the 250 ft-radius curve than with the 800 ft-radius curve, and they also traversed the 250 ft-radius curve more slowly. Drivers also exhibited more steering reversals on the 800 ft-radius curve. These results serve as a substantial demonstration that the hazard mangitude manipulation had an effect on driver behavior in this study with respect to curve approach and negotiation.

None of the CAS support concepts provded an abundance of significant main effects or interactions. However, there are indications that the auditory interface benefits driver behavior in that it led to shorter brake pedal RTs following a longitudinal alert than either the haptic or the combined interface. Furthermore, the auditory interface, when associated with the no-pulse braking longitudinal algorithm, led to slower curve entrance speeds than it did when combined with the pulse braking algorithm. However, the auditory interface led to slightly, but significantly, greater lane deviations than did either the haptic or combined interfaces as drivers traversed the curves.

The late onset of warning was more of a performance benefit to drivers than was the early onset of warning for curve approach. The late onset of warning led to shorter brake pedal RTs following both the longitudinal alert and warning than did the early onset. These results imply that drivers begin braking for a curve more quickly when the situation requires greater deceleration to attain a curve's design speed. However, this may mean only that drivers brake more quickly when the situation demands more intensive braking (to achieve the greater deceleration necessary to enter the curve at or near its design speed). Thus, the results are equivocal with respect to onset.

Directional warnings offered greater maximum decelerations than did the non-directional counterparts; however, the non-directional warnings led to slightly lesser lane deviations, especially in high hazard curves. With respect to the curve disturbance data, these were the only directionality effects obtained.

A list of recommendations based solely on the longitudinal curve disturbance data would be as follows:

- The auditory interface alone serves better as CAS support upon approach to the curve. However, during curve negotiation, the auditory interface may need to be supplanted by the combined interface to offer drivers more precision for curve execution.

- Data on the effects of onset of warnings were equivocal and so no recommendations are offered at this time.
- Directional warnings should be employed over non-directional warnings.
- The data were largely equivocal with respect to algorithm, and so no recommendations for algorithm are offered at this time.

# 8.0 Results--Subjective Assessments

## 8.1 Introduction

It is worthwhile in the development of CAS technologies to have an understanding of how acceptable drivers find the technologies. Driver acceptability of CAS may have an influence on the ultimate purchase of a vehicle equipped with CAS support. In addition, driver acceptability data in conjunction with performance measures indicate those situations where drivers find CAS support unacceptable despite what is considered good performance with it. It is possible that drivers may find some CAS technology unpalatable, yet they may still interact with it appropriately and use it successfully for collision avoidance. Results such as this can guide further CAS design modifications that lead toward increased driver acceptance while maintaining CAS operational performance goals. After completing the experimental runs in the Iowa Driving Simulator, all participants were asked to complete a questionnaire developed to provide some insight into drivers' subjective assessments of the CAS support they had experienced.

This section contains both results and brief discussions of the ANOVA conducted on 31 of the 34 debriefing questions presented following the completion of the experimental drive to the 48 participants who had some form of CAS support. The format for this section includes a breakdown of ANOVA results for each debrief question. Each question is presented individually in a box, with its associated scale given beneath it. For purposes of analysis, each debrief question was treated as a separate dependent measure in order to determine if participants' impressions of CAS support could be parsed on the basis of any of the independent variables or their interactions. The list of questions is contained in Appendix H. Each question is presented here with the number that corresponds to it in that appendix.

All of the 31 analyzed questions employed a scale numbered from 1 (at the left) to 7 (on the right). Prior to data analysis, the 31 analyzable questions were examined for negatively worded items. Those questions that were negatively worded (e.g., "Did you experience any confusion with the system as you worked to stay in your lane?") had their scales inverted so that 7 reflected a response on the left side of the scale. This was done so as to ensure that all responses toward the upper end of the scale (close to 7) implied a positive regard toward the CAS system in question. Those questions which were rescaled in this fashion will have both the *original* scale (the scale participants saw) and the *new* scale (used for analysis) presented along with the question. In those instances of rescaling, *all* significant results are interpreted and discussed in terms of the new (analyzed) scale.

A number of questions have been omitted from this section due to the absence of any statistically significant results. Two questions regarding driver trust of the CAS are presented here despite the absence of significant results associated with them. Three questions which asked participants to suggest changes in CAS design were not analyzed.

The following sections treat the lateral warning case, the longitudinal, curve approach case, and the lateral CAS during curve negotiation case.

### 8. 2 The Lateral Warning Case

| |
|---|
| 3) What is your opinion about the <u>duration</u> of the warnings to grab your attention? |
| \|_______\|_______\|_______\|_______\|_______\|_______\|_______\| |
| 1 2 3 4 5 6 7 |
| Far too short Far too long |

There was a significant main effect for Algorithm on responses to this question. ANOVA revealed an $F(1, 27) = 5.30, p < .029$. For TLC, $M= 4.292$, and for TTD, $M= 3.917$. Although ANOVA indicated that the means for the algorithm conditions are reliably different, both means are located near the midpoint of the scale, suggesting that the currently configured durations are judged to be near optimal.

| |
|---|
| 4) What is your opinion about the <u>magnitude</u> (i.e., loudness for auditory display, force for haptic display) of the warnings to grab your attention? |
| \|_______\|_______\|_______\|_______\|_______\|_______\|_______\| |
| 1 2 3 4 5 6 7 |
| Far too weak Far too strong |

Two main effects, for Interface and for Directionality, were uncovered. For the Directionality main effect, $F(1, 27) = 8.55, p < .007$. For directional presentation, $M= 4.565$, and for non-directional presentation, $M= 3.875$. It would appear that participants found the magnitude of warnings presented in a directional fashion stronger, though both means are near the midpoint, which is considered optimal. For Interface, $F(2, 27) = 5.04, p < .014$. For auditory interface, $M= 4.600$, for haptic interface, $M= 4.375$, and for combined interface, $M= 3.688$. Post-hoc analysis revealed that the locus of effect for the Interface main effect was between auditory and haptic versus combined. It would appear that overall, participants found the magnitude of warnings to be less than strong when they were presented in combination.

Further insight into the interface effects was provided by a significant interaction between Interface and Directionality. For this interaction, $F(2, 27) = 3.83, p < .035$. Table 8-1 contains the cell means for the Interface X Algorithm interaction.

**Table 8-1**
**Cell Means for The Interface X Directionality Interaction for Question 4**

| Directionality | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Directional** | 3.625 | 5.429 | 4.750 |
| **Non-Directional** | 3.750 | 3.875 | 4.000 |

A reading of this interaction tends to suggest differences in perceptions of magnitude for the interfaces when presenting directional information. The haptic directional CAS was judged to be a bit too strong, as is the combined interface. This difference is not apparent with non-directional CAS. It would appear that the interfaces are perceived to be close to an optimum magnitude in non-directional conditions.

8) Did you trust the collision warning system?

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Not at all | | | | | | Very much |

The Hazard Magnitude X Onset of Warning interaction was the only significant effect obtained for this question. For this interaction, $F(1, 27) = 5.14$, $p < .032$. The cell means for this interaction are contained in Table 8-2.

**Table 8-2**
**Cell Means for the Hazard Magnitude X Onset of Warning Interaction for Question 8**

| Hazard Magnitude | Onset of Warning | |
|---|---|---|
| | Early | Late |
| **Low** | 4.343 | 3.593 |
| **High** | 3.187 | 4.353 |

These results foremost suggest that while there are differences in levels of trust engendered by the CAS, generally speaking, participants were ambivalent about the CAS concepts (the overall average response to this question was 4.12). The significant differences obtained suggest that participants tended to trust the lateral CAS more so in situations where the system was geared to warn early during low magnitude lateral threats and where the system was geared to present late warnings during high magnitude lateral threats. This reasons for this pattern of responses are unknown.

| 9) Did you experience any confusion with the system as you worked to stay in your lane? | | | | | | | |
|---|---|---|---|---|---|---|---|
| Original: | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | Not at all | | | | | | Very much |
| New: | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| | Not at all | | | | | | Very much |

The main effect for Directionality was significant for this question, with $F(1, 27) = 6.40$, $p < .018$. It appeared as though participants found the directional presentation less confusing ($M = 4.542$) than the non-directional presentation ($M = 3.597$). This lends credence to the notion that directionally presented warnings can provide drivers with less ambiguous information about the nature of the lateral driving threat and about the kind of evasive response needed.

The significant Interface X Directionality interaction may shed more light on the level of confusion about directionality experienced relative to the specific interface design. For the Interface X Directionality interaction, $F(2, 27) = 4.71$, $p < .018$. Table 8-3 contains the cell means for this interaction.

**Table 8-3**
**Cell Means for the Interface X Directionality Interaction for Question 9**

| Directionality | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Directional** | 5.125 | 5.250 | 3.250 |
| **Non-Directional** | 2.875 | 4.125 | 3.791 |

It would appear that participants found the combined interface much more confusing than either the auditory or the haptic when the warnings were presented directionally. This may reflect participants' concerns of being bombarded with too much information even though it is presented in a directional fashion. Furthermore, it is notable that participants found the non-directional presentation of auditory warnings strongly confusing.

The Interface X Algorithm interaction was also significant, with $F(2, 27) = 5.56, p < .009$. Table 8-4 contains the cell means for this interaction.

**Table 8-4**
**Cell Means for the Interface X Algorithm Interaction for Question 9**

| Algorithm | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **TTD** | 5.125 | 4.750 | 3.166 |
| **TLC** | 2.875 | 4.625 | 3.875 |

From an inspection of this interaction, the discrepancy between TLC and TTD for auditory warnings is very noticeable. It would seem that participants found the auditory warnings much more confusing when TLC was in operation than when TTD was at work. Why this result was obtained is unclear. Possibly, TLC led to more CAS activations which, when presented in the auditory mode, were disturbing and more apparently unwarranted.

The last significant interaction for Question 9 was between Interface and Hazard Magnitude, with $F(2, 27) = 4.60, p < .019$. The cell means for this interaction are presented in Table 8-5.

**Table 8-5**
**Cell Means for the Interface X Hazard Magnitude Interaction for Question 9**

| Hazard Magnitude | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Low** | 4.625 | 4.375 | 2.791 |
| **High** | 3.375 | 5.000 | 4.250 |

There appear to be reliable differences among each of the three interfaces for those drives during which the high magnitude hazard had been presented. The haptic interface was the least confusing interface for the strong lateral threat, followed by the combined and then the auditory interface. However, when the weak lateral threat was introduced, the haptic and auditory interfaces were judged to be about equal with respect to confusion, and both of them were less confusing than the combined interface.

| 10) Do you feel that the system would help you avoid a potential crash? | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Not at all | | | | | | Very much |

There was a lone significant interaction with responses to this question. The Interface X Hazard Magnitude interaction was significant, with $F(2, 27) = 4.29$, $p < .024$. This interaction is depicted in Table 8-6.

**Table 8-6**
**Cell Means for the Interface X Hazard Magnitude Interaction for Question 10**

| Hazard Magnitude | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| Low | 4.750 | 3.750 | 2.750 |
| High | 3.625 | 4.000 | 5.125 |

Question 10 was in regard to participants' perception of how helpful they found the lateral CAS in avoiding potential crashes. Participants' judgements of the combined interface for helpfulness in avoiding potential crashes, in conjunction with their perceptions of confusion engendered by the combined interface, suggest that the combined interface is more confusing and not more helpful when the lateral threat is weak. These results may reflect perceptions that the combined interface is "overkill" or unnecessary when the threat is weak. Participants may have felt that either the auditory or the haptic interface is sufficient for weak threats. However, for those threats that are strong, the combined interface is not terribly confusing, relative to the other interfaces, and is judged to be rather helpful, again, relative to the other interfaces.

The haptic interface was judged more helpful for potential crashes than the auditory when the magnitude of the side threat was high. However, this effect is reversed when the threat is weak.

| 12) How much would you like to have the lane drift warning system in your car? | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Not at all | | | | | | Very much |

A main effect for Hazard Magnitude was uncovered for this question, with $F(1, 27) = 5.60, p < .025$. For high magnitude hazard, $M = 3.583$, and for low magnitude hazard, $M = 2.375$. What this suggests is that having experienced a high magnitude lateral threat, drivers show a moderate desire for the lateral CAS as it has been instrumented for this study.

A significant interaction for Hazard Magnitude and Onset of Warning may shed some additional light on driver perceptions of how much they might want to have the lateral CAS installed in their own cars. For Hazard Magnitude X Onset of Warning, $F(1, 27) = 9.12, p < .006$. The cell means associated with this interaction can be found in Table 8-7.

**Table 8-7**
**Cell Means for the Hazard Magnitude X Onset of Warning Interaction for Question 12**

| Hazard Magnitude | Onset of Warning | |
|---|---|---|
| | Early | Late |
| **Low** | 2.833 | 1.917 |
| **High** | 2.500 | 4.667 |

This interaction reveals that participants show a stronger desire for the lateral CAS when it provides a late warning for an obvious threat. The reason for this pattern is unknown, but may reflect a desire for protection when needed, but without nuisance alarms. Generally speaking, participants were lukewarm to the CAS concepts used in the study.

In its original presentation, Question 12 also asked participants to indicate how much they would be willing to pay for a CAS like the one they experienced in the experiment. It should be noted that not all participants were willing to respond to this portion of this question. Table 8-8 contains the mean dollar amounts provided by participants based on Interface and Directionality. Note that the non-directional auditory display has the lowest mean price associated with it.

**Table 8-8**
**Mean Dollar Amount Participants Would Be Willing to Pay for Similar Lateral CAS in Their Own Cars Based on Interface and Directionality of Warning Presentation**

| Directionality | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Directional** | 266.67 | 276.67 | 542.50 |
| **Non-Directional** | 58.33 | 512.50 | 125.00 |

## 8.3 The Longitudinal Warning Case

| 15) What is your opinion about the <u>duration</u> of the alerts or warnings to grab your attention? | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Far too short | | | | | | Far too long |

The Interface X Algorithm interaction was significant for responses to this question, with $F(2, 27) = 4.30, p < .025$. See Table 8-9. While there is some variation in responses, test participants viewed the warnings as generally near the optimum durations.

**Table 8-9**
**Cell Means for the Interface X Algorithm Interaction for Question 15**

| Algorithm | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| Pulse Braking | 3.375 | 4.375 | 4.142 |
| No Pulse Braking | 4.000 | 3.571 | 3.750 |

18) Did you experience the system as disturbing to your driving?

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Original: | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | Not at all | | | | | | Very much |
| New: | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| | Not at all | | | | | | Very much |

The Interface X Directionality and Interface X Algorithm interactions associated with this question were found to be statistically significant. For the Interface X Directionality interaction, $F(2, 27) = 4.06, p < .029$. The cell means for this interaction can be found in Table 8-10.

