HAPTIC AND AUDITORY INTERFACES AS A COLLISION AVOIDANCE TECHNIQUE DURING ROADWAY DEPARTURES AND DRIVER PERCEPTION OF THESE MODALITIES

by

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A dissertation proposal submitted in partial fulfillment
of the requirements for the degree

of

Doctor Of Philosophy

in

Engineering

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

April, 2006

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Laura Stanley
April 2006

Mom and Dad, I did it.
Shelly Hogan, thank you for your loyalty and steadfast support.
To the coal fields of Appalachia.

ACKNOWLEDGMENTS

I would like to express my gratitude to Mike Kelly and Robert Marley for their continued encouragement throughout my PhD program. Both have supported me in more ways than one and have been phenomenal mentors. I hope to have their mentorship for years to come. Dr. Marley, I will be waiting for you to return to the other side. To my Mother, always steadfast in her support, has given me the best graduation present one could receive, I've been waiting. To my Father, who established a model in himself, he provided me the encouragement to complete such an endeavor. To my grandparents who never had such an opportunity in Appalachia. To my grandmother whom I know is smiling. And to my biggest fan as I am her biggest fan, Shelly Hogan, we entered this "PhD land" together and I have walked the land, now it's your turn to finish the walk.

A special thanks to Western Transportation Institute's (WTI) Fellowship Program that has supported me not only financially, but in the development of a transportation oriented career that I believe will lead to a rewarding *road* ahead. WTI has provided many students the unique opportunity to conduct research, attend conferences, and to develop a network of colleagues and friendships that will be long lasting. Thank you to my committee, Michael Cole, Joe Stanislao, and Bruce McLeod, for their time throughout the dissertation process. Final thank you to: Suzanne Lassacher for assistance with the simulator and for her encouragement, Susan Gallagher WTI's Fellowship Program Coordinator, Aaron Miller with Drive Safety, the study participants, and financial sponsorship by Federal Highway Administration.

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ABSTRACT

Roadway departure fatalities accounted for 55 percent of all roadway fatalities in the United States in 2003. In an effort to reduce the number of roadway departures, many transportation agencies have introduced static rumble strips using physical alterations of the roadway surface in shoulder and/or centerline sections of the roadway. Recently, more advanced technology has been developed in the form of in-vehicle advanced lane departure warning systems that automatically detect the vehicle's lane position and warn of possible roadway departures. These systems are currently showing their value in some commercial trucks in Europe, and are now available in some U.S. passenger cars. Two critical factors will govern their ultimate success; (1) their ability to warn the driver in an effective and timely manner to make the correct action, and (2) their success in gaining driver trust and acceptance. The primary goal of this research was to better understand basic human factors principles of haptic and auditory interfaces as a collision avoidance technique during run-off-road and head-on collisions and driver perception of these modalities. In this simulator study, fifteen participants received alerting cues in three sensory modalities; haptic (seat vibration), auditory ("rumble strip" sound), and combined auditory and haptic sensory warnings. A preliminary psychophysical study was conducted to determine appropriate and comparable intensities of the warning modalities. The results of this study determined that the haptic modality produced significantly faster reaction times than both the auditory and combination modalities. The auditory modality produced significantly more maximum steering response than the haptic and combination condition. Drivers perceived the haptic modality to be the least annoying with least interference, while the combination modality was the most preferred in benefit of driving, most likely to purchase, level of trust, level of appropriateness, level of urgency, and overall preference. Haptic (seat vibration) warnings demonstrate promise as an alerting strategy over auditory and combination modalities in reducing roadway departures. With a decrease in reaction time, less erratic steering responses, and relatively advantageous perceptions from drivers, haptic warnings have the potential to better assist drivers in returning to the lane more quickly and safely.

CHAPTER 1

PROBLEM STATEMENT AND SIGNIFICANCE

Introduction

Roadway departure fatalities, which include those resulting from run-off-road and head-on collisions, resulted in 25,562 fatalities, accounting for 55 percent of all roadway fatalities in the United States in 2003 (FARS, 2003). In an effort to reduce the number of roadway departures, many transportation agencies have introduced static rumble strips in shoulder and/or centerline sections of the roadway. Static rumble strips are physical features placed in the roadway in the attempt to alert a driver of roadway departure through sensory warnings of sound and/or vibration. Virtual rumble strips' objectives are the same as physical rumble strips, yet require no costly infrastructure changes. Virtual rumble strip technology is located within the vehicle where these systems collect digital video or other electronic means to issue auditory warnings to the driver when departing the lane. Virtual rumble strips have greater potential for providing warnings via dynamic data metrics, allowing for more predictive warnings, hence permitting additional time for the driver to react. Recently, as part of the Intelligent Transportation Institute U.S. Department of Transportation's Intelligent Vehicle Initiative more advanced technology has been developed in the form of in-vehicle advanced lane departure warning systems. These systems are currently showing their value in reducing roadway departures in some commercial trucks in Europe, and are now available in some U.S. passenger cars. Two critical factors will govern their ultimate success: (1) their ability to warn the driver in an

effective and timely manner to make the correct action, and (2) their success in gaining the driver's trust and acceptance. This study presents a discussion and literature review of:

- factors contributing to run-off-road and head-on collisions,
- review of current practices of transportation agencies to prevent roadway departures,
- survey of the commercial availability of advanced lane departure avoidance systems, and
- system integration of advanced technology, common warning algorithms, and modalities of information presentation.

The purpose of the study is to gain a better understanding of basic human factor principles regarding two sensory modalities as a means to warn drivers of imminent dangers. The mode of presentation has the potential to influence how quickly the driver responds and whether the system will be accepted; further adding to the body of knowledge of how drivers respond and their corresponding perceptions to haptic and auditory warning interfaces.

Objective Statement

The study had three objectives: (1) to conduct a preliminary study to determine appropriate and comparable intensities for the auditory signal ("rumble strip" sound) and the haptic signal (seat vibration), (2) to compare driver responses to variations in haptic, auditory, and combined modalities of auditory and haptic, and (3) to determine driver

perception and acceptance of the presented modalities as a collision avoidance warning technique during incipient run-off-road and head-on collisions on rural two-way two-lane roads.

Hypotheses

The following hypotheses will be tested:

1) There are no significant difference in driver performance variables (reaction time, maximum steering response, root-mean-square (RMS) values of steering response, time to return to lane, time to return to steady state, number of steering reversals, number of incorrect maneuvers, maximum braking response, and minimum accelerator response) in the sensory modality of presentation, haptic (seat vibration), auditory ("rumble strip" sound), or combined auditory and haptic as a collision avoidance technique in warning the driver of run-off-road or head-on collision dangers.

$$H_o: u_1=u_2=u_3$$

$$H_a: u_1 \neq u_2 \neq u_3$$

Where, i = modality presentation (1 = Auditory sound when driver crosses centerline or shoulder threshold, 2 = Haptic vibration of seat when driver crosses centerline or shoulder threshold, 3 = Auditory sound when driver crosses centerline or shoulder threshold combined with haptic vibration of seat when driver crosses centerline or shoulder threshold).

2) There are no significant driver preferences in the sensory modality of presentation, haptic (seat vibration), auditory ("rumble strip" sound), or combined auditory and haptic used to warn the driver of run-off-road or centerline departures:

$$H_o: u_1=u_2=u_3$$
$$H_a: u_1 \neq u_2 \neq u_3$$

Where, i = modality presentation (1 =Auditory sound when driver crosses centerline or shoulder threshold, 2 = Haptic vibration of seat when driver crosses centerline or shoulder threshold, 3 = Auditory sound when driver crosses centerline or shoulder threshold combined with haptic vibration of seat when driver crosses centerline or shoulder threshold).

Delimitations and Limitations

There are three primary delimitations to this study. First, the study was delimited to drivers around the Bozeman community. Secondly, all testing was conducted under simulated conditions. Thirdly, all participants were tested to ensure they had "normal" hearing levels. This excluded individuals who may have hearing impairments. The primary limitations of this study are discussed in the following. Road conditions were designed to simulate real road driving, but exact conditions were nearly impossible to mimic. The major limitation of this study includes the small sample size used for both the Phase I and Phase II study. In addition, the sampling plan did not account for clothing, obesity, driver experience, or any dominate hand variations. Additionally, it is

difficult to recreate in a simulated environment the conditions under which drivers will incur run-off-road road/head-on collisions without creating simulator induced discomfort. Simulator induced discomfort includes much of the same symptoms as motion sickness, i.e. nausea being a "…normal response of a healthy individual, without organic or functional disorder, when exposed for a sufficient length of time to unfamiliar motion of sufficient severity" (Benson, 1978, p. 469). Detailed description of signs and symptoms of simulator induced discomfort can be found in Benson (1978), Kennedy & Frank (1985), and Reason and Brand (1975). These conditions usually include a fatigued driver and/or a distracted driver. To create a fatigued driver would require simulated driving for several minutes if not hours which has a high likelihood of leading to simulator induced discomfort. This study did as best possible to simulate a distracted driver. The distracter task described in this study was limited in its application, most people would not be distracted by looking over their shoulder to memorize letters on an index card. Nonetheless, the intention of the task was to get the driver to remove their eyes from the road in order to replicate distracted drivers who may normally depart the lane. This particular distracter task was done to minimize the number of variables while ensuring that driver's attention was in fact diverted from the primary task of driving.

CHAPTER 2

LITERATURE REVIEW

Introduction

Roadway departure fatalities, which include run-off-road and head-on collisions, accounted for 55 percent of all roadway fatalities in the United States in 2003. The number of people dying in run-off-road crashes and head-on collisions totaled 16,256 and 6,627, respectively, with an estimated total annual cost of $100 billion. In 2003, one-third of all traffic fatalities were run-off-road crashes, with two-thirds of traffic fatalities on rural roads (NHTSA, 2003). Run-off-road crashes are twice as likely to occur on rural road as on urban roads. Vehicles are most likely to leave the roadway along curves, yet most run-off-road fatalities occur on tangent sections. The higher proportion of crashes on tangent sections of the road is most likely due to the fact that the majority of road sections are tangent. However, driver performance on both tangent and curved roadway segments warrants further investigation because of the inherent dangers of each.

Head-on collisions occur when a vehicle crosses the centerline or median and crashes into an oncoming vehicle. The 1999 statistics from the Fatality Accident Reporting System (FARS) report that 18 percent of non-interchange, non-junction fatal crashes were due to two vehicles colliding head-on (FARS, 1999). Seventy-five percent of head-on crashes occur on rural roads, with 75 percent of head-on crashes occurring on undivided two-lane roads. One might think the high percentage of head-on collisions on undivided roads was due to failed passing attempts. In actuality most of these accidents

are due to unintentional maneuvers such as: the driver falling asleep, driver distraction, traveling too rapidly in a curve, or factors such as alcohol use and excessive speeding. Most head-on crashes are similar to run-off-road crashes in that the vehicle leaves the travel lane and similar unintentional maneuvers are likely to be at fault.

Currently, a national effort by the U.S. Department of Transportation is in effect in the deployment of Vehicle-Infrastructure Integration systems (VII). VII falls under the umbrella of the Intelligent Transportation System (ITS) where data are collected in an efficient and cost-effective manner that provides added value and understanding for all transportation stakeholders (Shladover, 2005). The intent of VII systems is to introduce technology to increase performance. As defined by the U.S. Department of Transportation, VII is the "establishment of vehicle to vehicle and vehicle to roadside communication capability nationwide to enable a number of new services that provide significant safety, mobility, and commercial benefits" (Retrieved on August 25, 2005 from http://www.its.dot.gov/vii/vii_init.htm). These systems are different than the conventional in-vehicle safety systems such as anti-lock brakes and air bags. Instead, VII systems focus on accident prevention by providing assistance to the driver. Recently in the reduction of run-off-road crashes, VII systems in the form of advanced collision avoidance systems have already been introduced both to the commercial trucking sector and a few models of U.S. passenger cars. In addition, this type of technology is more affordable than ever with greater technological advantages than years past.

Fundamental research questions regarding the VII systems, such as how to warn drivers effectively, have yet to be answered. Automated driving aids such as advanced

collision avoidance systems must balance the impact on driving performance and user acceptance. A system that does not adequately alert the driver can lead to driver distraction and annoyance, ultimately negatively impacting driving performance. Systems with high false alarms significantly reduce driving performance (Parasuraman, Hancock, & Olofinboba, 1997; Parasuraman & Riley, 1997). False alarms require the driver to divert attention to a "situation", and therefore reduce the amount of concentration devoted to normal control of the vehicle. False alarms can be annoying to drivers and at their worst can unsafely interfere with the driving task, causing more hazard than what initially might have existed. Unfortunately the design of collision avoidance systems has yet to meet the optimal point between effectively warning the driver while minimizing false alarms and gaining user acceptance. Many design questions remain unanswered, such as: will drivers be trained prior to use of such systems? Does training of such systems effectively prepare drivers? What interface effectively warns the driver? What timing algorithm effectively warns drivers of impending danger? How will drivers behave in response to such systems, with more caution, risk, or unchanged? How can engineers integrate such systems seamlessly?

The aim of this study is to investigate the integration of new technology on driver performance and perception. This paper introduces a case study into one application of an VII application: an in-vehicle advanced collision avoidance warning system. The research in this paper investigates driver perception and performance in response to varying warning modalities in the reduction of run-off-road and head-on collisions.

Factor Contribution to Run-Off-Road and Head-on Collisions

Road departure crashes occur most of often on dry roads (62 percent) and during good weather (73 percent). Day and night run-off-road crashes are equally split. Several factors contribute to run-off-road crashes and head-on collisions, including (FARS, 1992):

- Excessive speed (32.0 percent)
- Driver drowsiness or intoxication (20.1 percent)
- Lost direction control (16.0 percent)
- Evasive maneuvers (15.7 percent)
- Driver inattention (12.7 percent)
- Vehicle failure (3.6 percent)

One of the important factors contributing to run-off-road and head-on collisions is driver distraction. The advent of in-vehicle devices such as cellular phones, navigation aids, voice-based email access, and scrolling text messages, raises some questions regarding the safety of using these systems while operating the vehicle. Recent studies have shown that voice-based email systems (Lee, Caven, Haake, and Brown, 2001), navigation systems (Peters and Peters, 2001), and cell phones (Stanley, Kelly, and Lassacher, 2004) can distract drivers.

It has been predicted that the VII market utilizing recent and future advances in sensors, wireless technology, mobile computing, and global position systems will amount to a $15-$100 billion market (Ashley, 2001, Lee, McGehee, Brown, Reyes, Lee, J.D.). The success of VII systems will depend on the driving public's ability to safely share time between using these systems and safely navigating the vehicle.

Current Practices of Transportation Agencies

Current efforts by transportation agencies to reduce run-off-road crashes have included the installation of centerline and shoulder rumble strips. The benefit of rumble strips is the reduction of run-off-road crashes due to factors such as driver inattention, driver error, visibility issues, and fatigue. The sound and vibration that rumble strips generate when driven over are intended to alert the driver of the impending dangers of driving off the road. Research has shown that shoulder rumble strips are effective in reducing run-off-road crashes (Federal Highway Administration, 2004, Garder and Alexander, Griffith, 1999, Harwood, 1993), with reductions between 9 percent and 49 percent (Ligon, Carter, Joost and Wolman, 1985, Chaudoin and Nelson 1985, Griffith, 1999). Several types of rumble strips exist. The most common are milled rumble strips, shown in Figure1, which include grooves cut to specified dimensions placed transverse continuously along the direction of travel.



Figure 1. Picture of Milled Rumble Strips

(Courtesy of WSDOT)

The effectiveness of centerline rumble strips is inconclusive due to the recent installations of these types of rumble strips. Early field studies have shown that centerline rumble strips might be effective in reducing roadway departures. For example, the Colorado Department of Transportation has evaluated the effectiveness of centerline rumble strips over a 17 mile stretch of State Highway 119 (Outcalt, 2001) and found a 34 percent reduction in head-on collisions and a 37 percent reduction in cross-over sideswipe crashes over a 44 month period. Furthermore, a study conducted by the Delaware Department of Transportation found a 90 percent reduction of head-on collisions when comparing three years of before data and six years of after data. Further data found that crashes caused by drivers crossing over the centerline decreased by 60 percent (Turochy, 2004).

These field studies have shown promise in reducing run-off-road crashes and head-on collisions, but the reasons behind this potential for reduced crashes remain unknown. Little research has been done to better understand the driver behavior or driver comprehension of either shoulder or centerline rumble strips. A recent simulator based safety evaluation of the effect of centerline rumble strips on human performance and behavior showed they have some promise in gaining driver attention; however 27 percent of the participants tested reacted in an inappropriate manner by turning into the oncoming traffic. This might be due to the expectancy of *ad hoc* and *a priori* experiences with shoulder rumble strips. The expectancy with shoulder rumble strips is to correct the trajectory of the vehicle by turning left away from the edge of the roadway; while centerline rumble strips require the rightward steering away from oncoming traffic, which may be contrary to the driver's subconscious expectancy and experience of shoulder rumble strips (Noyce and Elango, 2004). The optimal offset distance of rumble strips from the edge line is an area that also needs further investigation. As reported in Turochy (2004) the offset currently in practice varies widely among states, from two to 36 inches with six inches being the most common, 23 percent use the six inch value, while 37 percent use a value based on the highway type and/or shoulder width.

Issues of Shoulder and Centerline Rumble Strips

Issues concerning rumble strips include: the accommodation of bicyclists and motorcyclists, noise complaints, costs, and the impacts during construction and maintenance.

Bicyclists and Motorcyclists

Bicyclists have complained of the reduced area of travel due to rumble strips and the discomfort when riding over the rumble strips. One state reported a motorcyclist hitting the rumble strip and losing control of the motorcycle (Turochy, 2004). A picture of a bicyclist near rumble strips is shown in Figure 2.



Figure 2. Bicyclist near rumble strips
(Courtesy of pedbikeimage.org)

Costs

Costs to install rumble strips among state reports vary widely - for example milled rumble strips generally range from $0.05 per linear foot to $1.50 per linear foot. 26 percent of states report costs less than or equal to $0.10 per linear foot (Turochy, 2004).

Noise Complaints

Several states have reported complaints by nearby residents regarding the noise the rumble strips generate. One state removed the milled shoulder rumble strips due to the number of complaints, while another state reported changing the offset distance to reduce the amount of noise (Turochy, 2004).

Other Issues

Rumble strips have the potential to store storm water, thereby not allowing proper drainage and causing greater susceptibility to water-related damage to the pavement structure. Many times during construction and maintenance projects, rumble strips have to be modified or removed to accommodate traffic that utilizes the shoulder, which can lead to negative impacts of milled rumble strips. It has been reported by emergency vehicles that during a police chase the rumble strips cause vehicle dynamic issues and ambulance personnel have reported interference with their cardiac monitor devices. States have noted a decrease in visibility and retro-reflective problems with the centerline pavement markings under nighttime conditions due to the buildup of snow, ice, salt, sand, or debris in the grooves of the rumble strips (Noyce and Elango, 2004). Finally, in some locations, especially rural roads, shoulders are not wide enough to properly install shoulder rumble strips.

Lane Departure Avoidance Systems

The commercial roadway departure systems show promise in the detection of run-off-road and head-on collisions, yet the technology and complex warning algorithms that comprise these systems are limited in that they are only as effective as the operator interpreting them. These systems must be designed for two critical factors that will govern their effectiveness: (1) warning the driver in an effective and timely manner to make the correct action, and (2) minimizing false alarms to increase the driver's trust and

acceptance. The success of these warning systems will depend on the driver interface and how well the algorithm fits the driver's capabilities and preferences.

Commercial Availability of Lane Departure Avoidance Systems

Roadway departure systems recently became commercially available in Europe for heavy truck applications and are now available in some higher-end passenger cars. Several passenger car manufacturers anticipate offering the technology in more of their vehicle models. Assistware, Inc. and Iteris, Inc. were among the first to develop such systems using computer vision and highly specialized algorithms that detect lane markings and alert the driver of potential dangers. The AutoVue™ Lane Departure Warning for passenger vehicles, developed by Iteris, consists of a small digital video camera and onboard computer that attaches to the windshield and continuously tracks visible lane markings, as shown below in Figures 3, 4, and 5:



Figure 3. Lane departure camera windshield mount unit
(http://www.iteris.com/av/AvtoVueCar.pdf)

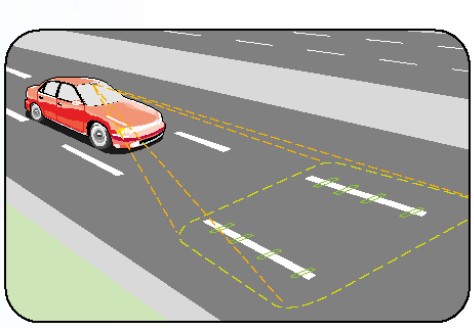


Figure 4. Example of camera mount in operation
(http://www.iteris.com/av/AvtoVueCar.pdf)

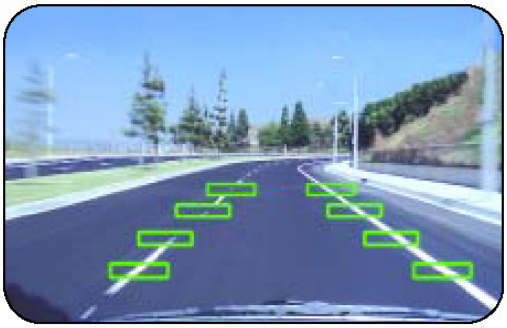


Figure 5. Lane departure warning computer imaging
(http://www.iteris.com/av/AvtoVueCar.pdf)

When the vehicle drifts out of the lane a rumble strip sound is emitted via the car's sound system, alerting the driver to make corrective action. In addition to these systems are other computer vision-based systems currently under development. The California PATH program has studied the use of in-road magnetic markers and magnetometer-equipped vehicles for lane tracking (Shaldover, Desoer, Hedrick, Tomizuka, Walrand, Zhang, Mcmahon, Peng, Sheikholeslam, and Mckeown, 1991).

Global Positioning Systems have shown promise in detecting vehicle placement for lane tracking (Galijan, Gilkey, and Turner, 1994).

Modalities of Information Presentation

The major modalities for information presentation to the driver are auditory, haptic, and visual. Driving is predominately a visual task that requires constant scanning of the roadway ahead, therefore leaving the visual channel at capacity (Lansdown, 1997). The major cause of crashes is the distraction of driver visual attention away from the road (Tijerina, 1995). The use of the visual channel in collision avoidance systems may unintentionally take the driver's attention away from the driving scene at the wrong time. Furthermore, Schiff and Arnone (1995, NHSTA) found that using non-visual systems to warn drivers in directing attention back to the roadway results in visual processing that is usually adequate enough to provide inputs for safe control of the vehicle. For example, placing a visual display to indicate the direction of travel the driver needs to achieve in order to maneuver to avoid a run-off-road or head-on collision might be of little benefit to the outcome. Because the visual channel has a region of capacity, other sensory channels need to be pursued to present necessary information to the driver.

The warning systems of the future may need to utilize multiple modalities to present information without overloading the mental system. When the visual modality is overloaded, drivers may drive more slowly and cautiously (Walker, Alicandri, Sedney, Roberts, Walker, 1991). Auditory displays have been found to be superior to visual displays in presenting warnings (Walker et.al., 1991). Labiale (1990) found that

workload was decreased when presenting navigation information auditorally versus visually. Research has shown that the auditory modal is better than visual modal for providing initial hazard alerts and for quickly presenting information to the drivers with regards to the magnitude of the situational hazard (Liu, 2001). A study done by Simpson et al 1985 and Sorkin 1987 found that operators respond to verbal warnings more quickly than visual warnings (Liu, 2001). According to the multiple resource theory if one is immersed in a heavily loaded visual display environment, auditory displays have the ability to improve time-sharing performances (Wickens, Sandry, and Vidulich, 1983). When drivers experience both visual and auditory modalities, (a multimodal display situation) it has been found possible to allow the processing of more information without significantly decreasing workload (Labiale, 1990, Dingus, Hulse, Mollenhauer, Fleischman, McGehee, and Manakkal, 1997).

The use of auditory modalities to warn of rear-end collisions has been found to increase safety. However reports by drivers have found that the auditory warnings can interfere with the driving task (Wheatley and Hurwitz, 2000). Research on haptic seat vibration as a collision avoidance technique is rather new and unexplored, but shows promise because of its high stimulus-response or ideo-motor compatibility (Wickens, 1992). Furthermore, in aviation experiments haptic cues did not interfere with the performance of concurrent visual tasks (Sklar, 1999) and speed reaction time (Janssen and Nilsson, 1993). Drivers performed similarly when presented with longitudinal haptic warnings (whole seat vibration) and auditory warnings (Lee and Hoffman, 2004).

A simulator study compared younger and older drivers' ratings of workload and performance while using a navigation system under high and low load driving conditions present visually only, aurally only, and multimodal. The results indicated that both auditory and multimodal displays produced better response times and less error than the visual-only display. Those using the multimodal display made the fewest errors. It was concluded that the visual display led to less safe driving due to the higher demands for driver attention (Liu, 2001). A study completed at the University of Iowa found using auditory warnings in reference to dangers of hitting a lead vehicle from the rear found that auditory warnings help drivers maintain safer distances with lead vehicles. However, the participative reactions auditory alerts were not as positive as hoped. Fifty-three percent of participants reported that the auditory warning interfered with their ability to drive safety and 59 percent said it was more difficult to concentrate on the driving task. Seventy-five percent agree that the warning tone was annoying (Wheatley and Hurwitz, 2000)

Haptic seat vibration cues in passenger cars as a collision avoidance technique is a relatively recent unexplored modality, in which the driver feels rather than sees or hears the warning. The motivation behind such interfaces is that haptic systems contain high stimulus-response or ideo-motor compatibility (Wickens, 1992) in which the stimulus matches the sensory feedback produced by the response. For example, if approaching the edge of the roadway the haptic display will produce a response that will turn the steering wheel in the necessary direction.

Haptic displays have been used in aviation for a number of years, such as the "stick shaker" that alerts the pilot of a potential stall. Pilots receiving visual and haptic alerts detected 83 percent and 100 percent of mode changes, respectively. The haptic cues did not interfere with their performance of concurrent visual tasks (Sklar and Sarter, 1999) Torque-based kinesthetic cues have been shown to reduce reaction time more than auditory cues (Gielen and Schnidt, 2004). Vibrotactile cues enhanced reaction time compared to visual cues (Diederich, 1995). Furthermore, combining visual cues with redundant cues via other sensory modalities speeds reaction times (Nickerson, 1973).

Studies have shown that haptic displays improve reaction time. Janssen and Nilsson (1993) compared headway adjustments of drivers who were alerted via light, warning buzzer, and a 'smart' gas pedal, which produced a force back to the operator when dangerously approaching the vehicle ahead. The 'smart' gas pedal was found to have the greatest effect. A vibrating seat does not produce the natural mapping of the 'smart' gas pedal or a turn the steering wheel turn in the necessary direction, therefore may have no effect in decreasing in run-off-road departures than other modalities. A simulator study conducted by Lee and Hoffman (2004) had drivers interact with an in-vehicle email system and a collision warning system that signaled a braking vehicle ahead by using auditory versus haptic seat vibration found that drivers performed similarly with haptic as with auditory warnings. Haptic cues offer promise not only in reducing response times, but in reducing annoyance of the driver and passenger. Lee and Hoffman (2004) found using a vibrating seat in longitudinal warnings was perceived as less annoying and more appropriate than auditory or visual warnings.