**Table 8-10**
**Cell Means for the Interface X Directionality Interaction for Question 18**

| Directionality | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Directional** | 5.875 | 5.250 | 4.336 |
| **Non-Directional** | 3.875 | 5.086 | 5.000 |

It would appear that participants found the combined interface more disturbing than the other two interfaces when the directional warnings (counterforce on accelerator pedal proportional to speed error) were presented. This may reflect a feeling that the combined interface coupled with the accelerator counterforce led to feelings "information overload" on the part of participants. Under conditions of non-directional warning presentation, the auditory interface was more disturbing than either the haptic or combined interfaces.

The Interface X Algorithm interaction was also significant with respect to participants' assessments of CAS disturbance of driving. For Interface X Algorithm, $F(2, 27) = 6.64, p < .005$. Table 8-11 presents the cell means associated with this particular interaction. Note, however, that all means are at or above the midpoint.

**Table 8-11**
**Cell Means for the Interface X Algorithm Interaction for Question 18**

| Algorithm | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Pulse Braking** | 5.500 | 4.375 | 5.461 |
| **No Pulse Braking** | 4.250 | 5.961 | 3.875 |

The haptic interface appears more disturbing than either of the other interfaces when pulse braking was used upon approach to a curve. It again should be noted that the haptic interface was not perceived by participants as overly disturbing within this algorithm. A more noticeable difference was noted between the haptic interface and both other interfaces when no pulse braking was employed. It appears that the haptic interface is much less disturbing than either auditory or combined when no pulse braking is a part of the curve approach algorithm.

| 21) Did you experience any confusion with the system as you approached a curve? | | | | | | | |
|---|---|---|---|---|---|---|---|
| Original: | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | Not at all | | | | | | Very much |
| New: | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| | Not at all | | | | | | Very much |

ANOVA revealed a main effect of Directionality, with $F(1, 27) = 8.66, p < .007$. Participants found the longitudinal CAS less confusing when directional presentation of warnings was used. For directional, $M = 5.656$, and for non-directional, $M = 4.406$. As has been seen before, neither the directional nor the non-directional warnings was rated as overly confusing.

The interaction between Interface and Directionality was also significant. For this interaction, $F(2, 27) = 4.31, p < .024$. These cell means can be found in Table 8-12.

**Table 8-12**
**Cell Means for the Interface X Directionality Interaction for Question 21**

| **Directionality** | **Interface** | | |
|---|---|---|---|
| | **Auditory** | **Haptic** | **Combined** |
| **Directional** | 6.375 | 6.000 | 4.592 |
| **Non-Directional** | 3.500 | 4.967 | 4.750 |

The significance of this interaction allows for a refinement of the interpretation of the directionality main effect. Both the auditory and haptic interfaces engendered low levels of confusion when providing directional information.

| 22) Do you feel that the system would help you avoid a potential crash? | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Not at all | | | | | | Very much |

With this question, only a single main effect was detected, and that was for Onset of Warning. For this effect, $F(1, 27) = 6.47, p < .017$. Participants indicated a belief that the longitudinal CAS would help them avoid a potential collision in situations where they were presented with late ($M = 4.7763$) rather than early warnings ($M = 3.5000$).

23) To what extent do you believe the curve approach warning system would be of benefit to you in your everyday driving?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

There was a significant main effect for Onset of Warning for responses associated with this question. ANOVA indicated an $F(1, 27) = 26.41$, $p < .0001$. Participants tended to believe that the curve approach CAS would be of greater benefit to their everyday driving with late warning onsets rather than with early warning onsets ($M = 4.3084$ and 2.3333, respectively). Note, however, the means are at or below the midpoint of the scale, indicating at best, only moderate perception of benefit.

24) How much would you like to have the curve approach warning system in your car?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

If other than "Not at all," ask "How much would you be willing to pay?"________________

Although there were no significant effects obtained for responses to this question ($M = 3.44$), it may be worthwhile to note how much participants would be willing to pay for the longitudinal CAS for their own cars. Note that, again, the non-directional auditory display has the lowest mean price associated with it. As mentioned before, not all participants were willing to respond to this portion of this question. As indicated in Table 8-13, the range is between an average of $75.00 and $282.50.

**Table 8-13**
**Mean Dollar Amount Participants Would Be Willing to Pay for Similar Longitudinal CAS in Their Own Cars Based on Interface and Directionality of Warning Presentation**

| Directionality | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Directional** | 266.67 | 205.00 | 282.50 |
| **Non-Directional** | 75.00 | 280.00 | 92.86 |

## 8.4 Lateral Warning During Curve Negotiation

| 28) Did you experience the system as disturbing to how you drove through the curve? | | | | | | | |
|---|---|---|---|---|---|---|---|
| Original: | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | Not at all | | | | | | Very much |
| New: | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| | Not at all | | | | | | Very much |

ANOVA revealed a significant main effect for Directionality on responses to this question, with $F(1, 27) = 5.82, p < .023$. Participants found lateral directional warnings less disturbing ($M$ = 5.1361) than lateral non-directional warnings ($M$= 3.9694) as they drove through the curves . This indicates an appreciation for directional maneuvering information as curves are negotiated, or perhaps that because deliberate curve exceedences are common, participants perceived the CAS concepts as consonant with their deliberate actions.

| 31) Did you experience any confusion with the system as you drove through the curve? | | | | | | | |
|---|---|---|---|---|---|---|---|
| Original: | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | Not at all | | | | | | Very much |
| New: | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| | Not at all | | | | | | Very much |

The Interface X Directionality interaction was significant for this question, with $F(2, 27) = 4.11, p < .028$. The cell means can be found in Table 8-14.

**Table 8-14**
**Cell Means for the Interface X Directionality Interaction for Question 31**

| Directionality | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| **Directional** | 5.733 | 5.608 | 4.250 |
| **Non-Directional** | 3.875 | 4.733 | 5.125 |

It appears that under conditions of directional response information, the combined interface is judged as moderately confusing when negotiating a curve, but more confusing than either the auditory or haptic interface. Under conditions of non-directionality, the auditory interface was found to be the most confusing of the three interfaces tested for curve negotiation.

In addition, the Interface X Algorithm interaction was also significant for Question 31. For this interaction, $F(2, 27) = 3.79, p < .036$ (see Table 8-15).

**Table 8-15**
**Cell Means for the Interface X Algorithm Interaction for Question 31**

| Algorithm | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| TTD | 5.483 | 4.483 | 5.125 |
| TLC | 4.125 | 5.858 | 4.250 |

Under the TLC algorithm during curve negotiation, the haptic interface was judged to be the least confusing of the three interfaces. However, under TTD, this is reversed and the haptic interface is the most confusing of the three interfaces with respect to maintaining one's lane while driving through a curved portion of roadway.

Finally, Table 8-16 indicates the mean dollar amount participants would consider paying for an analogous CAS support. As indicated by the table, the average amount ranged from $62.50 to $500.00.

**Table 8-16**
**Mean Dollar Amount Participants Would Be Willing to Pay for Similar Curve Negotiation CAS in Their Own Cars Based on Interface and Directionality of Warning Presentation**

| Directionality | Interface | | |
|---|---|---|---|
| | Auditory | Haptic | Combined |
| Directional | 225.00 | 205.00 | 500.00 |
| Non-Directional | 62.50 | 143.75 | 75.00 |

### 8.5 General Conclusions and Recommendations Based on Subjective Assessments

The debrief questionnaire was broken down into three sections, one for the lateral scenario involving lanekeeping, one for the longitudinal scenario involving approach to a curve, and one for the lateral scenario during curve negotiation. Each question in the debrief could be considered to be addressing a different dimension of driver impressions of the simulator experience. What follows in this next section is a presentation of general conclusions with respect to each dimension of the debrief. The absence of significant effects on a dimension is taken to mean that the non-significantly different interface concepts were equivalent with respect to that dimension.

#### 8.5.1 The Lateral Scenario

Effort: There were no significant differences associated with this dimension. The grand mean for this dimension was 5.45. This suggests that, overall, participants found the lateral CAS of low effort for lanekeeping.

Onset: There were also no significant differences associated with this particular dimension. The grand mean for participants' responses was 3.04. This tends to support a conclusion that participants found the onset of warnings to be appropriate.

Duration: Although the judgments of the duration of warnings reliably differed with respect to lateral algorithm, the means for the two algorithm conditions are located near the mean of the scale. The difference between the two appears to have no practical significance.

Magnitude: Warnings associated with the haptic and combined interfaces were judged to be stronger than with the auditory interface during directional warning presentation. The interfaces were essentially equal and optimal during non-directional warning presentation.

Appropriateness: There were no significant effects for this dimension. The grand mean was 3.96, which suggests that participants found the lateral CAS to be only moderately appropriate in its activations. This may mean that participants felt they had to deal with too many false or nuisance alarms (though this dimension does not address what, if any, is an "appropriate" or "acceptable" number of false alarms).

Disturbing: Again, no significant differences were obtained along this dimension. A grand mean of 4.92 indicates that participants found the lateral CAS somewhat disturbing to their normal driving in the simulator.

Beneficial for Normal Driving in Simulator: No significant differences were identified for this dimension. The grand mean for this dimension was 3.33, which implies a somewhat low driver perception of benefit for normal driving. Given a demonstration of driver performance advantages, this perception could be ameliorated by sufficient training with the CAS.

Trust: There were differential levels of trust engendered by the lateral CAS with respect to hazard magnitude and onset of warning. However, regardless of these differerences, the system was not readily trusted by participants. An educational program geared toward having CAS support in cars may lead to improvement of driver trust.

Confusion: Auditory and haptic directional warnings were equally less confusing than the combined directional warnings. When a non-directional presentation was used, the haptic and combined warnings were usually less confusing than the auditory warnings. Both the haptic and auditory interfaces were perceived to be less confusing than the combined interface when the interfaces were controlled by the TTD algorithm. The haptic interface was the least confusing interface for the strong lateral threat, followed by the combined and then the auditory interface. However, when the weak lateral threat was introduced, the haptic and auditory interfaces were judged to be equal with respect to confusion, and both of them were less confusing than the combined interface.

Benefit--Potential Collision: Participants judged that either the auditory or the haptic interface is may beneficial for avoiding potential crashes when the lateral threat is weak. However, for those threats that are strong, the combined interface is less confusing than the other interfaces, and is judged to be more helpful, again, relative to the other interfaces.

Benefit--Everyday Driving: No significant effects were obtained along this dimension. Average response to this dimension was 3.63, indicative of a general low perception of benefit for everyday driving.

Desire: The grand mean for this dimension was 3.35, which suggests little desire on participants' part for the lateral CAS. There was evidence that participants found the system more desirable when it produced late warnings for strong lateral threats. The project team interpreted this to mean that participants would want a lateral CAS that, all else being equal, only activates when ncecessary.

### 8.5.2 The Longitudinal Scenario

Onset: While there were no significant effects associated with this dimension, the average response rating was 4.18, which, at the midpoint, is an optimum rating. It would appear that participants found the longitudinal CAS onsets to be acceptable.

Duration: Although there was a significant interaction between Interface and Algorithm for this dimension, all of the mean values were located around the 4.00 midpoint. The centering around the midpoint suggests that the durations of the longitudinal warnings were judged to be acceptable.

Magnitude: The results did not reveal any significant differences among the independent variables with respect to this dimension. The grand mean was 3.96, suggesting that the magnitudes were judged to be near optimum.

Appropriateness: The grand mean of 4.09 implies only a perception of moderate appropriateness. This can be interpreted to mean that participants felt that the longitudinal system emitted too many false or nuisance alarms.

Disturbing: None of the interfaces was judged to be overly disturbing with respect to either directionality or algorithm. The haptic and auditory interfaces were less disturbing than the combined under conditions of a directional presentation of warnings. Under conditions of a non-directional presentation of warnings, the haptic and combined interfaces were both less disturbing than the auditory interface. The haptic interface appears more disturbing than either of the other interfaces when pulse braking was used upon approach to a curve. It also appears that the haptic interface is much less disturbing than either auditory or combined when no pulse braking is a part of the curve approach algorithm. This tends to support a conclusion that the haptic interface and pulse braking algorithm should not be implemented in combination in a longitudinal CAS based on driver perceptions that this combination is disturbing.

Beneficial--Normal Driving in Simulator: A grand mean of 3.93 and the absence of significant differences indicates that participants found the longitudinal CAS only mildly beneficial for their driving.

Trust: A grand mean of 4.44 suggests only a modest level of trust for the longitudinal system.

Confusion: With a directional presentation of warnings, the auditory and haptic interfaces were judged to cause much less confusion than did the combined interface. However, for non-directional presentation, the haptic and combined interfaces were less confusing than the auditory interface. Overall, directional warnings were less confusing than their non-directional analogs.

Benefit--Potential Collision: Participants' perceptions of benefit for potential crashes could only be grouped on the basis of onset of warning. They found the system beneficial for crashes when presented with late rather than early warnings.

Benefit--Everyday Driving: The onset of warning effect noted immediately before occurs with this dimension as well. Late rather than early warnings are perceived as beneficial for everyday driving. This indicates that, all else being equal, drivers find the CAS beneficial to their everyday driving when it activates less (which it would do with a late onset configuration).

Desire: The amount of variability in responses to this dimension prevented the identification of reliable differences among the independent variables. The grand mean for this response was 3.88, which implies that participants were only moderately interested in owning the longitudinal CAS.

### 8.5.3 The Curve Negotiation Case

Frequency: Participants' perception of frequency of activations was rather varied, with a grand mean of 4.35. This is taken to mean that the system was judged to respond with the necessary frequency.

Appropriateness: A mean of 4.52 implies perception of a modest level of appropriateness. This, again, insinuates that participants were concerned about being presented with false alarms.

Disturbing: Directional presentation of warnings was appraised by participants to be less disturbing than non-directional presentation.

Beneficial--Simulator Curve: The grand mean of 3.44 implies that participants did not feel that the lateral CAS was beneficial for them when negotiating simulated curves in this study.

Trust: Participants indicated a modest level of trust for the lateral CAS during curve negotiation ($M$= 4.16).

Confusion: The haptic and auditory interfaces are equally less confusing than the combined interface during directional warning presentation. However, the haptic and combined interfaces are less confusing than the auditory during non-directional presentation. The haptic interface is much less confusing than either the auditory or combined interfaces when controlled by the TLC algorithm. The auditory and combined interfaces are less confusing than the haptic, however, when controlled by the TTD algorithm.

Benefit--Potential Collision: As has been seen before, the system was judged to be only modestly beneficial for avoding a potential collision ($M$= 4.11).

Benefit--Everday Driving: The system was seen as only slightly beneficial for everday driving ($M$= 3.38).

Desire: Participants level of desire to own the lateral CAS for curve negotiation was low ($M$= 2.97).