Warning Algorithm Strategies

The success of collision avoidance system is not only dependent on the interface of warning presentation, but also on the warning algorithm. Algorithms determine when to issue warnings and their success is a balance between effectively issuing warnings and gaining trust and acceptance by the driver. A sudden vibration of the seat or loud auditory warning might startle the driver leading to an unsafe driving maneuver and if it occurs frequently then driver acceptance will be low. The algorithm must issue timely and appropriate response from the driver and must minimize nuisance warnings if the driver is to accept the system (Bliss et. 1992).

There are many lane departure warning algorithms, the advantages and disadvantages of each are discussed per National Highway Traffic Safety Administration's Run-Off-Road Collision Avoidance Countermeasures Using IVHS Countermeasures 1995, 1999 Report. In general increasing the complexity of the algorithm results in warning systems that provides fewer false alarms and more time for the driver to react, but require more sensors, greater calculations, and usually are more sensitive to errors in the data generated by the sensors. This sensitivity might outweigh the advantages by generating more false alarms than the simpler algorithms.

Although the objective of this paper is not to study warning algorithms it is important to note that the techniques available have advantages and disadvantages. Research is currently being conducted on the development of effective warning algorithms. One more recent approach includes a fuzzy-logic-based approach called "variable rumble strips" where the warning threshold is allowed to vary according to the

risk of the vehicle departing the road (Pilutti and Ulsoy, 2003). Below is a description of two common algorithms (Tijeriana, 1995).

Algorithm 0th Order. The 0th order Algorithm or "Electronic Rumble Strip" is the simplest of algorithms and is solely based on the lateral position of the vehicle. The algorithm makes no assumptions about the upcoming roadway geometry or vehicles dynamics (besides position). The 0th order algorithm equation is given below:

$$\text{If } d \leq 0, \text{ then warn driver}$$

Where d = distance between the outside edge of the tire to the lane boundary

This algorithm is similar to current shoulder or centerline rumble strips. Advantages include the understanding by the driver; the driver knows that point at which the warning will be generated and because there is so little calculation necessary (no high order terms) few errors will result. The disadvantage of this algorithm is that it completely ignores time and trajectory of the vehicle. This can lead to a greater number of nuisance alarms in small angle departure conditions. Furthermore, this emphasis on looking only at absolute position results in warnings only occurring when the vehicle is already traveling parallel to the roadway or approaching the edge at a severe angle, leaving the driver with little time to react.

Algorithm 1st Order Time-to-Line-Crossing. The Time-to-Line-Crossing algorithm utilizes the vehicle's current lateral position and lateral velocity and predicts

the time before the vehicle's tire will cross the lane boundary. If the time to lane crossing reaches a certain threshold (usually around 1 second), a warning is generated. The equation is shown below:

$$\text{If } d / vl < tl, \text{ then warn driver}$$

Where d = distance between the outside edge of the tire to the lane boundary

v l = lateral velocity of vehicle heading towards edge of lane

t l = the minimum time threshold till vehicle crosses edge of lane

Because the time-to-line crossing algorithm includes lateral velocity and time to crossing as prediction variables, an early warning will be generated if the driver is approaching the edge of the roadway more quickly than with the 0th order algorithm. The disadvantage of this algorithm is the possibility of errors in calculating lateral velocity. Because lateral velocity is a derivative of lateral position, any errors in lateral position might amplify the lateral velocity leading to an increase in false alarms or delayed warnings. Also, this algorithm assumes constant lateral velocity; which might not always be the case because the driver might have the steering wheel in varying positions leading to late warnings.

Graded and Single-Stage Warnings. Graded and single-stage warnings have distinct strategies and important implications in warning the driver of impending danger ahead. There is an important trade-off between effectively warning the driver and

providing trust and acceptance of such warnings. A graded warning presents a degree of warning based on the severity of the danger. The signal for a driver quickly approaching the edge of the roadway will be presented with a louder warning than if they are approaching at a slower rate as opposed to a single-stage warning that produces the signal when a certain threshold has been exceeded). The intent of graded warnings is to enhance drivers' perception and response by priming the drivers' response, and ultimately promoting acceptance and trust of the system (Lee and See, 2004). In the simulator study conducted by Lee and Hoffman (2004), the graded warnings led to a greater safety margin and a lower rate of inappropriate response to nuisance alarms. also In addition,, drivers trusted the graded warnings more than the single-state warnings. Furthermore, there was no indication that graded warnings lead to less preparedness than single-stage warnings in longitudinal alert strategies. The down side of the graded alerts is the higher rate of nuisance alarms than with single-stage alerts.

Benefits and Limitations of Simulation in Research Driver Behavior

Driving simulation has been used as a safe, cost-effective and valid technique in measuring driver responses to weather, road condition, distractions and others. A recent study completed by the *Driving Assessment and Consultancy Center* of Perth, Australia found that driving simulation is a safer and more economical method than on-road testing to assess the driving performance of older adult drivers (Lee, Cameron and Lee 2003). Through state-of-the-art simulation, it is possible to place drivers in a realistic environment that allows for the isolation of experimental variables. Furthermore, only

simulation provides for the replication of experimental road conditions to formulate accurate driving comparisons.

Caution should be used when using simulation to investigate on-road driver behavior. This shortcoming is relevant to all studies of lab-based human behavior studies, where participants are aware of the task demands and are being measured (Naatanen & Summala, 1976). Some have argued that simulator studies are limited in their accuracy to predict driver behavior (e.g., Kiefer, 2000; Lee, McGehee, & Brown, 2000). Nevertheless, most researchers acknowledge that simulation allows flexibility in experimental design and is valuable in measuring driving behavior (Lee et al., 2000; McGehee, Mazzae, & Baldwin, 2000).

CHAPTER 3

METHODS

Phase I Study

Prior to testing the principal hypotheses of this experiment (Phase II) it was necessary to determine the appropriate decibel level of the auditory signal and intensity of vibration to be used in the modality presentations. This was done by performing a cross-modality matching experiment on fifteen participants. Participants completed a consent form approved by Montana State University's Human Participant Board (see Appendix A, B). In Phase I participants matched the magnitude of a stimulus across a stimulus modality (e.g., perceived loudness ≥ perceived vibration intensity, etc). Participants were compensated $10.00 for the one hour test (see Appendix C). This experiment was done to ensure that drivers are being warned at the same perceived intensity level across all modality presentations to reduce the chance of one modality having a greater impact on driver responses due to differences in driver perception of stimulus intensities. Otherwise, such an effect could be a significant source of unwanted error. Previous studies in this area have failed to include this critical control when designing their experiments. Thus, it was imperative that a valid protocol for addressing this issue be developed and tested.

This study utilized the psychophysical approach for the cross-modality matching. Psychophysical methods are concerned with human sensation and how it relates to external physical stimuli. For example, auditory sensations can vary from "loud to soft"

and tactile sensations can vary from “light to heavy”. The principle relationship between sensory reactions to external physical stimuli can be described as using “more than,” “different than,” or “same as” techniques and can be modeled using the so-called Steven's Power Law, or psychophysical power law, as provided in Equation 1 (Stevens, 1960):

$$S = kI^{n}$$

Equation 1. Psychophysical Power Law

Where: S = sensory magnitude

k = constant, dependent upon unit of measurement of stimulus

I = intensity of physical stimulus

n = exponent that is experimentally determined for each sensory continuum.

As provided in the Power Law, a non-linear relationship exists between a given physical stimulus and its corresponding sensation. For example, as sound energy increases, humans will detect the increase, but at a proportionally lower rate (depending upon frequency). Common examples of experimentally-determined exponents (n) which help illustrate such relationships can be found in Table 1 (Stevens, 1960).

Table 1. Examples of Power Law Exponents (Stevens, 1960).

Stimuli	Condition	Exponent (n)
Loudness	dB @ 3kHz	0.67
Taste	salt	1.4
Taste	sucrose	1.3
Cold	metal contact on arm	1.0
Warmth	metal contact on arm	1.6
Muscle force	static exertion	1.7
Heaviness	lifting objects	1.45
Electric shock	current through fingers	3.5

Several psychophysical methods/protocols have been developed for establishing design parameters, each appropriate under differing design objectives. The key protocol used in Phase I follows the "Method of Limits." As previously stated, an objective of Phase I is to establish a physical intensity level for both auditory and haptic stimuli that would be approximately equally perceived by the users. Again, this will help mitigate the possibility of biasing experimental results due to unequal perception of stimulus intensity across the two modalities (auditor and haptic). The Method of Limits was chosen for this experiment as it is very adaptable to help establish "points of subjective equality" (or

PSE) across multiple stimulus levels and/or modalities. Hence, the result of this procedure is a "cross-modality" matching of stimulus intensities.

The Method of Limits adapted for the Phase I experiment began with the experimenter setting the predetermined auditory level and then taking the participant through three sets of two trials of continuous ascending and/or descending levels of haptic intensity. The experimenter asked the participant to determine where they perceive the equivalence location of haptic intensity to auditory intensity. Specifically, the experimenter asked; “based on the provided auditory signal, please rate the point at which you feel the vibration of the seat is equivalent in intensity to the auditory signal”. This was used to determine the thresholds or points of participative equality of haptic and auditory intensities.

The general procedure described above is most often described as "determination of absolute threshold" and follows that provided in Fernandez and Marley (1998). This is contrasted by the concept of "difference thresholds" in which the design parameter may be predicated upon understanding the full range of subjective equality (low-high, light-heavy, etc). In sum, the current experiment sought to utilize the absolute threshold protocol to determine PSE between the auditory and haptic sensory modalities of interest. This protocol is one of several methods under the overall psychophysical approach.

Absolute Thresholds

The specifics of the protocol to determine PSE for the two modalities in question are described in detail below (*note:* the simulator’s sound system is limited in that it

generates sound as one unit; in which all sounds i.e. engine noise, ambient traffic, wind, etc. play at the same decibel level):

1. With the auditory decibel level already established and participant seated in the simulator on the IVIBE® seat, the experimenter presented the haptic stimulus intensity to the participant in continuous ascending (A) and descending (D) trials. The initial order of presentation (A or D) was determined randomly (see Appendix D).
   - ⇒ Trial 1: Ascending trial begins at an intensity level of the haptic stimulus that will not be likely detected and gradually increased until the participant reports that the stimulus is perceived as "equal to" the established auditory intensity. The intensity of this level was recorded.
   - ⇒ Trial 2: Descending trial begins at a haptic intensity level that will most certainly be perceived as greater than the auditory signal (basically "full-strength"), then gradually decreased until the participant reports equality between the two stimuli. Again, the haptic intensity at this level is recorded.
2. Ascending and descending trials were repeated three times in alternating order.
3. The equivalence threshold will be determined by averaging the recorded haptic levels across all trials.

An accelerometer was placed under the legs of the driver to measure the vibration intensity (measured in gravitational forces) at the four quadrants of the seat. A sound

meter was placed at the driver's ear to measure the decibel level of the sound intensity. Average mean g forces from each of the four quadrants from the fifteen Phase I participants was used in testing the Phase II hypothesis.

Acceleration Data Collection and Instrumentation

The ± 5 g tri-axial accelerometer (ADXL05EM-3 Module Analog Devices, Norwood MA), as shown in Figure 6, was placed under the legs of a driver to measure acceleration in volts at four quadrants of the seat.

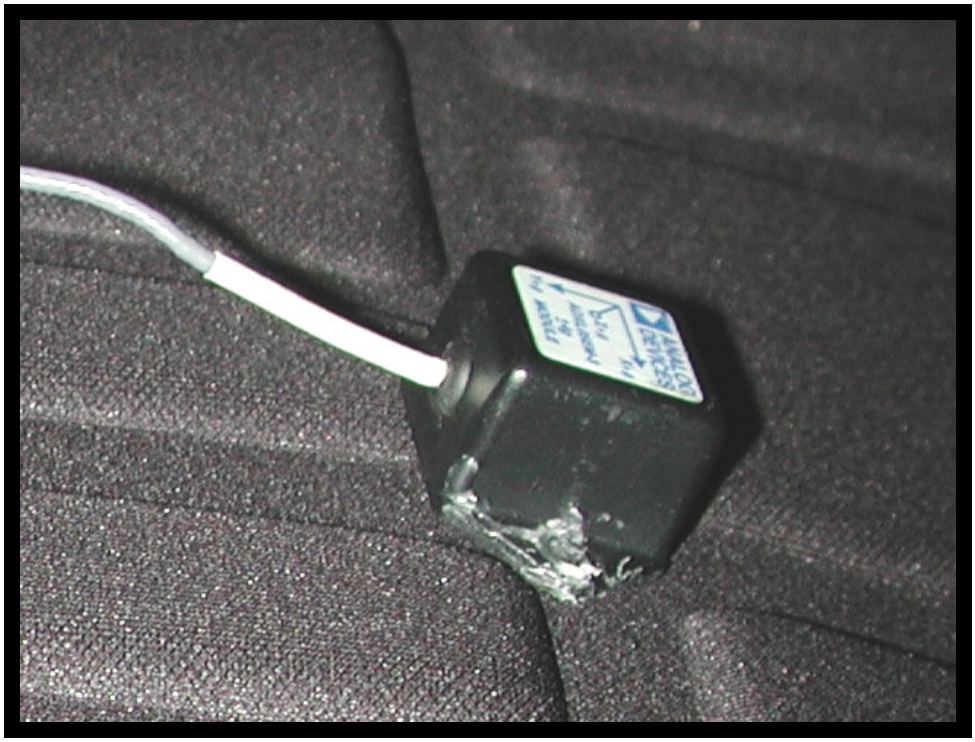


Figure 6. ADXL05EM-3 Module Analog Devices Accelerometer

The accelerometer was placed in the center of the four quadrant locations shown in Figure 7.

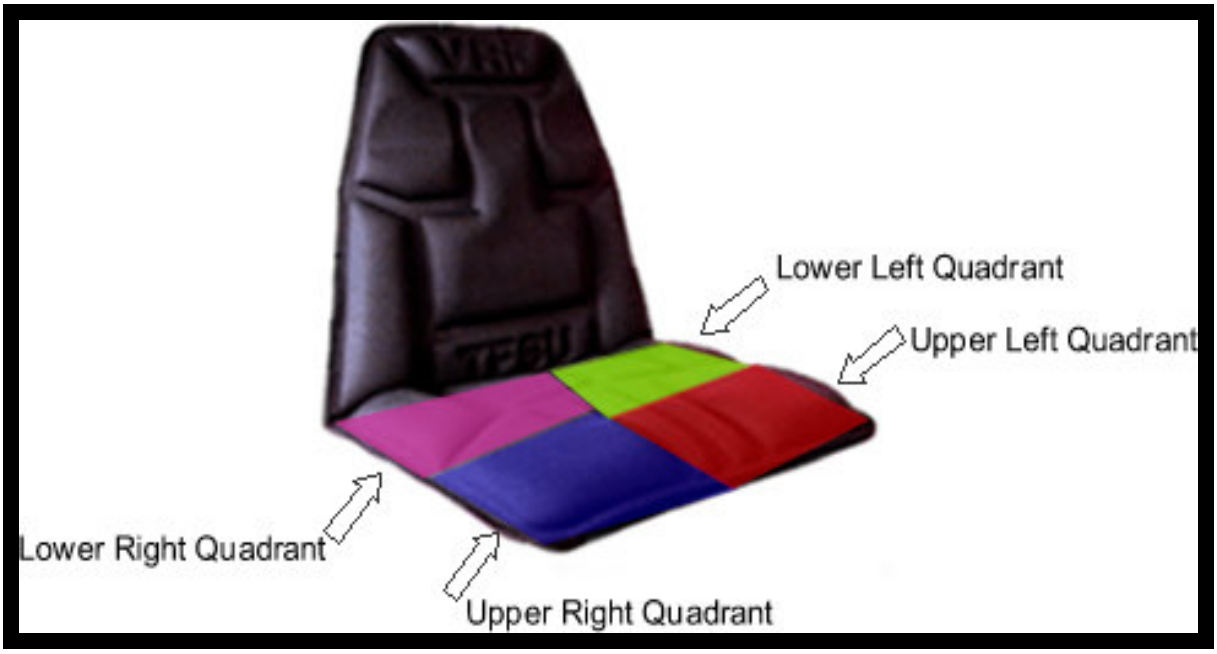


Figure 7. Accelerometer Measurement Quadrant Locations

The sensitivity of the accelerometer was .5 volts (v) per gravitational force (g). In order to obtain the g forces the Equation 2 was used.

$$g's = \frac{volts}{volts/g}$$

Equation 2. Gravitational Force Conversion from Volts

The corresponding conversion of volts to g's is demonstrated in the Figure 8 below.

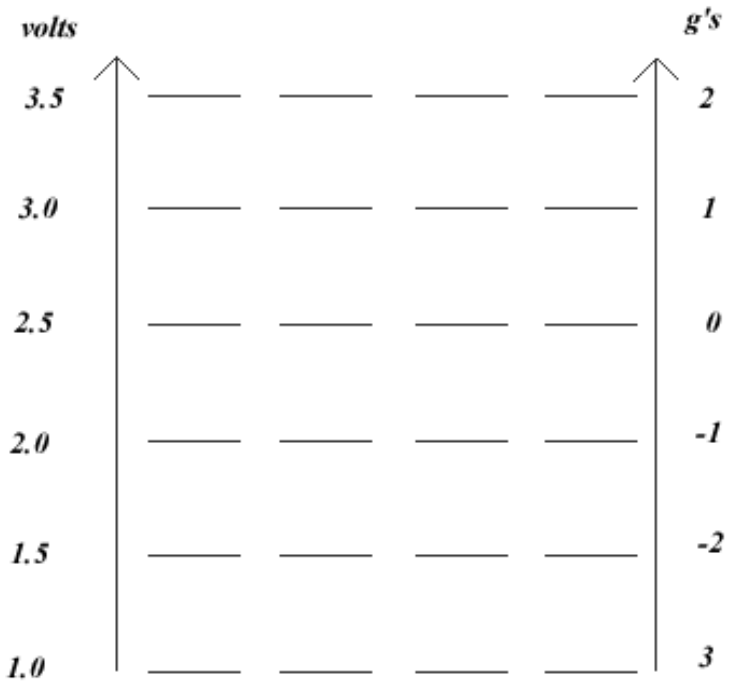


Figure 8. Volts to g forces equivalency calculation

The accelerometer required three channels on the SCB- 68 Connector Block (National Instruments, Austin TX), see Figure 9, which was connected via a cable to a 12-bit 6024E Data Acquisition (DAQ) Card (National Instruments, Austin TX) to a laptop computer. The complete configuration is shown in Figure 10.

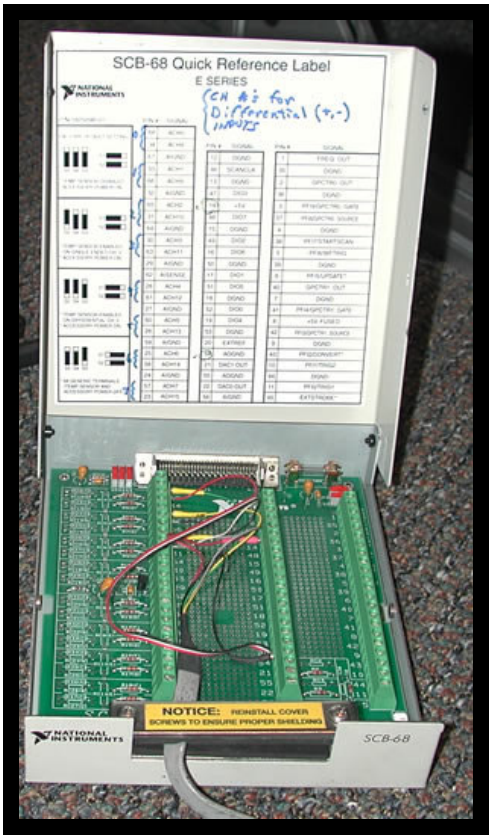


Figure 9. National Instruments SCB-68 Connector Block

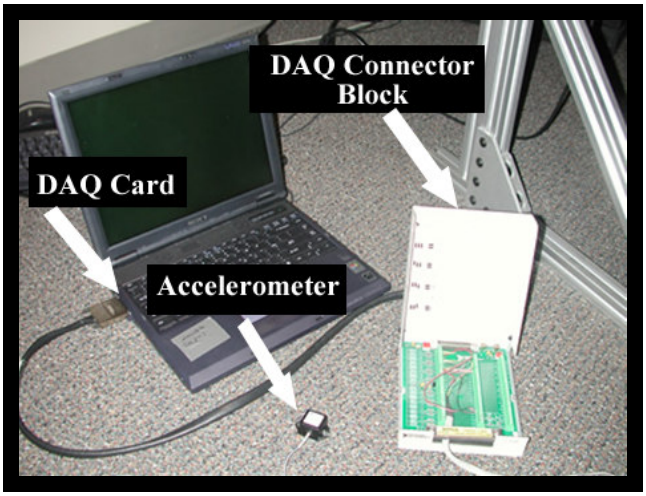


Figure 10. Accelerometer Measurement Equipment Configuration

The final configuration enabled the measurement of acceleration data in the x, y, and z – direction. All data acquisition was programmed through the data acquisition system - Labview™ 5.1 (National Instruments, Austin TX) and data were not electronically filtered. From this the resultant acceleration levels among three mutually perpendicular axes, vertical (az), longitudinal (ax), lateral (ay) as per International Standard (ISO 2631/1, 1985), as shown in Figure 11 and 12 were calculated.

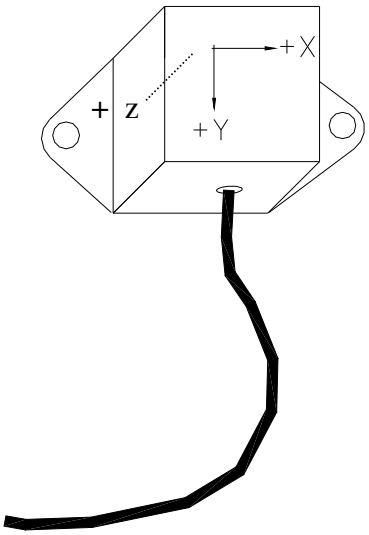
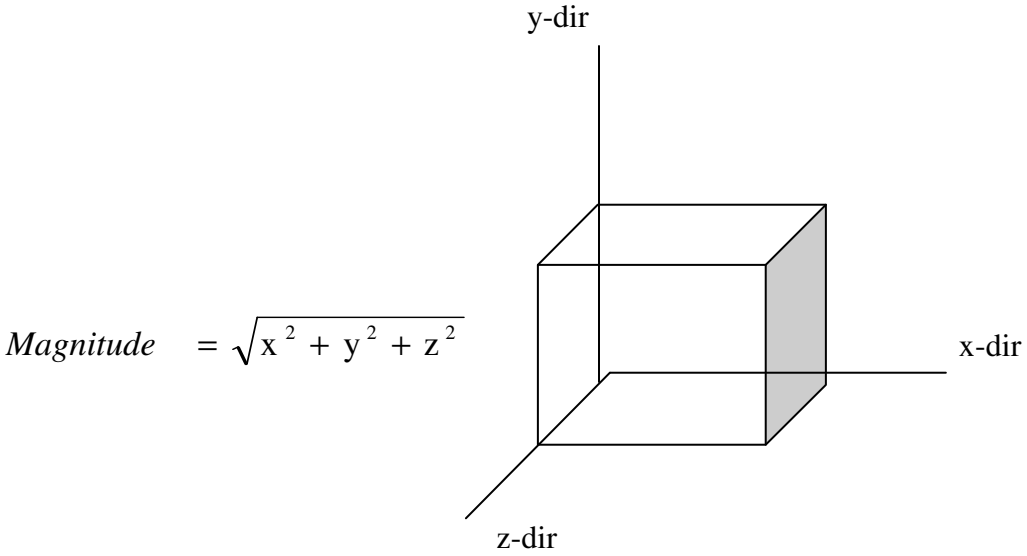


Figure 11. Orientation of Axis on Accelerometer. +X, +Y, and +Z conforming to the right hand rule

Calculation of the magnitude of the resultant acceleration data was computed as the equation below indicates:



$$Magnitude = \sqrt{x^2 + y^2 + z^2}$$

where x = acceleration (m/sec^2) in x-direction, y = acceleration (m/sec^2) in y-direction, and z = acceleration (m/sec^2) in z-direction.

Figure 12. Resultant Acceleration Calculations

Sound Level and Instrumentation

A GR 1565-B (General Radio) sound-level meter was placed at the participant's ear level and adjacent to the left and right ear to measure the "rumble" strip warning sound that participants heard during the test. The sound meter contains a microphone that detects sound as an electrical signal and then amplifies it to a meter that indicates the sound-pressure level. The sound-level was measured at four exposure levels all when driving at a constant 55mph: 1) when participant vehicle was within the lane and no warning was issued, 2) when participant vehicle was out of the lane and the auditory signal was issued, 3) when participant vehicle was out of the lane and the haptic signal was issued 4) when participant vehicle is out of the lane and both the auditory and haptic warnings were issued.

Prior to all measurements the sound-level meter was calibrated with the accompanied sound level calibrator. A picture of the sound-level meter and calibrator are shown in Figure 13.



Figure 13. General Radio 1565-B/1567 Sound Level Meter/Calibrator
(photo courtesy http://www.biostad.com/product.asp?id=601&source=froogle)

IntellIVIBE® User Interface

A screenshot of the IntellIVIBE® software used in this study is shown in Figure 14. This software was customized to better assist the experimenter in real-time monitoring of the haptic seat vibration. As shown in Figure 14 the onset of haptic warning is indicated in the window. This window was not crucial in the experimental methods, but served as an indicator to the actual real-time issuance of the haptic warning.

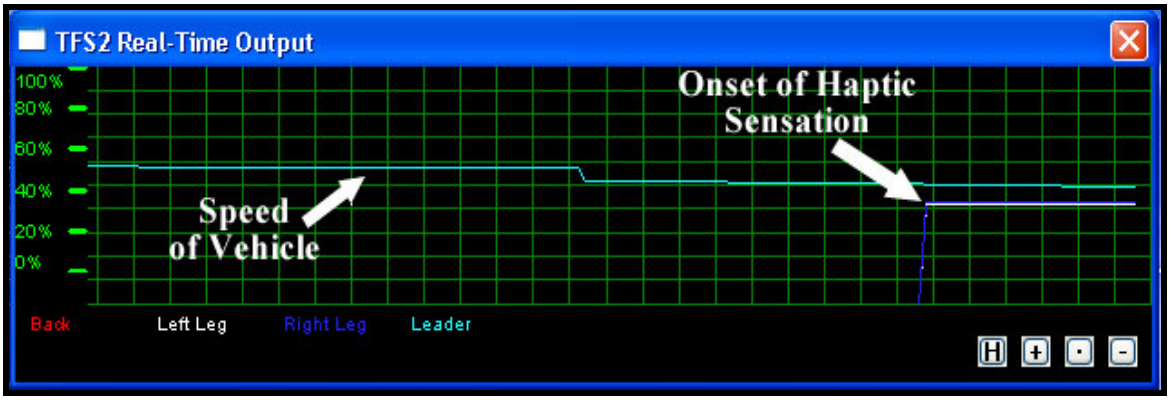


Figure 14. IntellIVIBE® Real-Time Output Console

The screenshot in Figure 15 indicates the final configurations determined from Phase I for the IntellIVIBE® software. The software has the ability to generate site-specific vibration at differing locations within the seat, but for this study only the legs received the vibration. Future studies could use such software configurations to better understand if site-specific haptic warnings would be beneficial in assisting drivers.