There was a great deal of variability within the subjective assessment data. This may be attributed, in part, to the novelty of the CAS concepts, and, in part, to the nature and specificity of the questions. For example, the fact that there were sometimes hazard effects on questions that asked about driving in general suggests that in the future, such questions might best be asked after a period of general driving. While the variability in the data makes it difficult to identify patterns of subjective preference, there are fairly firm recommendations based on subjective impressions that can be made with respect to the CAS design aspects evaluated in the current study. The term "preference" is adopted as a general way of reflecting CAS aspects which participants regarded more positively than others.

Directionality: 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.

Interface: The indications from the subjective assessments are that either the haptic or auditory interface as currently configured should be selected over the combined interface.

Onset: 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.

Algorithm: The overall degree of variability associated with algorithm (that is, the paucity of significant algorithm effects) suggests that further research needs to be conducted to evaluate a suitable CAS algorithm.

CAS Acceptance: 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).

## 9.0 General Conclusions

This report presents the results of an exploratory study of Collision Avoidance System (CAS) concepts suitable for roadway departure collision avoidance. This work was executed under Phase I, Task 3 of the National Highway Transportation Safety Administration (NHTSA) Roadway Departure Collision Avoidance System Specification Program to develop performance specifications for countermeasures that prevent or reduce the severity of single vehicle roadway departure crashes. According to the 1991 General Estimates System (GES) crash data, this crash type accounts for approximately 20.8% of all crashes, and 37.4% of all fatal crashes in the United States. Countermeasures that could prevent or reduce the severity of even a fraction of these crashes would have a significant benefit to society.

The purpose of the study was to evaluate following items from a driver-oriented perspective:

a) Multiple system concepts (haptic versus auditory versus combined-modality interfaces; directional versus non-directional driver warnings; alternative lane keeping warning/intervention algorithms; warning/control thresholds; alternative speed warning/intervention algorithms). It is important to assess a wide variety of factors early in the program to identify fruitful directions for future research. Thus, assessment of multiple system concepts was deemed critical.

b) Normal driving situations (general lanekeeping on a straightaway, general curve negotiation). It is important to assess the effects of CAS concepts on normal driving.

c) Key collision hazard scenarios (e.g., roadway departure at curves due to excessive speed, roadway departure on straightaway due to driver inattention or incapacitation). These scenarios allow for initial feasibility and effectiveness assessments in the context of key driving conditions associated with roadway departure crashes.

d) Assessments of driver acceptance of various CAS concepts, especially in terms of false or nuisance alarm impacts on driver behavior to support effectiveness estimates. If roadway departure collision avoidance systems are to be viable, they must be acceptable to drivers. Furthermore, they must be used in the manner intended by the system designers. It is worthwhile to begin such assessments early on in the simulator testing.

Sixty-four volunteers participated in a study conducted at the Iowa Driving Simulator (IDS), a 6-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 and 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 non-directional), Onset (early CAS onset or late CAS onset), and Algorithm (Time-to-Line-Crossing or TLC versus Time-to-Trajectory Divergence or TTD for lanekeeping and No-pulse vs. pulse braking for approach to a curve). All participants were assigned to either high hazard or low magnitude hazard conditions based on two collision hazards. 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. The longitudinal or curve disturbance involved approach at highway speed to a curve for which no speed sign was posted; low hazard magnitude was equated to approach to an 800 ft-radius curve and high hazard magnitude was equated to approach to a 250 ft-radius curve. In addition, participant performance was assessed during normal (non-hazard) lanekeeping on a straightaway and during normal (non-hazard) curve negotiation early and late in a simulator session which lasted approximately 40 minutes. Five separate analyses were conducted and the following conclusions were reached for each analysis.

The general conclusions drawn from the general lanekeeping data analysis are the following:

- CAS support is associated with more precise lanekeeping under normal straightaway driving conditions (for both Early and Late driving segments).

- TLC causes relatively more driver workload than TTD (for both Early and Late driving segments).

- Early Onset settings lead to more CAS activations (a potential source of driver irritation) both early and late in the driving segments but it also leads 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.

The pattern of results for the lateral disturbance data was 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:

- Driver performance with CAS support did not statistically differ from performance of drivers without CAS support. However, there was a marginally significant trend toward fewer roadway departure crashes with CAS support than without.

- Trends in the data, though not statistically significant at the selected criteria, suggest that CAS may provide benefits in terms of earlier driver response, reduced roadway departure extent and acceleration, and more controlled evasive steering maneuvers.

- 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. Directional displays appear to be beneficial in high hazard situations.

- The TLC algorithm appears to be of greater benefit than TTD under high hazard situations.

The general conclusion to be drawn from the results of the data analysis for normal curve negotiation are that CAS support did not significantly alter driving behavior for normal curve negotiation. Drivers were driving close to the design speed for the curve and so the CAS support was generally not needed. At present, these data do not provide any strong evidence of a problem with any CAS support feature. Thus, it is appropriate to move on to an assessment of the impact of CAS on the curve hazard data. Based on the results of the general curve negotiation results, it is recommended that all CAS concepts be retained and other results be used to discriminate among them.

The longitudinal or curve hazard analysis yielded the following results:

- The most obvious conclusion that can be drawn strictly from the data on the longitudinal curve disturbance is that hazard magnitude had a rather strong effect on participants' driving behavior. Participants entered the 250 ft-radius, high hazard, curve at a slower speed than the 800 ft-radius, or low hazard, curve. Participants also exhibited greater maximum and mean decelerations with the 250 ft-radius curve than with the 800 ft-radius curve, and they also traversed the 250 ft-radius curve more slowly. Drivers also exhibited more steering reversals on the 800 ft-radius curve. These results serve as a substantial demonstration that the hazard magnitude manipulation had an effect on driver behavior in this study with respect to curve approach and negotiation.

- None of the CAS support concepts involved an abundance of significant main effects or interactions. However, there are indications that the auditory interface benefits driver behavior in that it led to shorter brake pedal RTs following a longitudinal alert than either the haptic or the combined interface. Furthermore, the auditory interface, when associated with the no-pulse braking longitudinal algorithm, led to slower curve entrance speeds than it did when combined with the pulse braking algorithm. However, the auditory interface led to slightly, but significantly greater lane deviations than did either the haptic or combined interfaces as drivers traversed the curves.

- Data on the effects of warning onset were equivocal. Late onset led to shorter brake reaction times (Rts) but this may simply reflect the fact that the driver had to begin braking sooner to smoothly negotiate the curve. Thus, no recommendations are offered with regard to this CAS feature.

- Directional warnings offered greater maximum decelerations than did the non-directional counterparts; however, the non-directional warnings led to slightly lesser lane deviations, especially in high hazard curves. With respect to the curve disturbance data, these were the only directionality effects obtained.

The last set of results focussed on subjective assessments by the participants who had some form of CAS support. While there were a number of inconsistencies in the subjective assessment data, the following trends were noted:

- 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) 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).

Based on these results taken as a whole, it appears that the concept of roadway departure CAS has potential, especially in terms of preventing roadway departures on a straightaway due to driver inattention. The curve approach CAS support concepts did not demonstrate any superiority over unsupported drivers but this may reflect weaknesses in the methodology used and the difficulty in thwarting the driver's normal information processing. Still, it is worthwhile to continue investigations into the development of better CAS concepts for avoidance roadway departures at curves as well as methods to test such concepts.

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. Early onset is advised for the lateral CAS concept, but a late-onset CAS may be preferred for the longitudinal (curve approach) 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 nonetheless indicates that driver acceptance will need to be a primary 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 factor remains a key element in achieving such gains.

## REFERENCES


Burke, M. W., Gilson, R. D., & Jagacinski, R. J. (1980). Multi-modal information processing for visual workload relief. *Ergonomics, 23*, 961-975.

Farber, B., Farber, B., A., Godthelp, H., & Schumann, J. (1991). *State of the art and recommendations for characteristics of speed and steering support systems* (Deliverable Report DRIVE V1041/GIDS-CON01). Haren, The Netherlands: Traffic Research Centre, University of Groningen.

Farber, B., Naab, K., & Schumann, J. (1991). *Evaluation of prototype implementation in terms of handling aspects of driving tasks* (Deliverable Report DRIVE V1041/GIDS CON3). Haren, The Netherlands: Traffic Research Institute, University of Groningen.

Fenton, R. E. (1966). An improved man-machine interface for the driver-vehicle system. *IEEE Transactions on Human Factors in Electronics, HFE-7*(4), 150-157.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin Company.

Gilson, R. D., & Fenton, R. E. (1974). Kinesthetic-tactile information presentation -- Inflight studies. *IEEE Transactions on Systems, Man, and Cybernetics, 4*, 81-90.

Godthelp, H. (1984). *Studies of human vehicle control.* Soesterburg, The Netherlands: TNO Institute for Perception.

Godthelp, J. (1990). *The use of an active gas pedal as an element of an intelligent driver support system: Literature review and exploratory study* (Report No. 1990 B-17). Soesterberg, The Netherlands: TNO Institute for Perception.

Godthelp, H., & Schumann, J. (1991). The use of an intelligent accelerator as an element of a driver support system. *Proceedings of the 24th International Symposium on Automotive Technology and Automation (ISATA) Conference*, pp. 615-622.

Godthelp, H., & Schumann, J. (1993). Intelligent accelerator: An element of driver support. In A. M. Parkes and S. Frantzen (Eds.), *Driving future vehicles* (pp. 265-274). London: Taylor and Francis.

Jagacinski, R. J., Flach, J. M., & Gilson, R. D. (1983). A comparison of visual and kinesthetic-tactual displays for compensatory tracking. *IEEE Transactions on Systems, Man, and Cybernetics, 13*, 1103-1112 .

Jagacinski, R. J., Miller, D. P., & Gilson, R. D. (1979). A comparison of kinesthetic-tactual and visual displays via a critical tracking task. *Human Factors, 21*, 79-86.

Janiga, D. V., & Mayne, R. W. (1977). Use of a nonvisual display for improving the manual control of an unstable system. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-7*, 530-537.

Janssen, W. H. (1989). *The impact of collision avoidance systems on driver behaviour and traffic safety: Preliminaries to studies within the GIDS projects* (Deliverable No. GIDS MAN1). Groningen, The Netherlands: Traffic Research Institute, University of Groningen.

Janssen, W. H., & Nilsson, L. (1990). *An experimental evaluation of in-vehicle collision avoidance systems* (DRIVE Project V1041, GIDS Report No. GIDS/MAN2). Haren, The Netherlands: Traffic Research Center, University of Groningen.

Janssen, W. H., & Nilsson, L. (1993). Behavioural effects of driver support. In A. M. Parkes and S. Frantzen (Eds.), *Driving future vehicles* (pp. 147-155). London: Taylor and Francis.

Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd ed.). Englewood Cliffs, NJ: Prentice-Hall.

MacDonald, W. A., & Hoffmann, E. R. (1980). Review of relationships between steering wheel reversal rate and driving task demand. *Human Factors, 22*, 733-739.

McGehee, D.V., Dingus, T. A., & Horowitz, A. D. (1994). An experimental field test of automotive headway maintenance/collision warning visual displays, *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, pp. 1099-1103.

McRuer, D. T., Allen, R. W., Wier, D. H., & Klein, R. H. (1977). New results in driver steering control models. *Human Factors, 19*, 381-397.

Mirchandani, P. B. (1972). An auditory display in a dual-axis tracking task. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-2*(3), 375-380.

Muto, W.H., & Wierwille, W.W. (1982). The effect of repeated emergency response trials on performance during extended duration simulated driving. *Human Factors, 24*, 693-698.

Nilsson, L, Alm, H., & Jansson, W. (1991). *Collision avoidance systems -- Effects of different levels of task allocation on driver behavior* (Report No. GIDS/MAN3). Soesterberg, The Netherlands: TNO Institute for Perception.

Paris, C. R., Gilson, R. D., Thomas, M. H., & Silver, C. (1995). Effect of synthetic voice intelligibility on speech comprehension. *Human Factors, 37*, 335-340.

Pline, J. L. (Ed.) (1992). *Traffic engineering handbook* (4th ed.). Englewood Cliffs, NJ: Prentice Hall.

Pomerleau, D., Kumar, B., Everson, J., Kopala, E., & Lazofson, L. (1995). *Run-off-road collision avoidance using IVHS countermeasures: Task 3 report - Volume 1* (Contract No. DTNH22-93-C-07023). Pittsburgh, PA: Carnegie-Mellon University Robotics Institute.

SAS Institute (1992). *SAS/STAT User's Guide, Version 6* (4th ed.). Carey, NC: Author.

Schiff, W., & Arnone, W. (1995). Perceiving and driving: Where parallel roads meet. In P. Hancock, J. Flach, J. Caird, & K. Vicente (Eds.), *Local applications of the ecological approach to human-machine systems* (pp. 1-34). Hillsdale, NJ: Lawrence Erlbaum.

Schumann, J., Godthelp, H., Farber, B., & Wontorra, H. (1993). Breaking up open-loop steering control actions: The steering wheel as an active control device. In A. Gale et al. (Eds.), *Vision in vehicles IV* (pp. 321 - 332). Amsterdam: Elsevier.

Schumann, J., Lowenau, J., & Naab, K. (in press). The active steering wheel as a continuous support for the driver's lateral control task. To be published in A. G. Gale et al. (Eds.), *Vision in vehicles V.*

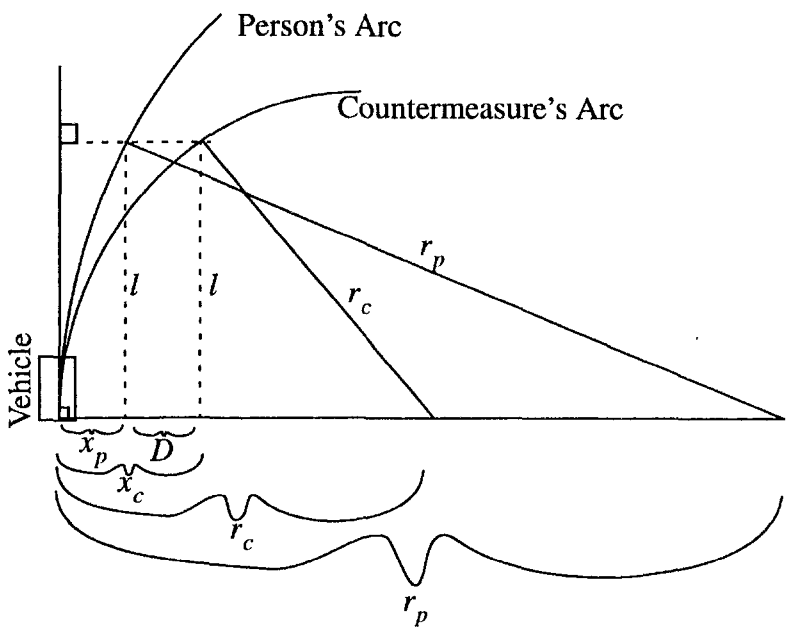
Tijerina, L. (1995, January). *Key human factors research needs in IVHS crash avoidance* (Paper No. 950250). Paper presented at the Transportation Research Board 74th Annual Meeting, Washington, DC (to be published in *Transportation Research Record*).

Vinje, E. W., & Pitkin, E. T. (1972). Human operator dynamics for aural compensatory tracking. *IEEE Transactions on Systems, Man, and Cybernetics*, *SMC-2*(4), 504-512.

Wickens, C. D. (1992). *Engineering psychology and human performance* (2nd ed.). New York: Harper Collins.

# Appendix A:

## Mathematical Derivation of TTD Calculation




$$r_c^2 = l^2 + (r_c - x_c)^2 \qquad r_p^2 = l^2 + (r_p - x_p)^2 \qquad D = |x_c - x_p|$$

$$x_c \approx \frac{l^2}{2r_c} \qquad x_p \approx \frac{l^2}{2r_p} \qquad D \approx \left|\frac{l^2}{2r_c} - \frac{l^2}{2r_p}\right|$$

$$D \approx \frac{l^2}{2}\left|\frac{1}{r_c} - \frac{1}{r_p}\right|$$

$$l \approx \sqrt{\frac{2D}{\left|\frac{1}{r_c} - \frac{1}{r_p}\right|}}$$

where:
$r_p$ = turn radius of person (1/m)
$r_p$ = turn radius of countermeasure (1/m)
$D$ = distance apart for TTD calculation (~1.1m)
$l$ = distance ahead arcs are D meters apart (m)
$x_p$ = displacement of person's arc at $l$ (m)
$x_c$ = displacement of countermeasure's arc at $l$ (m)
$v$ =vehicle velocity (m/sec)
$TTD$ = time to trajectory divergence (seconds)

$$TTD \approx \frac{l}{v} \qquad TTD \approx \frac{\sqrt{\frac{2D}{\left|\frac{1}{r_c} - \frac{1}{r_p}\right|}}}{v}$$

## Appendix B:

## The "Slowing Distance" Longitudinal Algorithm

The current algorithm of the curve warning system is as follows:

1. *Get the current location [latitude/longitude] from the controller.*

The CMUcontroller currently uses differential GPS to get the position. Accuracy at slow speeds is $\pm$ 3 meters. At highway speeds there is a latency problem with the current GPS receiver that reduces the accuracy to about $\pm$ 10 meters. We are trying to improve that by various methods. Getting a receiver with 10 Hz update rate (current one has 1Hz update rate) could reduce the effects due to latency.

2. *Project the current location on to a previously recorded path or to a road in the commercial map database.*

The ETAK Premium database has a claimed accuracy of 40 feet from the centerline.

3. *Starting at the projected point, extract the road geometry (list of lane center points and turn-radius information) for a specified lookahead distance.*

Curvature information is either calculated directly from the geometry of the lane center points or recorded from the encoder on the steering wheel and stored explicitly in the map (for more accuracy). Lookahead distance varies based on current speed and type of road. We use distance equivalent to about 4 - 6 s of travel as the lookahead distance. It is purely empirical and needs some tuning]

4. *For each lane center point within the lookahead distance, calculate the target speed.*

s_t = 3.1174539 * sqrt[r * (e+f)];

where:
s_t = Target speed for that point (meters/sec)
r = Radius of curvature at that point (1/m)
e = Superelevation at that point (m/m)
f = Lateral coefficient of friction (g)
(Ref: Page 164, Traffic Engineering Handbook)

For the initial experiments we fix the superelevation at 0.08m/m. Lateral coefficient of friction is the difficult one to estimate. The range 0.4 to 0.6 seems to be a reasonable window for dry conditions. This is a very early result and more discussion about this is included in the following section

5. *Decide whether to ALERT or WARN if the current speed is higher than the system's estimated safe speed.*

Explanation: There is a small difference between ALERT and WARN modes. After driving for a while without any audible alert or warning from the system, the driver is not attentive and accordingly his reaction time should be taken into consideration in the calculation. The reaction time ($T_d$) reduces the available distance-budget by the amount ($cur\_speed * T_d$). This reduced distance_budget in turn determines the estimated safe speed at the current point. ALERT signal is issued if current velocity ($V_o$) is greater than the estimated safe alert speed ($V_{alert}$) at the same point according to equation A below. Currently the ALERT is an audible tone, since we don't have the control of the accelerator pedal on our testbed. For ALERT, Battelle suggested a 0.5 s, 1000Hz tone followed by 0.6 s of silence (for a total of 1.1 s to give the driver a chance to respond).

Once an ALERT is issued, for the next 5 seconds (5 s is arbitrary; needs to be tested and modified) the system ignores the driver reaction time in its calculation of safe speed. This is reasonable because the driver has heard an ALERT tone in the immediate past and should either be decelerating or at least prepared for further input/warning from the system. WARN signal is issued if current velocity ($V_o$) is greater than the estimated safe warn speed ($V_{warn}$) at the same point, according to equation B below. The warning is a continuous repetition of a short tone, where the repetition rate is proportional to the difference between actual current speed and estimated safe speed at the current point.

Note: The actual calculation of the tone repetition rate uses ratio of ($V_o$ - $V_{warn}$) / $V_{warn}$ (instead of using difference ($V_o$ - Vwarn); 5 mph over speed limit is bad in 20mph zone but is more tolerable in a 60 mph zone).

If no further WARN condition exists in the 5 sec time period after an ALERT has been issued, the system reverts back to ALERT mode.

Algorithm:
Considering
- current speed,
- target/design speed,
- safe deceleration and
- the driver reaction time

the safe (ideal) current velocity needed to accomplish this is calculated. Here is the slowing distance algorithm suggested by Battelle solved for velocity instead of distance.

Calculate either $V_{alert}$ or $V_{warn}$:

$$V_{alert} = SQRT\,[(V_t)^2 + 2a * (D_{cur} - V_o * T_d)]$$

Where:
V_alert = Ideal (desired) Safe speed at the current location
D_cur = Distance from curve to trigger alert
V_o = Initial velocity (m/sec)
V_t = Target/design velocity for curve (m/sec)
T_d = Human reaction time (approx. 1.5 seconds)
a = Assumed deceleration driver will perform (0.17 to 0.3 g)

For any of the road points within the lookahead distance in front of the vehicle, if V_alert smaller than the vehicle's current velocity (V_o), an ALERT is triggered.

**OR**

V_warn = SQRT [(V_t)^2 + 2a * D_cur]

Where:

V_warn = Ideal (desired) Safe speed at the current location
D_cur = Distance from curve to trigger warn
V_o = Initial velocity (m/sec)
V_t = Target/design velocity for curve (m/sec)
T_d = Human reaction time (approx. 1.5 seconds)
a = Assumed deceleration driver will perform(0.17 - 0.3 m/sec^2)

For any of the road points within the lookahead distance in front of the vehicle, if V_warn smaller than the vehicle's current velocity (V_o), a WARNING is triggered.

Note: The second equation is really the second term of the "slowing distance equation" from earlier drafts of the plan, solved for velocity instead of distance.

6. *Get the next location and go to step 2.*

Several Issues

The literature on roadway condition, road-tire interaction and highway geometry suggests that the traction available for the safe passage is a based on many independent variables with large variation.

Examples include:
- Road surface macro structure
- Road surface micro structure
- Condition of the tire
- Tire inflation
- Road condition due to weather, etc.

Above factors along with following conditions determine the safe speed for a particular point in the curve.

- Curvature
- Super elevation, shoulder etc.
- Visibility
- Horizontal Stopping Sight Distance, Spiral transitions, grade
- Driver comfort (deceleration and lateral movement) and
- Experience of the driver and how they negotiate the curve.

Along with this if you add issues like driver reaction time, false alarms, vehicle capability (location of CG of the vehicle, ABS) it becomes more complex.

The measurement of road condition due to weather (in-vehicle or infrastructure) and how it affects traction itself is a major issue that needs to be addressed. Our initial search indicates there are no readily (commercially) available vehicle mounted sensors that can measure road surface conditions like, snow, ice and waterdepth and wheelslip.

The information in the literature mostly deals with "how to design roads", (where they consider worst case conditions) rather than answer "given the road condition/geometry what is the safe speed").

Side friction coefficient and superelevation:

The AASHTO traffic engineering handbook gives a table where the design speed (in mph) is compared with minimum radius in (ft). It is obtained from the equation:

$$R = \frac{V * V}{15 (e + f)}$$

R = radius of curvature in ft
V = is speed of the vehicle in mph
e = rate of super elevation (feet/ft of width)
f = coefficient of side friction between tire and road

Superelevation:

Values for superelevation "e" vary from 0.04 to .12. The text says: "Maximum superelevation rates are established with consideration of operation at slow speeds, and under snow and icing conditions. In North America it is a historical practice to design high-speed highways with maximum superelevation rates of 0.08 to 0.10 feet/ft. In special cases it is 0.12 and in urban areas 0.06 to 0.08 are common".

Side Friction:

Values for sidefriction "f" vary from 0.17 at 20mph to 0.1 at 70mph. "Design values assumed for side friction are a function of both measured and observed coefficients of friction under various road conditions, as well as consideration of driver comfort. AASHTO [A Policy on Geometric Design of Highways and streets, 1990. American Association of State Highway and Transportation] recommends design side friction factors as shown in one of the figures where the above range of values (0.1 to 0.17) for sidefriction are depicted".

But the discussion says: "The design of curves as proposed by the AASHTO policy is based on the implied assumption that the vehicle tracks the curve as it is designed. It is not possible if the curve is unspiraled. Research not only confirms the AASHTO design assumption is invalid, but the dynamics of driving on curves are quite different from design assumptions. Typical and critical (aggressive) drivers track unspiraled curves in a manner that produces significantly greater friction demands on the tire/roadway interface than they are intended by AASHTO design policy. As a result the intended factor of safety in the AASHTO design policy is much less than anticipated".

Since the values for *e* and *f* are picked for worst case condition in designing the roadways, it becomes very difficult to arrive at a safe warning speed using the same set of design equations.

At the same time, the report titled "Road surface characteristics: their interaction and their optimization" prepared by "OECD SCIENTIFIC EXPERT GROUP - Organization for Economic Co-operation and Development, France. 1984" presents a graph that shows the influence of water depth on Peak Lateral Friction for both full treaded and smooth tires.

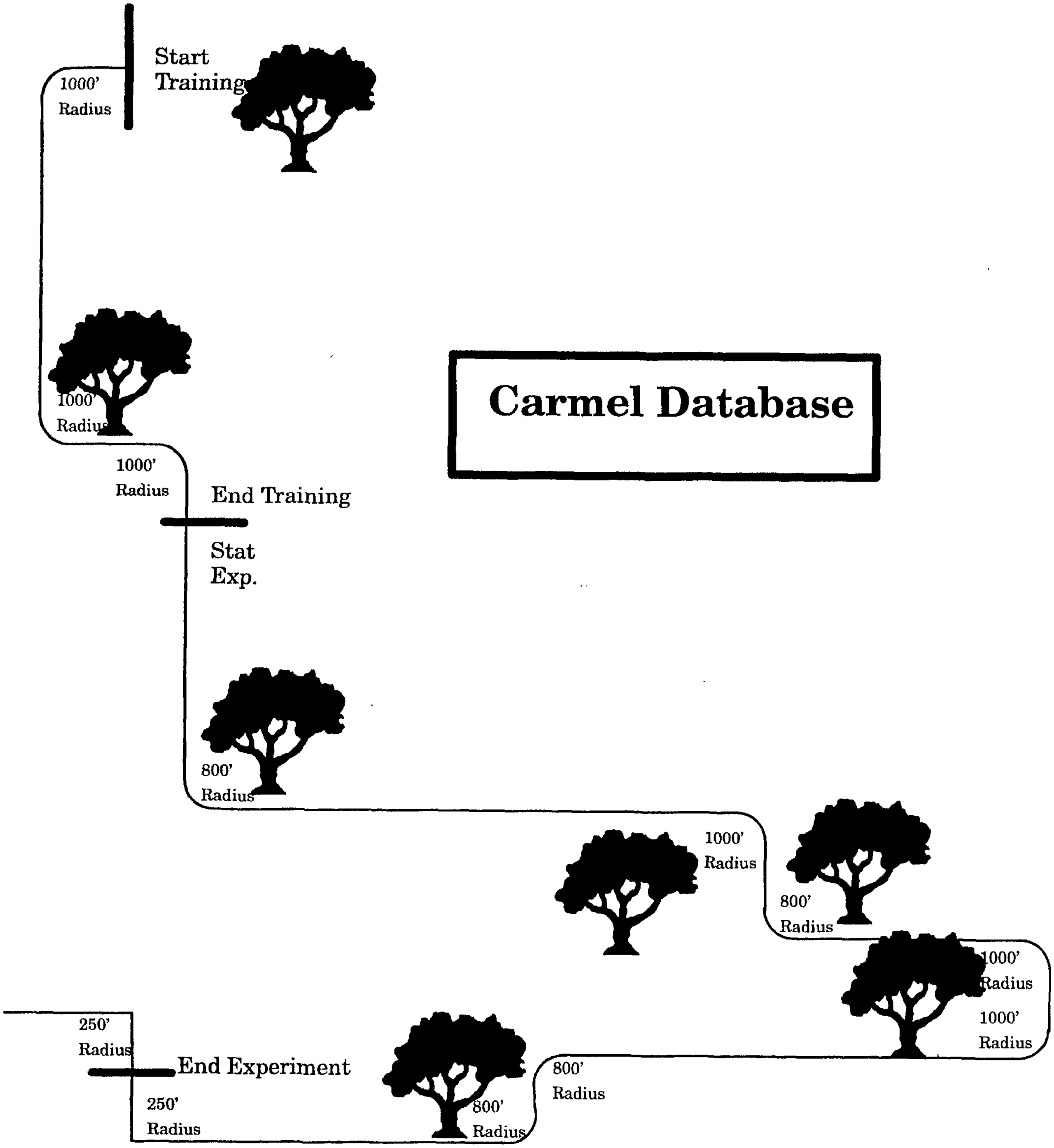
FULL TREAD: DRY CONDITION .9
WET CONDITION .8 at 20 mph
.55 to .68 at 40 mph
.2 to .6 at 60 mph

SMOOTH TREAD: DRY CONDITION .9
WET CONDITION .6 at 20 mph
.35 to .5 at 40 mph
.15 to .35 at 60 mph

These data indicate that AASHTO guidelines are very conservative and wetness of the road and condition of the tire can influence the friction by a huge range. If you are traveling in a well designed road and under dry conditions, it is possible to take the curve at more than twice the design speed. Then, what is the speed at which we should warn the driver?