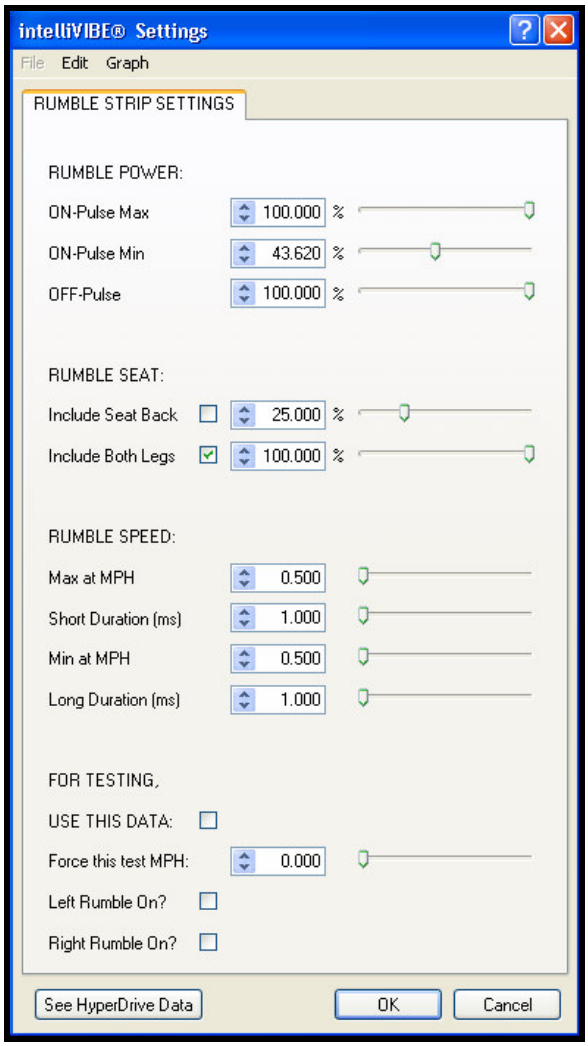


Figure 15. IVIBE® Seat Settings User Interface

Hearing Test

The hearing test for this study was performed using an online hearing test created by World Hearing™. This test was used primarily for those potential participants who think they may need supplemental hearing aids due to some hearing loss with age or other factors. The test was designed to determine whether individuals have any

significant range of hearing loss that could have influenced test results in an unknown manner. It was by no means a replacement for a professional calibrated hearing test. Due to time and cost constraints the use of the online hearing test was the most feasible solution to ensuring all participants had apparent "normal" hearing prior to their participation in the study. The user interface used by the experimenter is shown in Figure 16. The hearing test was divided into three categories, low (250Hz-500Hz), middle (1KHz-2KHz), and high (4KHz-8KHz) frequencies in order to determine if any participants had hearing loss on those frequencies.

The test setup began with the experimenter (who has no hearing loss) placing the mouse pointer over the "START" bar, as shown in Figure 16, and adjusted the volume to a minimal hearing level (the point at which just barely noticeable).

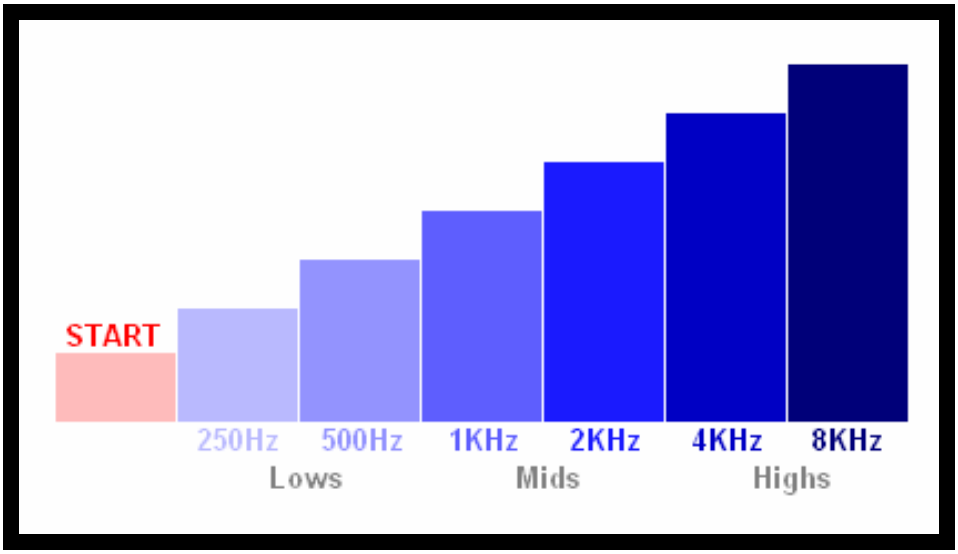


Figure 16. User Interface for Hearing Testing
(http://www.worldhearing.com/worldhearing_016.htm)

Prior to the start of the online hearing test, participants were fitted with headphones (Maxell HP-300F) and placed in a quiet environment without distraction. They were then asked to raise their hand when they heard a tone. The experimenter then proceeded to place the mouse pointer over each blue pure-tone test bar starting at 250Hz. If the participant raised their hand the experimenter would proceed to the next highest frequency range, eventually covering all frequencies of 250 Hz, 500 Hz, 1 KHz, 2 KHz, 4 KHz, 8 KHz. If the participant could not hear one or more of the frequencies then they were excluded from the study, as it is suggested that they may have some hearing loss.

Phase II Description of Participants

Fifteen participants whose ages and gender were consistent with those tested in Phase I were recruited for Phase II. This was done to reduce any unknown variation in participant population characteristics. Since the intended users of collision avoidance systems will be a mixture of male/female of all ages, the intent of this study is not to investigate the effects of age or gender. Gender and age were treated as nuisance factors, though further research may study the effects of age and/or gender on varying modalities in collision avoidance systems.

Participants were recruited through local advertisements on the Montana State University campus and throughout the Bozeman community (see Appendix E). All participants had a valid driver's license, normal or corrected normal vision, normal hearing, and were not susceptible to motion sickness. Participants completed a consent form approved by Montana State University's Human Participant Board (see Appendix

B, F). Potential participants complete a pre-screening questionnaire to identify and disqualify those who have medical conditions or histories that might indicate increased levels of risk (e.g., headaches and motion sickness) in the simulation environment (see Appendix G). Omitted from this sample were those persons who do not choose to respond to the solicitation for human participant participants and/or who do not qualify based on the pre-screening questionnaire. Solicitation for participation continued until a sufficient sample was reached.

Participants were compensated at $30.00 for their participation (see Appendix C). The first session lasted approximately one hour (includes one training scenarios and one testing scenario), the second and third session lasted approximately one hour each (includes one training scenario, one testing scenario, and questionnaire completion).

Phase II Study Procedures

Prior to testing sessions, participants completed screening questionnaires directed primarily at identifying susceptibility to simulator induced discomfort (SID), including nausea, headaches, and dizziness (see Appendix G). Participants who qualified were then trained and tested using Western Transportation Institute's high-fidelity driving simulator. All participants were acclimated to the driving simulator by completing a series of three scenarios, each lasting approximately four to five minutes. Training began with relatively gentle drives designed to minimize SID. At the completion of training, participants completed a follow-up questionnaire on any SID symptoms they may have experienced (Appendix H).

Prior to testing each participant completed a participant history questionnaire on information regarding years of driving experience, average vehicle miles traveled in a year, accident history, occupation, history of licensure status (i.e. revoked license), any medical conditions, current medications, and participation in any driving education program (see Appendix I). Acquiring a detailed history of the participant characteristics relating to driving performance is not only a relatively low cost procedure, it has the potential to further explain any variation in the data.

Experimental design consists of a randomized block design, where the participant is the block, with three modality treatments per participant (haptic, auditory, haptic & auditory combination). The experimental design is shown in Table 2:

Table 2. Experimental Design

Participant Number	Treatment Order
1	Combo, Auditory, Haptic (Replicate 1,2)
2	Combo, Auditory, Haptic (Replicate 1,2)
3	Combo, Auditory, Haptic (Replicate 1,2)
4	Combo, Auditory, Haptic (Replicate 1,2)
5	Combo, Auditory, Haptic (Replicate 1,2)
6	Auditory, Haptic, Combo (Replicate 1,2)
7	Auditory, Haptic, Combo (Replicate 1,2)
8	Auditory, Haptic, Combo (Replicate 1,2)
9	Auditory, Haptic, Combo (Replicate 1,2)
10	Auditory, Haptic, Combo (Replicate 1,2)
11	Haptic, Combo, Auditory (Replicate 1,2)
12	Haptic, Combo, Auditory (Replicate 1,2)
13	Haptic, Combo, Auditory (Replicate 1,2)
14	Haptic, Combo, Auditory (Replicate 1,2)
15	Haptic, Combo, Auditory (Replicate 1,2)

Testing was conducted on three separate days where participants drove 10-minute scenario on each day; within each testing scenario participants experienced one modality of presentation. Presentation of modality was randomly assigned to each participant using Counterbalanced Latin Squares Design. To reduce any effects of circadian rhythms all participants were tested between the hours of 3:00 p.m. and 6:00 p.m. Participants were given instructions to obey all traffic signs and drive as they normally would. Based on aforementioned data regarding crash analysis statistics, most roadway departures occur on rural roads during good weather conditions. Therefore, the testing scenarios were rural in nature with two-way two-lane road geometry during good weather/roadway conditions and traffic control devices (i.e. speed limit signs).

It should be noted that the visual modality has been omitted in this study because it is believed that the visual channel is already saturated (Lansdown, 1997) and adding a visual warning may remove visual attention away from the road (Tijerina, 1995). Additionally, if a driver is distracted and/or fatigued (i.e. asleep) then the likelihood of the driver seeing the warning is minimal.

A distracter task was given to all participants at the same section of roadway approximately three minutes into the scenario. This distracter task was modeled after Tijerina et. al. (1996), in which the participants were instructed to look over their shoulder and memorize seven letters on an index card (see Appendix J). After receiving the warning and returning to steady state the participants were asked to report the letters they remember to the experimenter while continuing to drive. During this time a wind gust was generated from east to west or west to east by the experimenter to enable a

centerline or shoulder crossing. Approximately five minutes into the scenario, the same driver distracter was issued, this time using a different index card of letters. Concurrently, a wind gust was administered west to east or east to west depending on the first wind gust direction. Each participant was presented a directional wind gust randomly to eliminate any priming response from the first wind gust.

The warning algorithm used in this study utilized a variation of the 0^{th} Order Algorithm as mentioned in Chapter 1. The warning algorithm for this study was modeled after that of current practices transportation agencies offset values for shoulder rumble and centerline rumble strips; the focus of this paper is not the particular algorithm, rather the effect of modality in warning the driver. The most common offset of rumble strips used by transportation agencies is six inches from the outside edge of the lane; this value was the specified threshold for this study.

Apparatus

Data was collected in Western Transportation Institute's driving simulation laboratory. This laboratory is equipped with a 345 square feet light and sound controlled room containing a DriveSafety™ 500C simulator running HyperDrive ™ Simulation Authoring Suite software and Vection™ simulation software version 1.9.8 (connected to control room). The simulator is comprised of a cut-down 1996 Saturn SL sedan cab with fully functional controls, five rear projection plasma displays arranged in a semicircle around the front of the cab providing a 150-degree field of view and rear-view mirror, five audio speakers, a simulator operator station, and associated computers. The simulator provides physics-based vehicle dynamics. The graphics systems render

realistic driving scenarios including geometrically correct urban and rural roadways, traffic control devices, cultural features, ambient traffic, pedestrians, animals and other features. Realistic auditory effects of traffic, engine noise, and wind noise are generated by the 3-D audio system. The *500c DriveSafety*™ simulator relies on the *Vection*™ software to make driving in the simulator a more realistic experience. The *Vection*™ software comprises the following subsystems in Table 3:

Table 3. Vection Software Components

Audio	engine noise, wind, traffic, sirens, tire screeches and horns can be integrated into the simulation experiment and triggered by a designated event
Vehicle Dynamics	vehicle's response (i.e., ride, handling, performance) to driver control inputs and interactions with the simulated roadways are modeled using the vehicle's chassis, suspension, tires, engine and transmission behavior
Visual	extensive library of real-time graphics and visual database models are available for the visual rendering process.

Pictures of the simulator are shown in Figure 17.



Figure 17. DriveSafety™ 500C High-fidelity simulator

In order to generate seat vibration the simulator was equipped and programmed with the IVIBE® Tactile Feedback Seating Unit which when the participant reaches the specified threshold the bottom portion of the seat vibrated to warn the driver, a picture is shown in Figure 18. The IVIBE® Tactile Feedback Seating Unit included a customized

interface and was controlled by IVIBE's® IntelliVIBE® software. The intensity and frequency of vibration used in Phase II was determined based upon the results in Phase I.



Figure 18. IVIBE® Tactile Feedback Seating Unit (left) in Simulator (right)

The simulator generated auditory signals through the car's internal speakers using a prerecorded "rumble strip" sound for line crossings. The auditory, haptic, and combined auditory and haptic warnings persisted for as long as the driver was beyond the specified threshold.

Scenario Description

The scenario consisted of the following elements:

- ~6-minute scenario
- Straight rural road
- 2 wind gust
- ~ 4 miles
- Speed limit 55mph

- 0 slope
- No ambient traffic
- Clear weather and road conditions
- Daytime

A screen shot of the scenario from Hyperdrive software has been shown in Figure 19 to indicate the beginning and end points of the scenario and corresponding wind gust/distracter task locations.