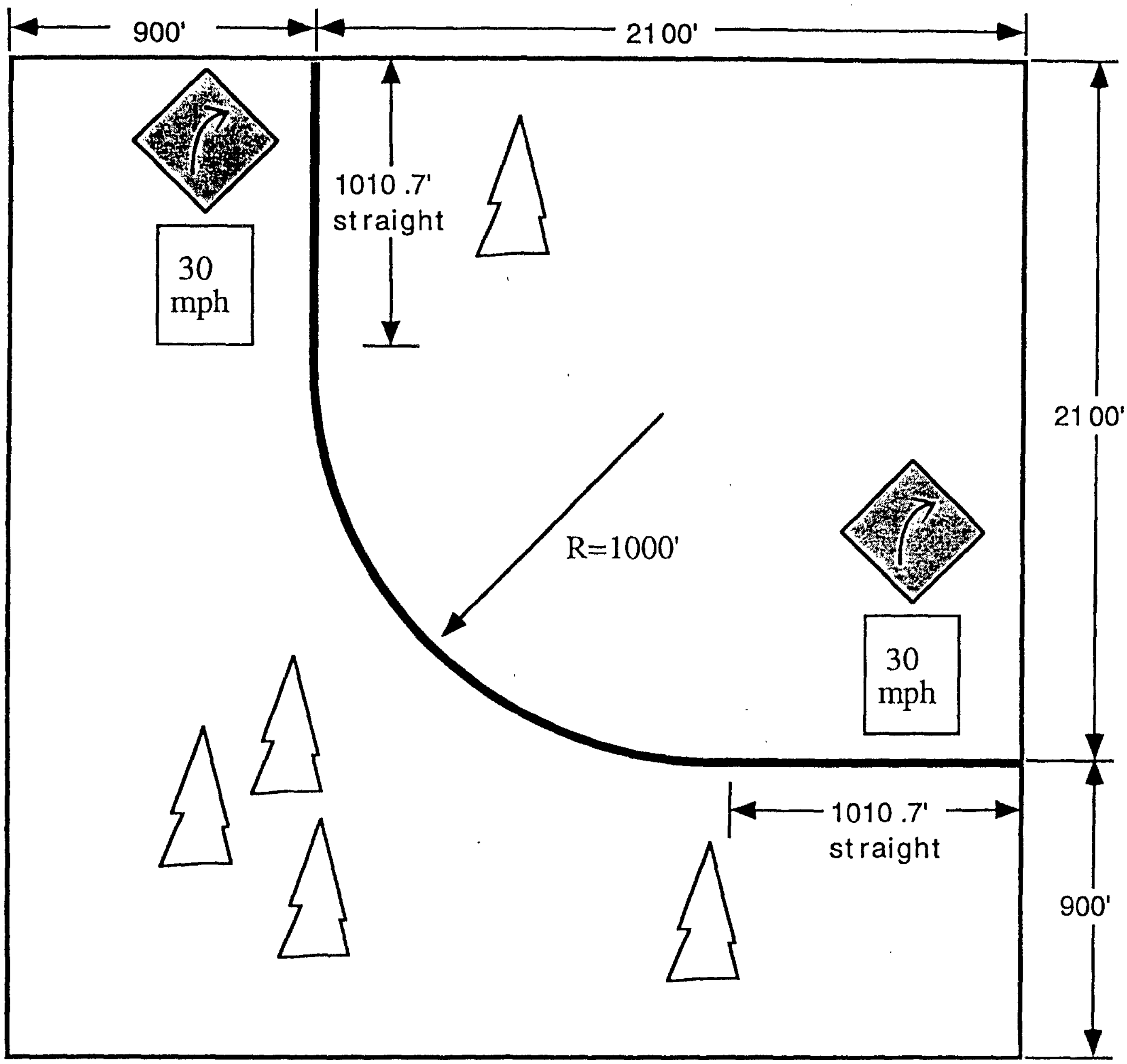
## Appendix C:

## Roadway Course Schematics and Tiles


Start
Training
1000'
Radius
1000'
Radius
1000'
Radius
End Training
Stat
Exp.
800'
Radius
1000'
Radius
800'
Radius
1000'
Radius
1000'
Radius
800'
Radius
800'
Radius
250'
Radius
End Experiment
250'
Radius
Carmel Database

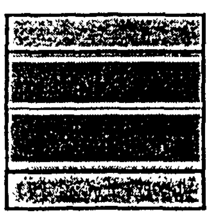
# CMU tile1

**Rural primary curve**




**Road surface:**

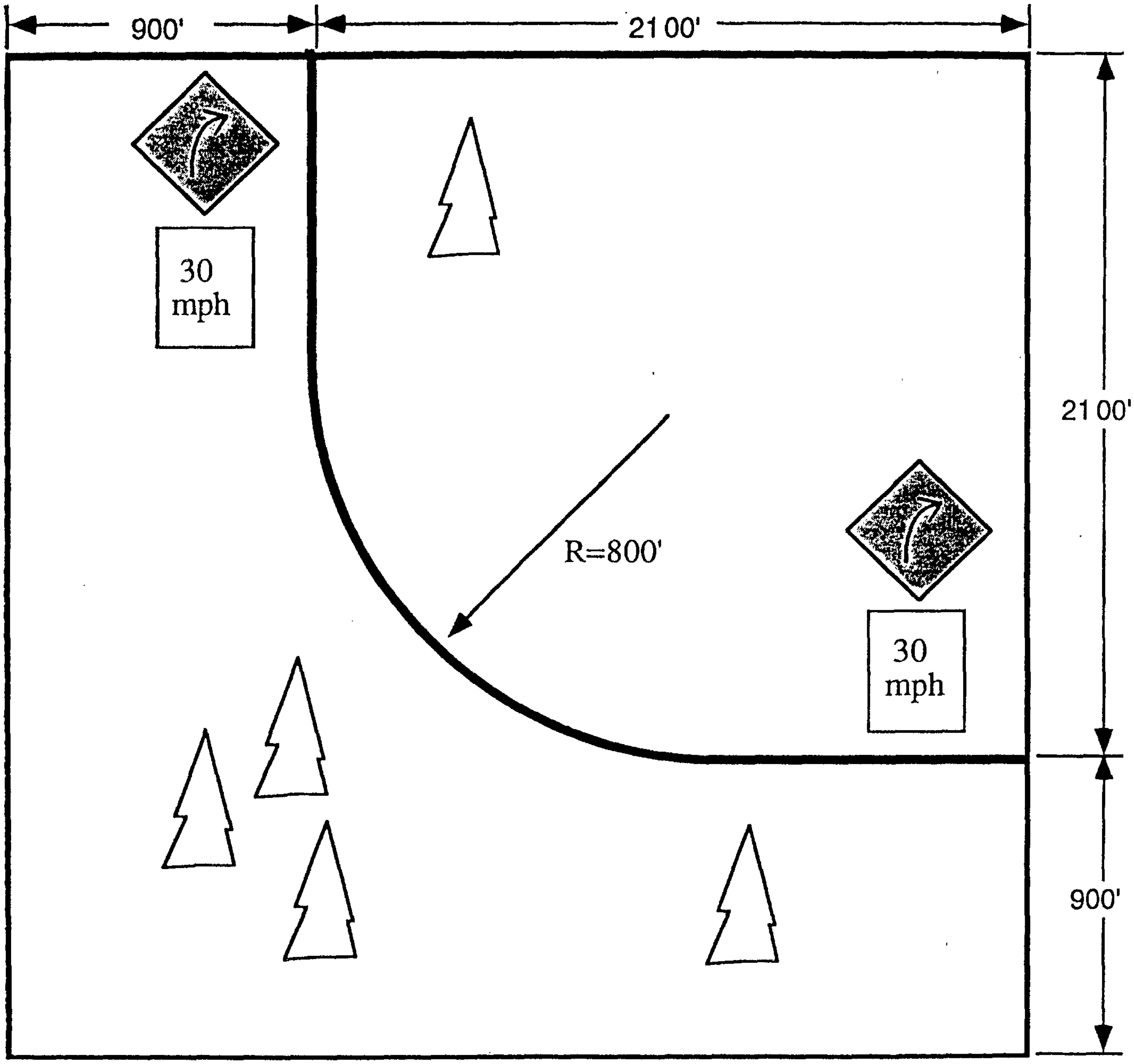
- Dry road, no snow berms
- 10' grass berm to ditch
- Full barrier with edgelines




3000'X3000' area
1000' radius
4% superelevation
176' spirals
Curve warning signs
Posted 30 mph

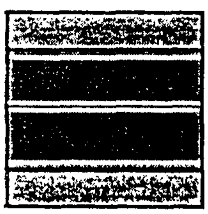
# CMU tile2

**Rural secondary curve**




**Road surface:**

Dry road, no snow berms
10' grass berm to ditch
Full barrier with edgelines

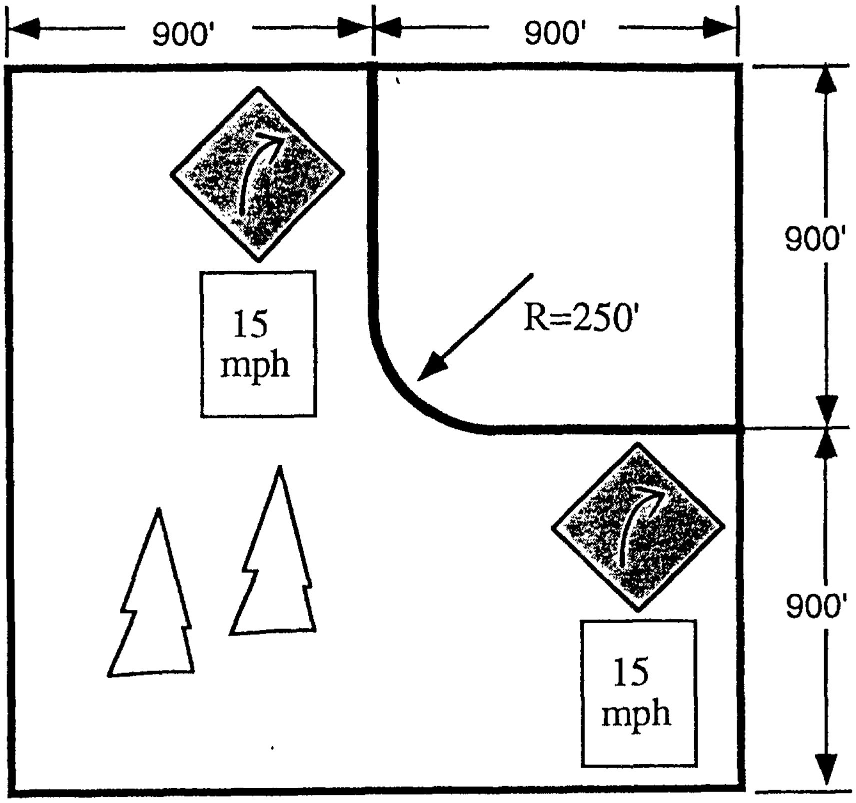


10' lanes
3' gravel shoulders

3000'X3000' area
800' radius
No superelevation
No spirals
Curve warning signs
Posted 30 mph

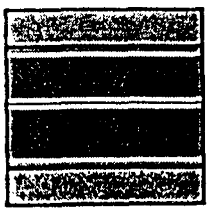
# CMU tile4

**Rural short radius secondary curve**




**Road surface:**

Dry road, no snow berms
10' grass berm to ditch
Full barrier with edgelines

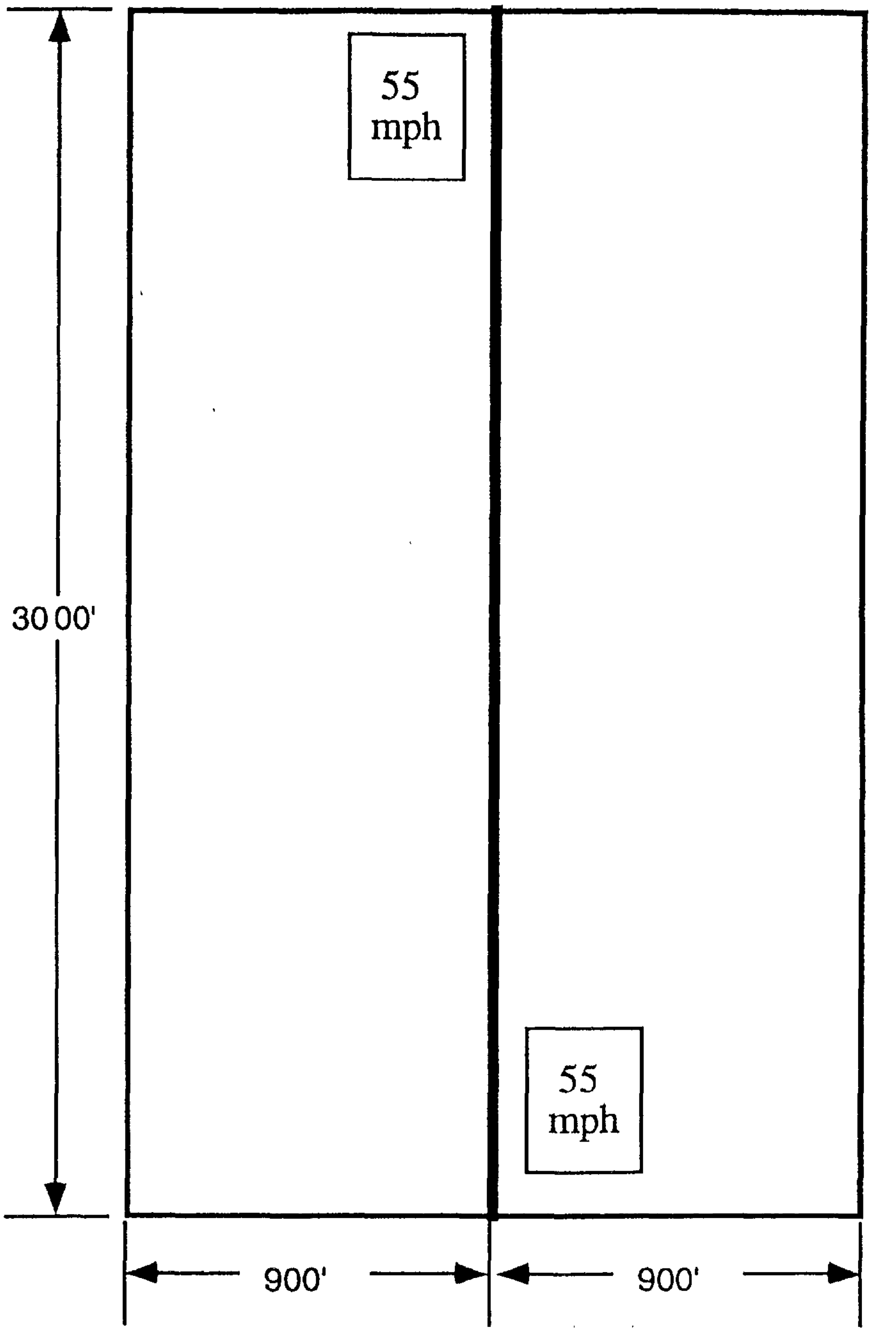


10' lanes
3' gravel shoulders

1800'X1800' area
250' radius
No superelevation
No spirals
Curve warning signs
Posted 15 mph

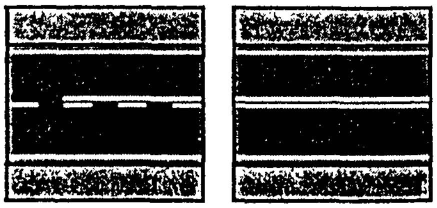
# CMU tile5

**Straight, flat**




**Road surface:**

Dry road, no snow berms
10' grass berm to ditch
Full barrier with edgelines

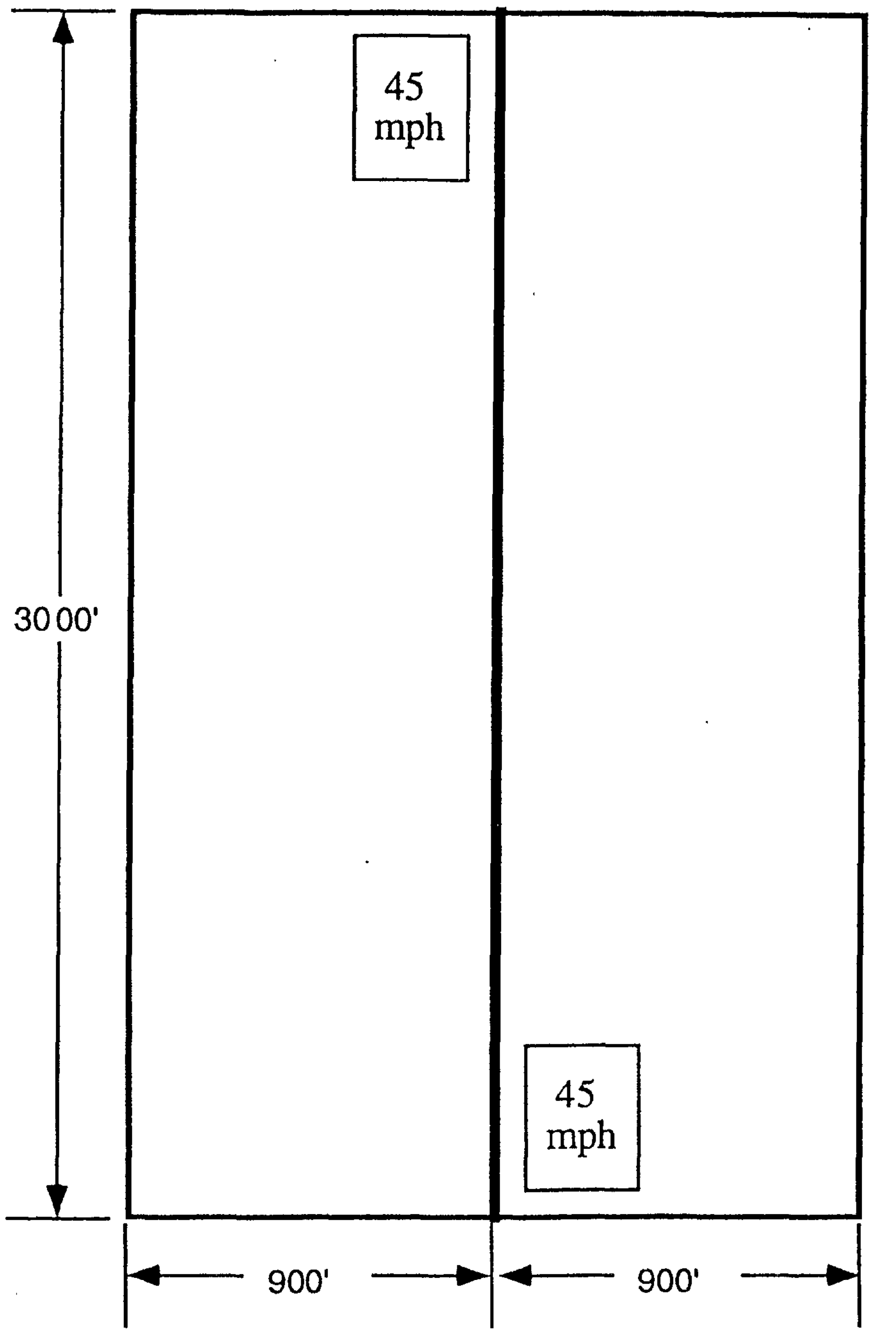


10' lanes
3' shoulders

3000'X1800'
Posted 55 mph

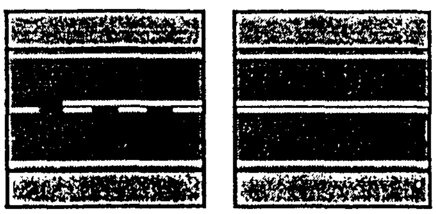
# CMU tile7

**Straight, flat**




**Road surface:**

Dry road, no snow berms
10' grass berm to ditch
Full barrier with edgelines



10' lanes
3' shoulders

3000'X1800'
Posted 45 mph

## Appendix D:

## University of Iowa Information Sheet for Test Participants

INFORMATION SUMMARY

Project Title: Run-Off-Road Crash Avoidance Using IVHS Countermeasures

Principal
Investigator: Richard Romano

Thank you for agreeing to participate in this study. The objective of this study is to better understand how advanced technology might be used to avoid certain types of crashes. In particular, this study examines crashes that might occur due to drifting out of one's travel lane. It also examines crashes that might occur if a vehicle departs the roadway at a curve.

For the purposes of testing, you will be asked to drive a route for about one hour. This drive is on a 2-lane undivided roadway with light traffic. You will be traveling at highway speeds and you should obey traffic signs, posted speed limits, and safe rules of the road. As part of the drive, we will occasionally ask you to perform tasks while driving. For example, we may ask you to check your mirrors or read a card presented by your research host.

Your participation in this study will greatly enhance our understanding of normal driving performance, as well as the nature of driver support systems. It is important to remember that we are testing various driving situations and warning systems. This is not an intelligence test and we are not trying to uncover poor driving on your part. Your name will not be associated with your data. Your participation is voluntary. You may discontinue participation at any time without penalty or loss of benefits to which you are entitled. You should understand that you have the right to ask questions at any time and that you can contact Richard Romano at 335-5697 for information about the study and your rights.

I have discussed the above points, including the information required by the Iowa Fair Information Practices Act, with the subject or the legally authorized representative, using a translator when necessary. It is my opinion that the subject understands the risks, benefits, and obligations involved in participation in this project.

| | | | |
|---|---|---|---|
| Investigator | Date | Witness | Date |

## Appendix E:

## Informed Consent Form for Task 3 Simulator Study

CONSENT FORM

Project Title: Run-Off-Road Crash Avoidance Using IVHS Countermeasures

Principal
Investigator: Richard Romano

I certify that I have been informed about the study in which I am about to participate. I have been told the procedures to be followed and how much time is involved. I have also been told that all records which may identify me will be kept confidential. I understand the possible risks and the possible benefits to me and to others from the research.

I have been given adequate time to read the attached summary. I understand that I have the right to ask questions at any time and that I can contact Richard Romano at 335-5697 for information about the research and my rights.

I understand that my participation is voluntary and that I may refuse to participate or withdraw my consent and stop taking part at any time without penalty or loss of benefits to which I may be entitled. I hereby consent to take part in this research project.

____________________________________
Signature of Participant

**Appendix F:**

**Scripts for Audio Tapes**

## <<1. Baseline Script>>

Thank you for coming in today. Before you begin your drive today, we would like to provide you some information. The study you are participating in is sponsored by the National Highway Safety Administration. or the NHTSA. Together with the NHTSA, we are evaluating the effectiveness of new automotive safety technologies that may prevent or reduce the severity of car crashes where the car runs off the road. Instead of a real vehicle, you will be driving in a simulator for about 40 minutes. We are interested in your suggestions and comments on the driving simulators realism on long and curvy rural roadway. If you find that you are approaching a curve too fast or if you are about to depart from your lane of travel, you should take whatever action you judge most appropriate to ensure safe driving.

While you are in the simulator, a research host will accompany you during your drive and will asked you to perform various tasks, such as counting the number of bars on a card.

If you have any questions, please feel free to ask you research host. Again, thank you participating today! We hope you enjoy your experience on the Iowa Driving Simulator.

**<<2. Auditory–No; Haptic–Yes; Directional–No>>**

Thank you for coming in today. Before you begin your drive, we would like to provide you some information. The study you are participating in is sponsored by the National Highway Traffic Safety Administration, the NHTSA. Together with the NHTSA, we are investigating the effectiveness of new automotive safety technologies that may prevent or reduce the severity of car crashes where the driver runs off the road. You will be driving for about 40 minutes on the Iowa Driving Simulator.

The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, the steering wheel will vibrate briefly. This indicates that you may need to steer to avoid departing your lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast for a curve ahead, the accelerator pedal will vibrate briefly. If you continue to drive too fast you will receive one additional vibration on the accelerator pedal. These vibrations indicated that you may need to slow down to safely negotiate the upcoming curve.

While you are in the simulator, a research host will accompany you during your drive and will asked you to perform various tasks. While you drive, your research host will ask you to count the number of bars on a card. This will be demonstrated once you are in the simulator.

To review, there are two technologies installed on the vehicle you will be driving. One alerts if you about to deviate from the lane either to the right or to the left by vibrating the steering wheel briefly. The second technology alerts you if your speed is too fast for an approaching curve by vibrating the accelerator pedal briefly. During the drive, it is possible that a waning may be present when you feel you are fully in control of the vehicle. Please use your judgment accordingly.

If you have any questions, please feel free to ask your research host. Again, thanks for participating today! We hope you enjoy your experience on the Iowa Driving Simulator!

**<<3. Auditory–No; Haptic–Yes; Directional–Yes>>**

Thank you for coming in today. Before you begin your drive, we would like to provide you some information. The study you are participating in is sponsored by the National Highway Traffic Safety Administration, the NHTSA. Together with the NHTSA, we are investigating the effectiveness of new automotive safety technologies that may prevent or reduce the severity of car crashes where the driver runs off the road. You will be driving for about 40 minutes on the Iowa Driving Simulator.

The safety systems that you will be driving today alert you if you are approaching a curve too fast or if you deviate from your lane. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, the car will momentarily turn in the direction that will take you vehicle back into the lane. This input will only be provided briefly an therefore only begins to move the steering wheel in the appropriate direction—you must continue controlling the steering wheel to ensure that your vehicle remains within you lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast for a curve ahead, the accelerator pedal will vibrate briefly. If you continue to drive too fast for the approaching curve, the accelerator pedal will push back against your foot and the vehicle will begin to decelerate until you have reached a sage speed for the up coming corner.

While you are in the simulator, a research host will accompany you during your drive and will asked you to perform various tasks. While you drive, your research host will ask you to count the number of bars on a card. This will be demonstrated once you are in the simulator.

**<<4 Auditory–Yes; Haptic–No; Directional–No>>**

Thank you for coming in today. Before you begin your drive, we would like to provide you some information. The study you are participating in is sponsored by the National Highway Traffic Safety Administration, the NHTSA. Together with the NHTSA, we are investigating the effectiveness of new automotive safety technologies that may prevent or reduce the severity of car crashes where the driver runs off the road. You will be driving for about 45 minutes on the Iowa Driving Simulator.

The safety systems that you will be driving today alert you if you are approaching a curve too fast or if you deviate from your lane. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone. The tone indicates to you that you may need to steer to avoid departing you lane.

In addition, the car also will alert you if you are driving too fast for an approaching curve. If you are driving too fast for a curve ahead, you will briefly hear a different tone. The tones indicate that you may need to slow down to safely negotiate that upcoming curve.

While you are in the simulator, a research host will accompany you during your drive and will asked you to perform various tasks. For example. while you drive, your research host will ask you to count the number of bars on a card. This will be demonstrated once you are in the simulator.

To review, there are two systems installed on the vehicle you will be driving. One alerts if you are about to deviate from the lane either to the right or to the left by providing a tone. The second technology alerts you if your speed is too fast for an approaching curve by generating a different tone. It is possible that a warning may be presented when you feel you are fully in control of the vehicle. Please use you best judgment and act accordingly.

If you have any questions, please feel free to ask your research host. Again, thanks for participating today! We hope you enjoy your experience on the Iowa Driving Simulator!

To review, there are two systems installed on the vehicle you will be driving. One alerts you if you are about to deviate from the lane either to the right or to the left by providing a tone that comes from the direction you are heading. The second alerts you if your speed is too fast for an approaching curve by generating a different tone. If you continue to drive too fast you will hear a continuos warning. It is possible that a warning may be presented when you feel you are fully in control of the vehicle. Please use you best judgment and act accordingly.

If you have any questions, please feel free to ask your research host. Again, thanks for participating today! We hope you enjoy your experience on the Iowa Driving Simulator!

**<<5. Auditory–Yes; Haptic–No; Directional–Yes>>**

Thank you for coming in today. Before you begin your drive, we would like to provide you some information. The study you are participating in is sponsored by the National Highway Traffic Safety Administration, the NHTSA. Together with the NHTSA, we are investigating the effectiveness of new automotive safety technologies that may prevent or reduce the severity of car crashes where the driver runs off the road. You will be driving for about 45 minutes on the Iowa Driving Simulator.

The safety systems that you will be driving today alert you if you are approaching a curve too fast or if you deviate from your lane. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone coming from the right side of the vehicle if you are heading for the shoulder and the left side of the vehicle if you are heading across the center line. The tone indicates to you that you may need to steer to avoid departing your lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast for curve ahead, you will briefly hear a different tone. If you continue to drive too fast you will her a continuos auditory tone. This tone will become more urgent of you continue to go too fast for the approaching curve.

While you are in the simulator, a research host will accompany you during your drive and will asked you to perform various tasks. For example. while you drive, your research host will ask you to count the number of bars on a card. This will be demonstrated once you are in the simulator.

To review, there are two systems installed on the vehicle you will be driving. One alerts you if you are about to deviate from the lane either to the right or to the left by momentarily turning the steering wheel in the direction that will take your vehicle back to the center of your lane. The second technology alerts you if your speed is too fast for an approaching curve by vibrating the accelerator pedal briefly and pushing back against your foot. It is possible that a warning may be presented when you feel you are fully in control of the vehicle. Please use you best judgment and act accordingly.