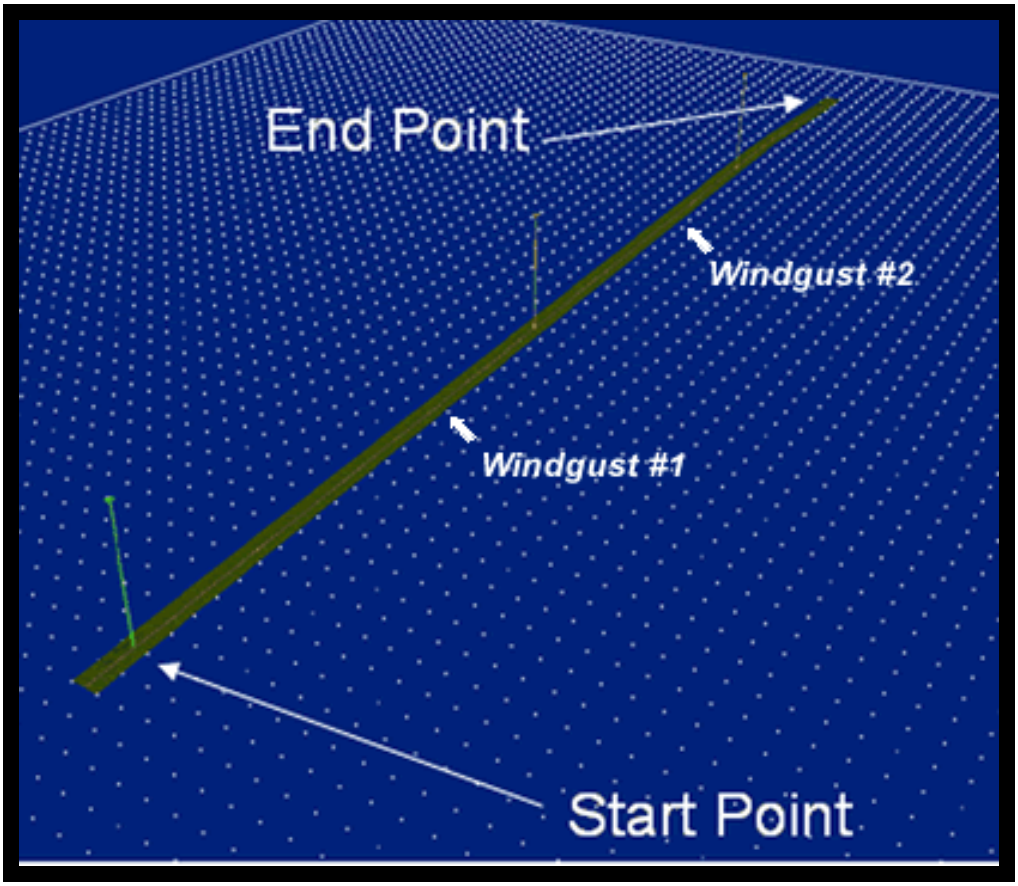


Figure 19. Hyperdrive Testing Scenario Layout

Figure 20 indicates, with reference to the participant vehicle, the lane warning threshold locations. The right warning was issued when the participant vehicle's right front wheel was six inches beyond the outer most lane-marking. The left warning occurred when the participant vehicle's left front wheel came in direct contact with the centerline lane marking.

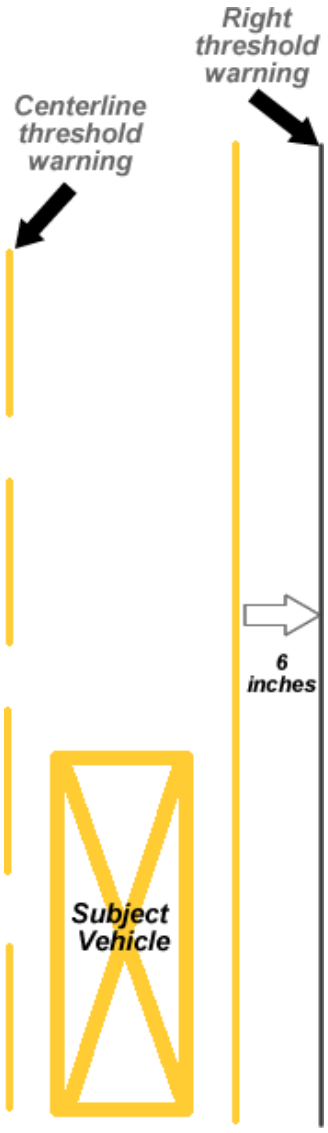


Figure 20. Diagram of Warning Threshold Locations

Distracter Task

Before the distracter task was given the experimenter ensured the participant was driving at the posted speed limit (55mph) to minimize effects of varying speeds on driver responses. The distracter task was initiated by the experimenter twice during each scenario. The task required participants to look over their right shoulder and memorize the letters on an index card and to remain looking over their shoulder until they receive the warning that they have drifted out of the lane. During the memorizing task the experimenter would issue a wind gust using a remote control (see Figure 21) from East to West or West to East depending on treatment order to enable the participant's vehicle to drift out of the lane and receive the specified warning. The first distracter task occurred at the same location approximately two miles from start of the scenario and the second distracter task occurred about two miles from the initial distracter task number to experimenter while continuing to drive. Each distracter task used a different index card of letters. The direction of the wind gust was randomly predetermined for each participant to eliminate any priming response from the first wind gust. The programming for enabling the wind gust and auditory warning signal can be found in Appendix K.



Figure 21. Remote Control Used for Initiating Wind Gusts

Driver Attitudes

After completion of the driving scenarios, participants completed a questionnaire ranking their perceptions of the modalities presented (see Appendix L). The purpose was to compare rankings among the modalities to determine if preferences existed. Drivers ranked their preferred modality on the following criteria: benefit to driving, purchasing likelihood, level of trust, annoyance, interference, appropriateness, urgency, and overall preference. The survey design and content was modeled after Lee, Hoffman, & Hayes, (2004). Prior to answering the survey questions, all participants were informed of the real-world purpose of the in-vehicle warning modalities. The following statements were provided verbatim from the experimenter to the participant to ensure each participant

fully understood the criterion. The participant was then asked to rank in order of preference, from most favorite to least favorite, based upon:

- Criterion 1: Benefit to driver – "Which modality do you think would benefit your driving experience the most?"
- Criterion 2: Purchasing likelihood – "Which modality you most likely purchase?"
- Criterion 3: Level of trust – "Which modality would you most trust in warning you of a roadway/lane departure (either left or right lane departure).
- Criterion 4: Annoyance – "Which modality would annoy you the least?"
- Criterion 5: Interference – "Which modality would interfere least with your ability to drive safely?"
- Criterion 6: Appropriateness – "Which modality do you think is most appropriate in warning you of a roadway/lane departure?"
- Criterion 7: Urgency – "Which modality do you think has the greatest level of urgency when warning of a roadway/lane departure?"
- Criterion 8: Overall preference – "Which modality do you prefer overall?

Statistical Analysis

Driver performance variables were managed and analyzed using Statistical Analysis System 9.0 (SAS) and MiniTAB 14.1. The statistical analysis of the driver

performance variables that followed parametric data assumptions (i.e. normally distributed, equal variances, interval level of measurement) was performed using General Linear Model (GLM) analysis of variance. When data violated the parametric data assumptions non-parametric statistical tests were conducted. The statistical model was a mixed with participant as a random factor and modality (auditory, haptic, combination) and location of warning (center or right) as fixed factors. Since each participant is measured at each level of the modality factor, participant is considered crossed with the modality factor. To test for differences between modalities at location of warning, a two-factor analysis of variance (ANOVA) was performed on the dependent variables, reaction time, time to return to lane, time to return to steady state, steering response, root-mean-square values of steering response, braking response, and accelerator response, by blocking over participants. For all post-hoc evaluations, a Tukey's pairwise comparison test was used to maximize the ability to determine significant difference among the factors, while minimizing the Type I error.

Given the modality treatment and two wind gust locations, each participant was tested under each of the treatments. Hence, there were six treatment combinations for each participant, arranged in random order: center/right location auditory warning modality, center/right location haptic warning modality, center/right location combination warning modality. The model generates a mixed model with modality treatment and

center/right location being a fixed variable and participants being a random factor. The constrained parameters model, is Equation 3:

$$Y_{ijk} = \mu + \tau_i + D_j + (\tau D)_{ij} + E_{ijk}$$

Equation 3. Constrained Parameters Model

Where:

μ = mean

τ_i = effect of ith level of warning modality

D_j = effect of jth level of warning location

τD_{ij} = interaction term of warning modality by warning location

E_{ij} = Residual error

For, i = 1, 2, 3, 4

j = 1, 2

An experiment wide alpha level of 0.05 was required in order to reject the null hypothesis for all results. The ANOVA table used for the calculations is shown in Table 4 below.

Table 4. ANOVA Calculations

Source	SS	df	MS	F
A	$SS_A = n\sum\left(\bar{Y}_{.j} - \bar{Y}_{..}\right)^2$	$a-1$	$MS_A = \frac{SS_A}{df_A}$	$F_A = \frac{MS_A}{MS_{AxS}}$
S	$SS_S = a\sum\sum\left(\bar{Y}_{i.} - \bar{Y}_{..}\right)^2$	$n-1$	$MS_S = \frac{SS_S}{df_s}$	
AxS	$SS_{AxS} = \sum\sum\left(Y - \bar{Y}_{i.} - \bar{Y}_{.j} + \bar{Y}_{..}\right)^2$ or $SS_{AxS} = SS_T - SS_A - SS_S$	$(a-1)(n-1)$	$MS_{AxS} = \frac{SS_{AxS}}{df_{AxS}}$	
T	$SS_T = \sum\left(Y_{ij} - \bar{Y}_{..}\right)^2$	$(a)(n)$		

For nonparametric data, number of steering reversals and number of incorrect steering reversals, a two-way chi-square test was conducted to determine where significant differences among the factors existed. The two-way Chi-square test is a technique for determining significance difference between the frequencies of occurrence, i.e. counts, in two or more categories with two or more groups. The equation for the chi-square test is shown in Equation 4 below.

$$X^2 = (\text{O-E})^2 / \text{E}$$

Equation 4. Chi-square Statistical Test

Where, O is the observed frequency, and E is the expected frequency

For driver preference analysis, the Friedman's non-parametric test (given that the data violates the assumptions of a parametric ANOVA) was applied to determine significant differences between the rankings. When Friedman's test indicated a significant difference among modality presentation then the Fisher's least significant difference method post-hoc multiple comparison test was used. The method can be described by Equation 5.

$$Q = \frac{12N}{s(s+1)} \sum_{i=1}^{s} \left[R_{i.} - \frac{1}{2}(s-1) \right]^2 ,$$

Where, $R_{i.} = \sum_{j=1}^{N} R_{i,j}$, N = number of rows in the table,
s = number of categories (columns)

Equation 5. Friedman's Statistical Test

A summary table of all statistical methods used in Phase I and Phase II has been provided in Table 5 below. The table demonstrates the type of data under investigation, the level of measurement, statistical method performed, and statistical software used in performing the analysis for Phase I and Phase II.

Table 5. Statistical Methods for Phase I and Phase II

	Type of Data	Level of Measurement	Statistical Method	Statistical Software
Phase II				
Reaction Time	Continuous	Continuous	GLM/Tukey's	SAS 9.0 / MiniTab 14.1
Time to Return to Lane	Continuous	Continuous	GLM/Tukey's	SAS 9.0 / MiniTab 14.1
Time to Steady State	Continuous	Continuous	GLM/Tukey's	SAS 9.0 / MiniTab 14.1
Number of Steering Reversals	Discrete	Categorical/Nominal	Chi-Square	MiniTab 14.1
Number of Incorrect steering Manuevers	Discrete	Categorical/Nominal	Chi-Square	MiniTab 14.1
Steering Responses	Continuous	Continuous	GLM/Tukey's	SAS 9.0 / MiniTab 14.1
Braking Response	Continuous	Continuous	GLM/Tukey's	SAS 9.0 / MiniTab 14.1
Acceleration Response	Continuous	Continuous	GLM/Tukey's	SAS 9.0 / MiniTab 14.1
Driver Attitudes	Discrete	Ordinal/Ordered	Friedman/Fisher's Exact	MiniTab 14.1
Phase I				
Quadrant Energy	Continuous	Continuous	One-Way ANOVA/Tukey's	MiniTab 14.1
Order of Trials	Continuous	Continuous	Paired t-test	MiniTab 14.1
Age Differences	Continuous/Discrete	Continuous/Binomial	Linear Regression/Logistic Regression	MiniTab 14.1
Gender Differences	Continuous	Continuous	Two Sample t-test	MiniTab 14.1

Sample Size Estimation Procedures

A sample size estimation was performed when fifteen participant were completed in order to determine the total number of participants needed to have a power level of 0.05. The power of the test is the probability of correctly rejecting the stated null hypotheses when it is false or the likelihood that a significant difference will be identified

when one exists. Equation 6 assisted in determining the sample size necessary in order to reach the specified power level.

$$n = \left[\frac{z_{\alpha/2}\sigma}{\mathrm{E}} \right]^2$$

Where, $\mathrm{E} = z_{\alpha/2} \cdot \frac{\sigma}{\sqrt{n}}$, $z_{\alpha/2}$ critical value,

σ = population standard deviation. n = sample size.

Equation 6. Sampling Size for Statistical Tests

Driving Response Dependent Variables

The dependent variables relating to driver performance were sampled at 15Hz. These include; reaction time, maximum steering response, root-mean-square (RMS) values of steering response, time to return to lane, time to return to steady state, number of steering reversals, number of incorrect maneuvers, maximum braking response, and minimum accelerator response. Reaction time was defined as the elapsed time between issuance of the warning to the point at which the participant turned the steering wheel two degrees from neutral in the clockwise or counterclockwise direction. Steering data was the steering input in degrees. Time to return to lane is defined as the time until the vehicle crossed the 0 lane position. Time to return to steady state was defined at the point where the steering response was minimized to less than five degrees of deflection in the positive or negative direction. The number of steering wheel reversals greater than five degrees at each lane departure was analyzed. The number of incorrect steering reversals included when participant responded to the warning by turning in the incorrect direction.

Acceleration and braking values measure the normalized accelerator and braking input value (0.0-1.0). Data management was performed using SAS 9.00 and MiniTAB 14.1 was used for statistical analysis.

The root-mean-square (RMS) values for steering deflection were used in the analysis given by Equation 7:

$$x_{\text{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots + x_N^2}{N}}$$

Equation 7. Root-mean-square (RMS)
Where x = variable of interest, N=number of observations

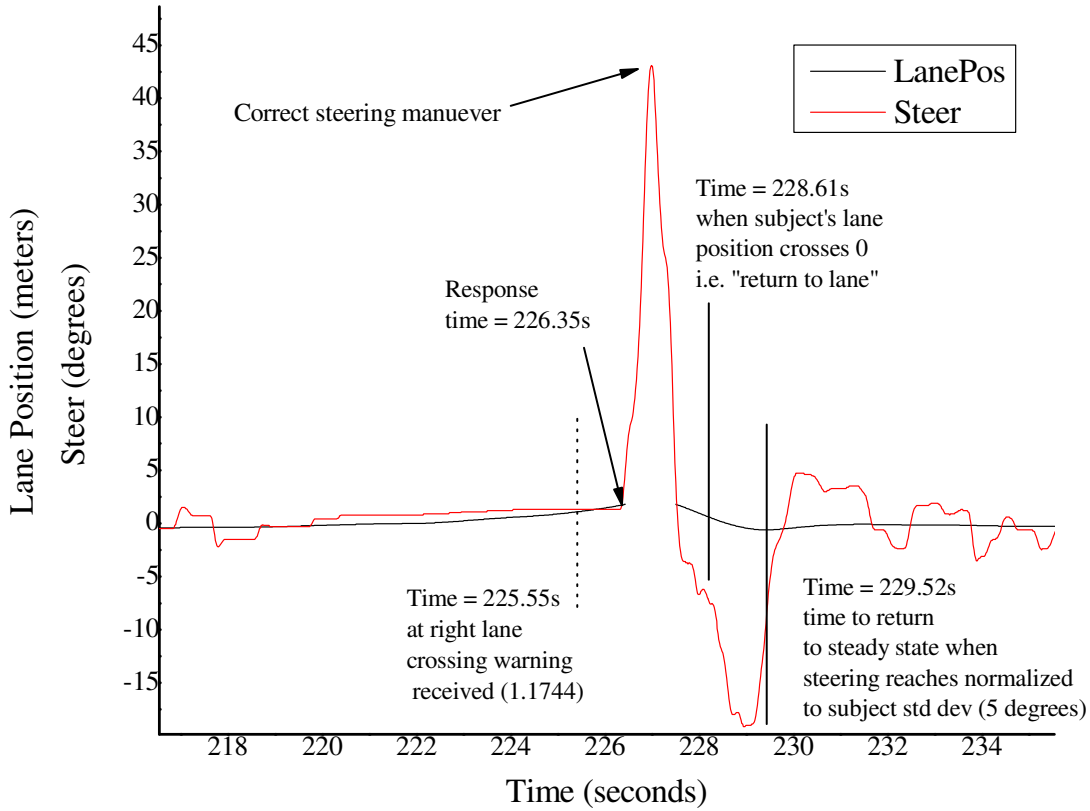
Acceleration and braking values measure the normalized accelerator and braking input value (0.0-1.0), respectively. Any value greater than 0.0 indicates that brake or accelerator pedal was being applied.

Figure 22 below demonstrates the data collection methods in obtaining response time, time to return to lane, time to return to steady state, correct/incorrect steering maneuvers, number of steering reversals, steering, accelerator and braking response window (for participant two, used as an example, for a combination warning received a haptic warning at right location). All data collected for response time, time to return to lane, return to steady state, correct/incorrect maneuvers, and number of steering reversals was performed using OriginPro 7.5 graphical analysis software. Steering responses,

acceleration, and braking were collected using SAS 9.1, code for the data analysis can be found in Appendix M.

Note: Supplemental materials for the Labview ™ user interface and diagram developed see Appendix N and Appendix O. Programming for the integration of the IVIBE® Tactile Seat with the Hyperdrive® Software can be found in Appendix P and Appendix Q.

Figure 22. Key data collection points for combination warning at right location



CHAPTER 4

RESULTS

Phase I Results

Participant Results

The mean age of the fifteen participants (five males and ten females) was 34.1 years (standard deviation 6.2 years, maximum = 49 years of age, minimum = 27 years of age). No participants were excluded due to failing the hearing test. The participant sampling plan for the Phase II study was focused on maintaining demographics similar to that in Phase I; this was done to minimize the potential for main effects of age found in Phase I (no main effects existed between genders).

Seat Vibration Results

Results from the three acceleration measurements taken in the x, y, and z-direction resulted in the calculated resultant g-force (measured in volts) at each quadrant section of the seat as indicated in Figure 23.

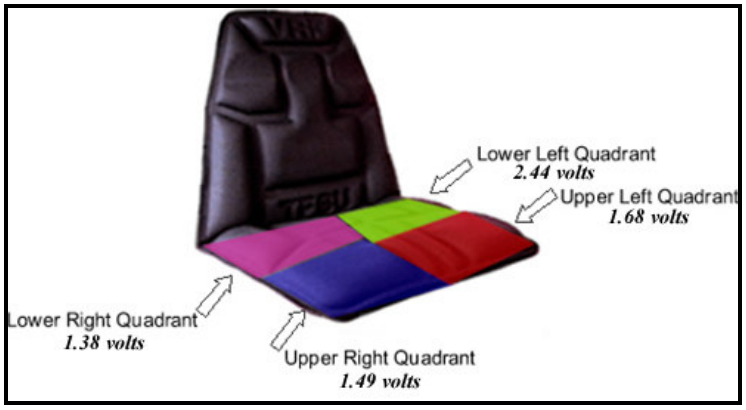


Figure 23. Vibration Intensity Measurements at Seat Quadrant Locations

The upper left quadrant measured -1.64 g (1.68 volts), lower left at -0.13 (2.44 volts), the upper right at -2.03 g (1.49 volts), and the lower right at -2.24 g (1.38 volts). The mean resultant for all quadrants was measured at 1.745 volts, standard deviation ± .476 volts. This voltage of 1.745 volts is equivalent to -1.51 g's with standard deviation of ± .55 g's. The graph demonstrates the variability that existed in the seat at different locations of the bottom portion of the seat (only the bottom portion issued a haptic sensation).

The interval plot Figure 24 demonstrates the variability in g-forces as measured in the four quadrants. Measurements are in arbitrary units established by IVIBE®. Each interval plot illustrates both the central tendency and variability of the data, the vertical line with horizontal line indicates the endpoints of the 95% confidence interval for the mean which is shown with the symbol. The symbol in the center is the data mean.

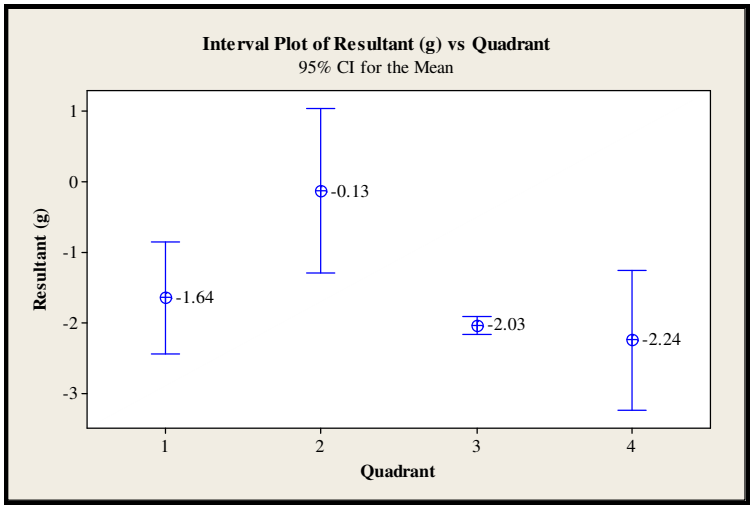


Figure 24. Interval Plot of Resultant in g's at Quadrant Locations
where 1 = upper left quadrant, 2 = lower left quadrant,
3 = upper right quadrant, 4 = lower right quadrant

The highest amount of measured acceleration energy was in the lower right portion of the seat at -2.24 g's. The least amount of acceleration was found in the lower left portion of the seat -.13 g's. A one-way analysis of variance determined that significant differences were found among the quadrant locations. The upper left, upper right, and lower right portion of the seat were near similar $p>0.05$, whereas Tukey's pairwise comparison test found that the lower left quadrant was significantly lower $F_{3,8} = 22.43$, $p=0.000$, than the other three locations. Table 6 presents the statistical data relating to the ANOVA for the quadrant locations.

Table 6. One-way ANOVA: Resultant (g) vs. Quadrant

Source	DF	SS	MS	F	P
Quadrant	3	8.174	2.725	22.43	0.000
Error	8	0.972	0.121		
Total	11	9.145			

IVIBE® Console Results

The graph in Figure 25 displays the interval plot of the haptic seat IVIBE® ™ console measurements. Each vertical line represents six measurements per participant upon performing the matched auditory-haptic intensity task. The graph demonstrates

both the variability within and variability between the participants. The mean value of the fifteen participants was 44.14 (standard deviation 10.04, minimum 21.20, maximum 82.10).

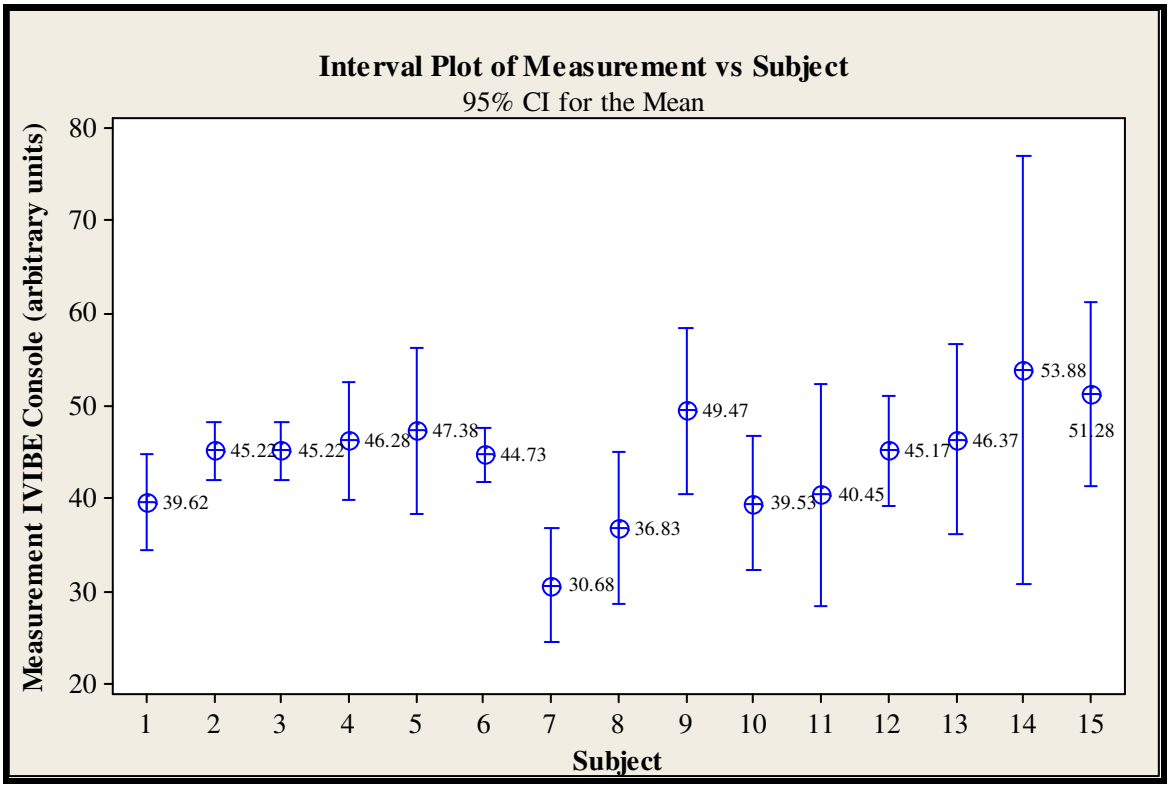


Figure 25. Interval plot of IVIBE® Haptic Seat Measurement

Figure 26 demonstrates the variability associated with ascending and descending trials. A paired t-test was conducted to determine if statistically significant differences existed in whether the order of trails affected participant response to the haptic seat stimulation. Participants reported a significantly higher, T=-40.93, p=0.000, response during the descending trial of 47.51 in comparison to the ascending trial of 40.77. This is to say when the experimenter began with a higher intensity of vibration and began

decreasing the haptic intensity, participants consistently reported a higher measurement than when beginning at a lower intensity and increasing the haptic intensity.