If you have any questions, please feel free to ask your research host. Again, thanks for participating today! We hope you enjoy your experience on the Iowa Driving Simulator!

**<<6. Auditory–Yes; Haptic–Yes; Directional–No>>**

Thank you for coming in today. Before you begin your drive, we would like to provide you some information. The study you are participating in is sponsored by the National Highway Traffic Safety Administration, the NHTSA. Together with the NHTSA, we are investigating the effectiveness of new automotive safety technologies that may prevent or reduce the severity of car crashes where the driver runs off the road. You will be driving for about 45 minutes on the Iowa Driving Simulator.

The safety systems that you will be driving today alert you if you are approaching a curve too fast or if you deviate from your lane. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone and feel the steering wheel vibrate. These warning indicate to you that you may need to steer to avoid departing your lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast for a curve ahead, you will briefly hear a different tone and feel a vibration on the accelerator pedal. If you continue to drive too fast you will hear and feel an additional tone and vibration. These warnings indicate that you may need to slow down to safely negotiate the upcoming curve.

While you are in the simulator, a research host will accompany you during your drive and will asked you to perform various tasks. For example. while you drive, your research host will ask you to count the number of bars on a card. This will be demonstrated once you are in the simulator.

To review, there are two systems installed on the vehicle you will be driving. One alerts you if you deviate from the lane either to the right or to the left by sounding a high-pitched tone and vibrating the steering wheel. The second technology alerts you if your speed is too fast for an approaching curve by generating a different tone and vibrating the accelerator pedal. It is possible that a warning may be presented when you feel you are fully in control of the vehicle. Please use your best judgment and act accordingly.

If you have any questions, please feel free to ask your research host. Again, thanks for participating today! We hope you enjoy your experience on the Iowa Driving Simulator!

## 7 Auditory–Yes; Haptic–Yes; Directional–Yes

Thank you for coming in today. Before you begin your drive, we would like to provide you some information. The study you are participating in is sponsored by the National Highway Traffic Safety Administration, the NHTSA. Together with the NHTSA, we are investigating the effectiveness of new automotive safety technologies that may prevent or reduce the severity of car crashes where the driver runs off the road. You will be driving for about 45 minutes on the Iowa Driving Simulator.

The safety systems that you will be driving today alert you if you are approaching a curve too fast or if you deviate from your lane. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone coming from the right side of the vehicle if you are heading for the shoulder and the left side of the vehicle if you are heading across the center line. In addition, the steering wheel will momentarily turn in the direction that will take you vehicle back into the lane. This steering input will only be provided briefly and therefore only begins to move the steering wheel in the appropriate direction you must continue controlling the steering wheel to ensure that you vehicle remains within your lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast curve ahead, you will briefly hear a different tone and feel the accelerator pedal vibrate. If you continue to drive too fast you will hear a continuous auditory tone and the accelerator pedal will push back against your foot and the vehicle will begin to decelerate until you have reached a safe speed fore the upcoming corner. The tone will become more urgent if you are going faster.

To review, there are two systems installed on the vehicle you will be driving. One alerts you if you deviate from the lane either to the right or to the left by providing a tone from the direction you are heading and momentarily turning the steering wheel in the direction that will take your vehicle back to the center of your lane. The second technology alerts you of your speed is too fast foe approaching curve by generating a different tone and vibrating the accelerator briefly. If you continue to drive too fast, your will hear a continuous auditory warning and the accelerator pedal will press back against your foot. If is possible that a warning may be presented when you feel you are fully in control of the vehicle. Please use your best judgment and act accordingly.

If you have any questions, please feel free to ask your research host. Again, thanks for participating today! We hope you enjoy your experience on the Iowa Driving Simulator!

## Appendix G:

## In-Vehicle Scripts

# IN-VEHICLE SCRIPT
# BASELINE CONDITION

Enter dome. Seat driver and assist then in adjusting the seat and mirrors.

After driver is comfortable...

E: To review, you will be driving today on a curvy rural two-lane highway today for about 40 minutes. Please observe the posted speed limits and drive as you normally do. We are interested in your driving experience. If you find you are approaching a curve too fast or if you are about to depart you travel lane, you should take whatever action you judge most appropriate to ensure safe driving. From time to time I will display this card with bars, please turn around when I ask you and tell me how many bars are displayed on the card.

Do you have any questions? <<all answers should come from the training script and worded accordingly>>

E: We should be ready in a moment. You will feel a bump as the motion base raises and then I will tell you when to begin. To start we will begin on a practice drive so that you are able to get a feel for the cars steering and brakes. All cars drive a little differently, so we would like you to get of used to the feel of this car.

E: Go ahead and begin driving. If the gear selector is not already in drive, please shift into drive. You may begin. Go ahead and accelerate to 65 mph and get a feel for the steering. It may be a little more sensitive than you are used to. << after the first curve ask for a card reading>>

<<once driver is at speed>>

E: OK, to get a feel of the brakes, go ahead and lightly press on the brakes.

How does the car feel? Are you comfortable with the temperature of the inside of the car? <<At the end of the practice portion>>

<<if you observe the driver a feeling comfortable with the drive, continue without slowing down>>

E: That is the end of the practice drive, we will continue driving now

<<Following the practice drive, limit conversation with the subject>>

# IN-VEHICLE SCRIPT
## <<2. Auditory–No; Haptic–Yes; Directional–No>>

Enter dome. Seat driver and assist then in adjusting the seat and mirrors.

After driver is comfortable...

E: To review, you will be driving today on a curvy rural two-lane highway for about 40 minutes. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, the steering wheel will vibrate briefly. This indicates that you may need to steer to avoid departing your lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast for a curve ahead, the accelerator pedal will vibrate briefly. If you continue to drive too fast you will receive one additional vibration on the accelerator pedal. These vibrations indicated that you may need to slow down to safely negotiate the upcoming curve.

If you find you are approaching a curve too fast or if you are about to depart you travel lane, you should take whatever action you judge most appropriate to ensure safe driving. From time to time I will display this card with bars, please turn around when I ask you and tell me how many bars are displayed on the card.

Do you have any questions? <<all answers should come from the training script and worded accordingly>>

E: We should be ready in a moment. You will feel a bump as the motion base raises and then I will tell you when to begin. To start we will begin on a practice drive so that you are able to get a feel for the cars steering and brakes. All cars drive a little differently, so we would like you to get of used to the feel of this car.

E: Go ahead and begin driving. If the gear selector is not already in drive, please shift into drive. You may begin. Go ahead and accelerate to 65 mph and get a feel for the steering. It may be a little more sensitive than you are used to. << after the first curve ask for a card reading>>

Go ahead and deviate to the left so you can experience how the steering vibrates. Now to the right.

<<once driver is at speed>>

E: OK, to get a feel of the brakes, go ahead and lightly press on the brakes.

How does the car feel? Are you comfortable with the temperature of the inside of the car? <<At the end of the practice portion>>

<<at the first curve have them drive 65 so they can experience the foot feedback>>

E: Just so you will experience what the gas pedal feedback feels like, why don't you drive 65 into the next curve.

<<if you observe the driver a feeling comfortable with the drive, continue without slowing down>>

E: That is the end of the practice drive, we will continue driving now.

<<Following the practice drive, limit conversation with the subject>>

## IN-VEHICLE SCRIPT
## <<3. Auditory–No; Haptic–Yes; Directional–Yes>>

Enter dome. Seat driver and assist then in adjusting the seat and mirrors.

After driver is comfortable...

E: To review, you will be driving today on a curvy rural two-lane highway for about 40 minutes. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, the car will momentarily turn in the direction that will take you vehicle back into the lane. This input will only be provided briefly an therefore only begins to move the steering wheel in the appropriate direction—you must continue controlling the steering wheel to ensure that your vehicle remains within you lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast for a curve ahead, the accelerator pedal will vibrate briefly. If you continue to drive too fast for the approaching curve, the accelerator pedal will push back against your foot and the vehicle will begin to decelerate until you have reached a sage speed for the up coming corner.

If you find you are approaching a curve too fast or if you are about to depart you travel lane, you should take whatever action you judge most appropriate to ensure safe driving. From time to time I will display this card with bars, please turn around when I ask you and tell me how many bars are displayed on the card.

Do you have any questions? <<all answers should come from the training script and worded accordingly>>

E: We should be ready in a moment. You will feel a bump as the motion base raises and then I will tell you when to begin. To start we will begin on a practice drive so that you are able to get a feel for the cars steering and brakes. All cars drive a little differently, so we would like you to get of used to the feel of this car.

E: Go ahead and begin driving. If the gear selector is not already in drive, please shift into drive. You may begin. Go ahead and accelerate to 65 mph and get a feel for the steering. It may be a little more sensitive than you are used to. << after the first curve ask for a card reading>>

Go ahead and deviate to the left so you can experience how the steering vibrates. Now to the right.

<<once driver is at speed>>

E: OK, to get a feel of the brakes, go ahead and lightly press on the brakes.

How does the car feel? Are you comfortable with the temperature of the inside of the car? <<At the end of the practice portion>>

<<at the first curve have them drive 65 so they can experience the foot feedback>>

E: Just so you will experience what the gas pedal feedback feels like, why don't you drive 65 into the next curve.

<<if you observe the driver a feeling comfortable with the drive, continue without slowing down>>

E: That is the end of the practice drive, we will continue driving now.

<<Following the practice drive, limit conversation with the subject>>

**IN-VEHICLE SCRIPT**
**<<4. Auditory–Yes; Haptic–No; Directional–No>>**

Enter dome. Seat driver and assist then in adjusting the seat and mirrors.

After driver is comfortable...

E: To review, you will be driving today on a curvy rural two-lane highway for about 40 minutes. The safety systems that you will be driving today alert you if you are approaching a curve too fast or if you deviate from your lane. The system will also alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone. The tone indicates to you that you may need to steer to avoid departing you lane.

In addition, the car also will alert you if you are driving too fast for an approaching curve. If you are driving too fast for a curve ahead, you will briefly hear a different tone. The tones indicate that you may need to slow down to safely negotiate that upcoming curve.

If you find you are approaching a curve too fast or if you are about to depart you travel lane, you should take whatever action you judge most appropriate to ensure safe driving. From time to time I will display this card with bars, please turn around when I ask you and tell me how many bars are displayed on the card.

Do you have any questions? <<all answers should come from the training script and worded accordingly>>

E: We should be ready in a moment. You will feel a bump as the motion base raises and then I will tell you when to begin. To start we will begin on a practice drive so that you are able to get a feel for the cars steering and brakes. All cars drive a little differently, so we would like you to get of used to the feel of this car.

E: Go ahead and begin driving. If the gear selector is not already in drive, please shift into drive. You may begin. Go ahead and accelerate to 65 mph and get a feel for the steering. It may be a little more sensitive than you are used to. << after the first curve ask for a card reading>>

Go ahead and deviate to the left so you can experience how the steering vibrates. Now to the right.

<<once driver is at speed>>

E: OK, to get a feel of the brakes, go ahead and lightly press on the brakes.

How does the car feel? Are you comfortable with the temperature of the inside of the car? <<At the end of the practice portion>>

<<at the first curve have them drive 65 so they can experience the foot feedback>>

E: Just so you will experience what the gas pedal feedback feels like, why don't you drive 65 into the next curve.

<<if you observe the driver a feeling comfortable with the drive, continue without slowing down>>

E: That is the end of the practice drive, we will continue driving now.

<<Following the practice drive, limit conversation with the subject>>

## IN-VEHICLE SCRIPT
## <<5. Auditory–Yes; Haptic–No; Directional–Yes>>

Enter dome. Seat driver and assist then in adjusting the seat and mirrors.

After driver is comfortable...

E: To review, you will be driving today on a curvy rural two-lane highway for about 40 minutes. The safety systems that you will be driving today alert you if you are approaching a curve too fast or if you deviate from your lane. The system you will drive will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone coming from the right side of the vehicle if you are heading for the shoulder and the left side of the vehicle if you are heading across the center line. The tone indicates to you that you may need to steer to avoid departing your lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast for curve ahead, you will briefly hear a different tone. If you continue to drive too fast you will her a continuos auditory tone. This tone will become more urgent of you continue to go too fast for the approaching curve.

If you find you are approaching a curve too fast or if you are about to depart you travel lane, you should take whatever action you judge most appropriate to ensure safe driving. From time to time I will display this card with bars, please turn around when I ask you and tell me how many bars are displayed on the card.

Do you have any questions? <<all answers should come from the training script and worded accordingly>>

E: We should be ready in a moment. You will feel a bump as the motion base raises and then I will tell you when to begin. To start we will begin on a practice drive so that you are able to get a feel for the cars steering and brakes. All cars drive a little differently, so we would like you to get of used to the feel of this car.

E: Go ahead and begin driving. If the gear selector is not already in drive, please shift into drive. You may begin. Go ahead and accelerate to 65 mph and get a feel for the steering. It may be a little more sensitive than you are used to. << after the first curve ask for a card reading>>

Go ahead and deviate to the left so you can experience how the steering vibrates. Now to the right.

<<once driver is at speed>>

E: OK, to get a feel of the brakes, go ahead and lightly press on the brakes.

How does the car feel? Are you comfortable with the temperature of the inside of the car? <<At the end of the practice portion>>

<<at the first curve have them drive 65 so they can experience the foot feedback>>

E: Just so you will experience what the gas pedal feedback feels like, why don't you drive 65 into the next curve.

<<if you observe the driver a feeling comfortable with the drive, continue without slowing down>>

E: That is the end of the practice drive, we will continue driving now.

<<Following the practice drive, limit conversation with the subject>>

**IN-VEHICLE SCRIPT**
**<<6. Auditory–Yes; Haptic–Yes; Directional–No>>**

Enter dome. Seat driver and assist then in adjusting the seat and mirrors.

After driver is comfortable...

E: To review, you will be driving today on a curvy rural two-lane highway for about 40 minutes. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone and feel the steering wheel vibrate. These warning indicate to you that you may need to steer to avoid departing your lane.

If you find you are approaching a curve too fast or if you are about to depart you travel lane, you should take whatever action you judge most appropriate to ensure safe driving. From time to time I will display this card with bars, please turn around when I ask you and tell me how many bars are displayed on the card.

Do you have any questions? <<all answers should come from the training script and worded accordingly>>

E: We should be ready in a moment. You will feel a bump as the motion base raises and then I will tell you when to begin. To start we will begin on a practice drive so that you are able to get a feel for the cars steering and brakes. All cars drive a little differently, so we would like you to get of used to the feel of this car.

E: Go ahead and begin driving. If the gear selector is not already in drive, please shift into drive. You may begin. Go ahead and accelerate to 65 mph and get a feel for the steering. It may be a little more sensitive than you are used to. << after the first curve ask for a card reading>>

Go ahead and deviate to the left so you can experience how the steering vibrates. Now to the right.

<<once driver is at speed>>

E: OK, to get a feel of the brakes, go ahead and lightly press on the brakes.

How does the car feel? Are you comfortable with the temperature of the inside of the car? <<At the end of the practice portion>>

<<at the first curve have them drive 65 so they can experience the foot feedback>>

E: Just so you will experience what the gas pedal feedback feels like, why don't you drive 65 into the next curve.

<<if you observe the driver a feeling comfortable with the drive, continue without slowing down>>

E: That is the end of the practice drive, we will continue driving now.

<<Following the practice drive, limit conversation with the subject>>

## IN-VEHICLE SCRIPT
## 7. Auditory–Yes; Haptic–Yes; Directional–Yes

Enter dome. Seat driver and assist then in adjusting the seat and mirrors.

After driver is comfortable...

E: To review, you will be driving today on a curvy rural two-lane highway for about 40 minutes. The safety systems that you will be driving today will alert you if you are approaching a curve too fast or if you are about to depart from your lane. If you are about to depart from your lane, that is, cross either the center line or the white line on the shoulder, you will briefly hear a tone coming from the right side of the vehicle if you are heading for the shoulder and the left side of the vehicle if you are heading across the center line. In addition, the steering wheel will momentarily turn in the direction that will take you vehicle back into the lane. This steering input will only be provided briefly and therefore only begins to move the steering wheel in the appropriate direction you must continue controlling the steering wheel to ensure that you vehicle remains within your lane.

In addition, the car will alert you if you are driving too fast for an approaching curve. If you are driving too fast curve ahead, you will briefly hear a different tone and feel the accelerator pedal vibrate. If you continue to drive too fast you will hear a continuous auditory tone and the accelerator pedal will push back against your foot and the vehicle will begin to decelerate until you have reached a safe speed fore the upcoming corner. The tone will become more urgent if you are going faster.

Do you have any questions? <<all answers should come from the training script and worded accordingly>>

E: We should be ready in a moment. You will feel a bump as the motion base raises and then I will tell you when to begin. To start we will begin on a practice drive so that you are able to get a feel for the cars steering and brakes. All cars drive a little differently, so we would like you to get of used to the feel of this car.

E: Go ahead and begin driving. If the gear selector is not already in drive, please shift into drive. You may begin. Go ahead and accelerate to 65 mph and get a feel for the steering. It may be a little more sensitive than you are used to. << after the first curve ask for a card reading>>

Go ahead and deviate to the left so you can experience how the steering vibrates. Now to the right.

<<once driver is at speed>>

E: OK, to get a feel of the brakes, go ahead and lightly press on the brakes.

How does the car feel? Are you comfortable with the temperature of the inside of the car? <<At the end of the practice portion>>

<<at the first curve have them drive 65 so they can experience the foot feedback>>

E: Just so you will experience what the gas pedal feedback feels like, why don't you drive 65 into the next curve.

<<if you observe the driver a feeling comfortable with the drive, continue without slowing down>>

E: That is the end of the practice drive, we will continue driving now.

<<Following the practice drive, limit conversation with the subject>>

## Appendix H:

## Debrief Questionnaire for Participants Who Experienced Some Form of CAS Support

**Roadway Departure Crash Avoidance System Specification Program:**
**Phase I Task 3 Iowa Advanced Driving Simulator Study**
**Debrief Questionnaire**

**Part A: Lateral Situation**

1) To what extent do you feel the system increased the effort required for lane keeping?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Not at all Very much

Comment:______________________________________________

______________________________________________________

2) What is your opinion about when, during lane keeping, the system activated?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Far too early Far too late

Comment:______________________________________________

______________________________________________________

3) What is your opinion about the <u>duration</u> of the warnings to grab your attention?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Far too short Far too long

Comment:______________________________________________

______________________________________________________

4) What is your opinion about the magnitude (i.e., loudness for auditory display, force for haptic display) of the warnings to grab your attention?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Far too weak Far too strong

Comment:______________________________________________

______________________________________________________

5) To what extent do you think the system activated appropriately to your lane drift?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:________________________________________________

6) Did you experience the system as disturbing to your normal driving?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:________________________________________________

7) Did you experience the system as beneficial to your normal driving?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:________________________________________________

8) Did you trust the collision warning system?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:________________________________________________

9) Did you experience any confusion with the system as your worked to stay in your lane?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:________________________________________________

________________________________________________

10) Do you feel that the system would help you avoid a potential crash?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:________________________________________________

________________________________________________

11) To what extent do you believe the lane drift warning system would be of benefit to you in your everyday driving?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:________________________________________________

________________________________________________

12) How much would you like to have the lane drift warning system in your car?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

If other than "Not at all," ask "How much would you be willing to pay?" ________________

Comment:________________________________________________

________________________________________________

13) If you could redesign the warning system for helping you stay in your lane, what would you concentrate on to make it easier or more useful?

Comment: ___________________________________________________________

_____________________________________________________________________

_____________________________________________________________________

**Part B: Longitudinal (Curve Approach) Situation**

14) What is your opinion about when, during approach to a curve, the longitudinal system activated?

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|

Far too early — Far too late

Comment:______________________________________________

______________________________________________

15) What is your opinion about the <u>duration</u> of the alerts or warnings to grab your attention?

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|

Far too short — Far too long

Comment:______________________________________________

______________________________________________

16) What is your opinion about the <u>magnitude</u> (i.e., loudness for auditory display, force for haptic display) of the alerts or warnings to grab your attention?

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|

Far too weak — Far too strong

Comment:______________________________________________

______________________________________________

17) To what extent do you think the system activated appropriately to the curve approach?

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|

Not at all — Very much

Comment:______________________________________________

______________________________________________

18) Did you experience the system as disturbing to your driving?

|____|____|____|____|____|____|____|

1 2 3 4 5 6 7

Not at all Very much

Comment:______________________________________________

______________________________________________

19) Did you experience the system as beneficial to your driving?

|____|____|____|____|____|____|____|

1 2 3 4 5 6 7

Not at all Very much

Comment:______________________________________________

______________________________________________

20) Did you trust the collision warning system?

|____|____|____|____|____|____|____|

1 2 3 4 5 6 7

Not at all Very much

Comment:______________________________________________

______________________________________________

21) Did you experience any confusion with the system as you approached a curve?

|____|____|____|____|____|____|____|

1 2 3 4 5 6 7

Not at all Very much

Comment:______________________________________________

______________________________________________

22) Do you fell that the system would help you avoid a potential crash?

|______|______|______|______|______|______|______|

1 2 3 4 5 6 7

Not at all Very much

Comment:______________________________________________

______________________________________________________

23) To what extent do you believe the curve approach warning system would be of benefit to you in your everyday driving?

|______|______|______|______|______|______|______|

1 2 3 4 5 6 7

Not at all Very much

Comment:______________________________________________

______________________________________________________

24) How much would you like to have the curve approach warning system in your car?

|______|______|______|______|______|______|______|

1 2 3 4 5 6 7

Not at all Very much

If other than "Not at all," ask "How much would you be willing to pay?"______________

Comment:______________________________________________

______________________________________________________

25) If you could redesign the system for approach to a curve, what would you concentrate on to make it easier or more useful?

Comment: ______________________________________________

______________________________________________________

______________________________________________________

**Part C: Curve Negotiation Situation (Lateral System Operation While in Curve)**

26) What is your opinion about how often, when driving through the curve, the lateral system activated?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Far too little Far too often

Comment:____________________________________________

__________________________________________________

27) To what extent do you think the system activated appropriately when driving through the curve?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Not at all Very much

Comment:____________________________________________

__________________________________________________

28) Did you experience the system as disturbing to how you drove through the curve?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Not at all Very much

Comment:____________________________________________

__________________________________________________

29) Did you experience the system as beneficial to how you drove through the curve?

|________|________|________|________|________|________|________|

1 2 3 4 5 6 7

Not at all Very much

Comment:____________________________________________

__________________________________________________

30) Did you trust the collision warning system when driving through the curve?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:_______________________________________________

_______________________________________________________

31) Did you experience any confusion with the system as you drove through the curve?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:_______________________________________________

_______________________________________________________

32) Do you feel that the system would help you avoid a potential crash?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:_______________________________________________

_______________________________________________________

33) To what extent do you believe the warning system would of benefit to you in your everyday driving?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

Comment:_______________________________________________

_______________________________________________________

34) How much would you like to have the curve negotiation warning system in your car?

|_______|_______|_______|_______|_______|_______|_______|

1 2 3 4 5 6 7

Not at all Very much

If other than "Not at all," ask "How much would you be willing to pay?"__________________

Comment:____________________________________________________________

____________________________________________________________________

35) If you could redesign the system for driving through a curve, what would you concentrate on to make it easier or more useful?

Comment: ____________________________________________________________

____________________________________________________________________

____________________________________________________________________

## Appendix I:

## Design Matrix for Roadway Departure Simulator Study

## Table of Independent Factors for Task 3 Driving Simulator Study

| Factor | Code | |
|---|---|---|
| | - | + |
| 1. Auditory Display System | NO | YES |
| 2. Haptic Display System | NO | YES |
| 3 Hazard Magnitude | LOW (equivalent steering wheel angle offset of 19.35° clockwise for 1.0 s to simulate light wind gust for lateral scenario; 800 ft.-radius curve for longitudinal scenario) | HIGH (equivalent steering wheel angle offset of 38.7° clockwise for 1.0 s to simulate heavy wind gust for lateral scenario; 250 ft.-radius curve for longitudinal scenario) |
| 4 Directionality | NON-DIRECTIONAL | DIRECTIONAL |
| 5 Warning Onset | EARLY (TTD = 1.13 s, with D = 0.75 m, lookahead of 1.2 s and 0.7 s TLC for lateral scenario; 0.17 g assumed deceleration and 2.5 s driver time delay budget for longitudinal scenario) | LATE (TTD = 1.13 s, with D = 0.55 m, lookahead of 1.2 s and 0.0s TLC for lateral scenario; 0.3 g assumed deceleration and 2.5 s driver time delay budget for longitudinal scenario) |
| 6 Algorithm | "A" (TLC for lateral scenario; no pulse "wake up" braking for longitudinal scenario) | "B" (TTD for lateral scenario; pulse "wake up" braking for 0.5 s at 10% of pedal pressure for longitudinal scenario |

**Design Matrix for Roadway Departure Phase 1 Simulator Study**

| Subject | Factor Level | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | - | - | - | - | - | - |
| 2 | + | - | - | - | - | - |
| 3 | - | + | - | - | - | - |
| 4 | + | + | - | - | - | - |
| 5 | - | - | + | - | - | - |
| 6 | + | - | + | - | - | - |
| 7 | - | + | + | - | - | - |
| 8 | + | + | + | - | - | - |
| 9 | - | - | - | + | - | - |
| 10 | + | - | - | + | - | - |
| 11 | - | + | - | + | - | - |
| 12 | + | + | - | + | - | - |
| 13 | - | - | + | + | - | - |
| 14 | + | - | + | + | - | - |
| 15 | - | + | + | + | - | - |
| 16 | + | + | + | + | - | - |
| 17 | - | - | - | - | + | - |
| 18 | + | - | - | - | + | - |
| 19 | - | + | - | - | + | - |
| 20 | + | + | - | - | + | - |
| 21 | - | - | + | - | + | - |
| 22 | + | - | + | - | + | - |
| 23 | - | + | + | - | + | - |
| 24 | + | + | + | - | + | - |
| 25 | - | - | - | + | + | - |
| 26 | + | - | - | + | + | - |
| 27 | - | + | - | + | + | - |

| Subject | Factor Level | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 28 | + | + | - | + | + | - |
| 29 | - | - | + | + | + | - |
| 30 | + | - | + | + | + | - |
| 31 | - | + | + | + | + | - |
| 32 | + | + | + | + | + | - |
| 33 | - | - | - | - | - | + |
| 34 | + | - | - | - | - | + |
| 35 | - | + | - | - | - | + |
| 36 | + | + | - | - | - | + |
| 37 | - | - | + | - | - | + |
| 38 | + | - | + | - | - | + |
| 39 | - | + | + | - | - | + |
| 40 | + | + | + | - | - | + |
| 41 | - | - | - | + | - | + |
| 42 | + | - | - | + | - | + |
| 43 | - | + | - | + | - | + |
| 44 | + | + | - | + | - | + |
| 45 | - | - | + | + | - | + |
| 46 | + | - | + | + | - | + |
| 47 | - | + | + | + | - | + |
| 48 | + | + | + | + | - | + |
| 49 | - | - | - | - | + | + |
| 50 | + | - | - | - | + | + |
| 51 | - | + | - | - | + | + |
| 52 | + | + | - | - | + | + |
| 53 | - | - | + | - | + | + |
| 54 | + | - | + | - | + | + |
| 55 | - | + | + | - | + | + |

| Subject | Factor Level | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 56 | + | + | + | - | + | + |
| 57 | - | - | - | + | + | + |
| 58 | + | - | - | + | + | + |
| 59 | - | + | - | + | + | + |
| 60 | + | + | - | + | + | + |
| 61 | - | - | + | + | + | + |
| 62 | + | - | + | + | + | + |
| 63 | - | + | + | + | + | + |
| 64 | + | + | + | + | + | + |

Notes:

- The coding in the design matrix follows *standard order* for the first six columns. Note that this design is a full factorial in six factors at two levels each.

-

This design will support all analyses of interest for this experiment. For example, one can define a new variable called "Driver Support" that has four levels:
- none,
- auditory only
- haptic only
- combined.

This new independent variables, along with "Hazard Magnitude" could be used to answer questions with respect to a given dependent variable (e.g., RT after hazard onset in the lateral scenario, Velocity into the curve in the longitudinal scenario). such as:

Do the mean levels of driver support differ?
Do the hazard mangnidudes lead to significant mean differences?
Is there an interaction between the effects of driver support levels and hazard magnitudes.

For each Driver Support level there will be 16 subjects per cell. For each of the two levels of Hazard Magnitude there will be 32 subjects per cell. Within each of the 4 x 2 or 8 cells of the interaction there will be 8 subjects per cell. ANOVA or regression techniques can be applied to the data.

- Given there is a driver interface, it is possible to define a new indepdent variable, "Driver Interface", with three levels:

- auditory only
- haptic only
- combined..

A second analysis can be conducted that is a 3 x 2 x 2 x 2 x 2 completely randomized ANOVA design (three levels of "Driver Interface", two levels of "Hazard Magnitude", two levels of "Directionality", two levels of "Warning Onset", and two levels of "Algorithm"). This analysis will use only the 48 subjects with a driver interface for analysis.

For example, a test of the main effect of directionality will compare the 24 subjects with a non-directional interface (averaged across all other factors), with the 24 subjects who had a directional interface (averaged across all other factors). Similar logic applies to all two-way interactions as well. ANOVA techniques or regression methods will be applied to the data.