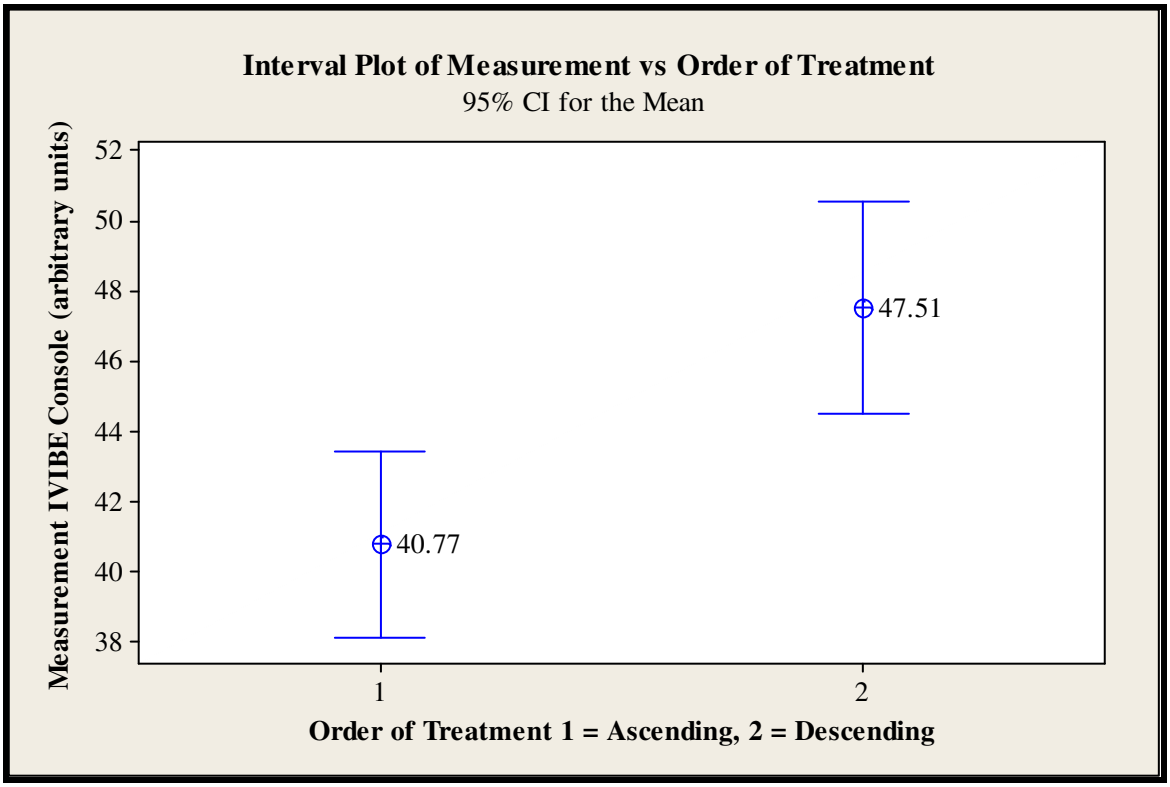


Figure 26. Interval Plot of IVIBE® Console Measurement vs. Trials

A two-sample t-test to compare the main effects of gender on responses was conducted to determine whether there is a statistically significant difference between males versus females. No significant differences T=1.68, p=0.098 were found between males and females. However, though not statistically significant, males tended to report a lower response of 41.81 in comparison to the female response of 45.70. Figure 27 demonstrates measurements based upon gender.

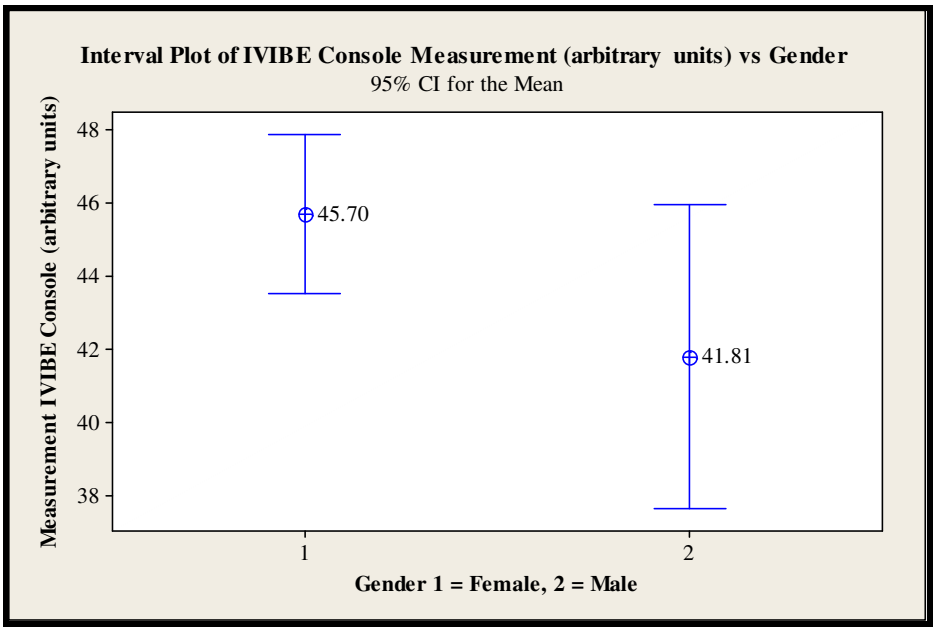


Figure 27. IVIVE Console Measurement of Males versus Females

In Figure 28 demonstrates the variability associated with age and response to the haptic seat stimulation as measured through the IVIBE® Console.

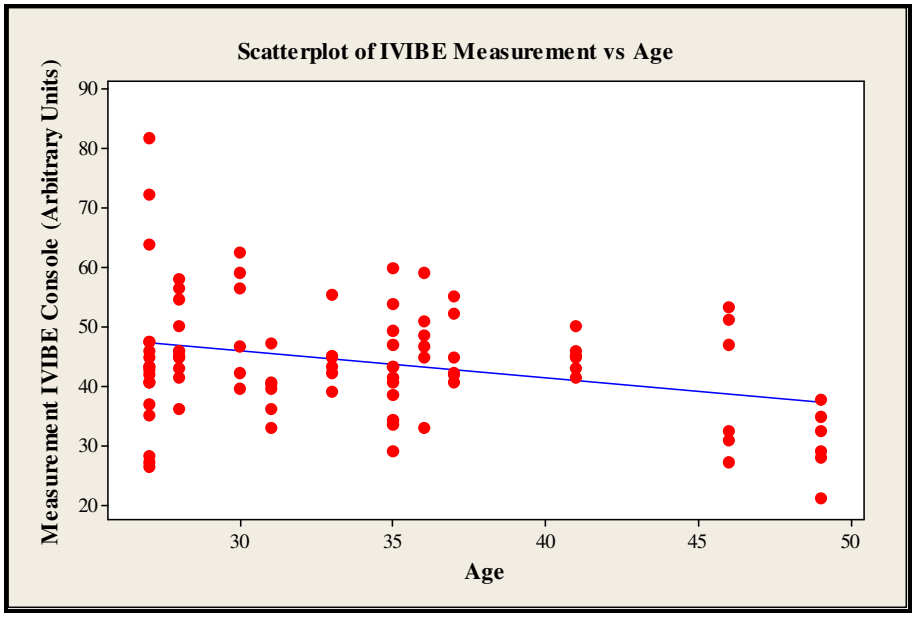


Figure 28. Scatter plot of IVIBE® Measurement by Age

A regression analysis was conducted to determine if a relationship of age and measurement exists. A possible trend with age was discovered but was not statistically significant (R^2 = 9.1%). It should be noted the sampling plan was not adequate to obtain an accurate representation of age effects (and gender effects). Future research should include a better understanding of age and gender effects. Nonetheless, the regression analysis is found in Table 7.

Table 7. Regression Analysis IVIBE® Measurement versus Age

Predictor	Coef	SE Coef	T	P
Constant	59.372	5.232	11.35	0.000
Age	-0.4480	0.1510	-2.97	0.004
S = 9.62791				
Regression equation is: Measurement = 59.4 - 0.448 Age				

A regression prediction equation was generated to better understand this relationship. The regression equation indicates as age increases the measurement response decreases by .448. For example, the mean age was approximately 34 years and therefore the mean measured response was 44.1. A person 50 years of age would have a mean response of 59.4 - .448(50) = 37.0, while a person 18 years of age would have a mean response of 59.4 - .448(18) = 51.3. Care should be taken in this calculated predicted regression equation as the adjusted R-square value indicates that it only accounts for 8.1% of the variability, therefore it does not fit the data very well.

To further investigate any relationship between age and measurement, participant age were placed into two categories, one category for those 35 years of age (number of samples = 42) and under and another category for those older than 35 years of age

(number of samples = 45). This allowed for analysis using binary logistic regression. The regression analysis found no significant differences among the categories were discovered ($p<0.05$). The graph in Figure 29 demonstrates the regression analysis.

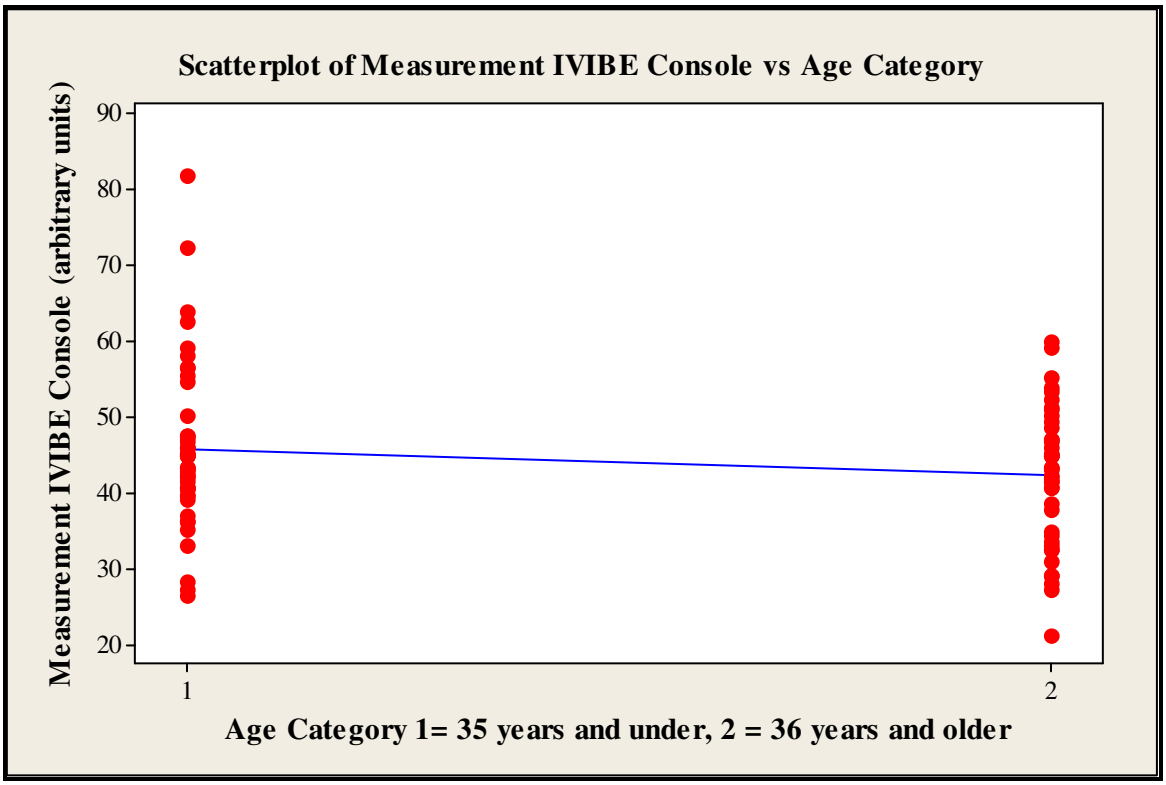


Figure 29. IVIBE® Console Measurement by Age Category

Sound-Level Measurement

The sound-level when participant vehicle traveling at 55mph within the lane and no warning was issued registered at 50 decibels. When participant vehicle was out of the lane and the auditory signal was issued the sound-level registered a maximum of 67 decibels. When participant vehicle was out of the lane and the haptic signal was issued the sound-level registered 60 decibels. Finally, when participant vehicle was out of the

lane and both the auditory and haptic warnings were issued the sound-level registered a maximum of 68 decibels.

Sound-Level and Haptic-Intensity Equivalence

The sound-level where participants deemed the haptic seat vibration energy matched that of the auditory-signal registered at 68 decibels. Which participants deemed perceptually equal in the seat's vibration energy of -1.51 g's (1.745 volts). Therefore the results from Phase I determined that a 68 decibel auditory warning was equivalent to ±1.51 g's. As a result, 1 g in the haptic seat's vibration energy was equivalent to approximately 45 decibels of sound from the auditory signal. This equivalency was maintained throughout the Phase II study.

Phase II Results

Fifteen drivers participated in the Phase II study. Table 8 demonstrates the demographics of the three treatment ordering groups based upon the Counterbalanced Latin Squares Design. The average age of the fifteen participants was 32.0 years of age with a standard deviation of 8.3 years of age, 11 females and four males. The participants used for the Phase II study were recruited to maintain demographic consistencies (mean age and proportion of males:females) with that from Phase I. All participants passed the hearing test, therefore no participants were excluded due to hearing loss at the aforementioned frequencies. All participants completed the study with no reports of moderate to severe simulator induced discomfort. The lack of reported simulator induced discomfort may have been due to the combination of the short duration of the testing

scenarios, minimal environmental clutter, straight roadway, and/or mostly younger population.

Table 8. Participant Descriptive Statistics and Group Assignment

Participant Number	Age	Gender	Treatment Order Grouping
1	30	F	Combo, Auditory, Haptic
11	25	F	Combo, Auditory, Haptic
12	29	F	Combo, Auditory, Haptic
13	44	F	Combo, Auditory, Haptic
15	28	M	Combo, Auditory, Haptic
Average	31.2 ± 7.4		
2	20	M	Auditory, Haptic, Combo
3	21	F	Auditory, Haptic, Combo
4	35	F	Auditory, Haptic, Combo
5	48	F	Auditory, Haptic, Combo
9	36	F	Auditory, Haptic, Combo
Average	32.0 ± 11.7		
6	44	M	Haptic, Combo, Auditory
7	30	F	Haptic, Combo, Auditory
8	27	M	Haptic, Combo, Auditory
10	35	F	Haptic, Combo, Auditory
14	28	F	Haptic, Combo, Auditory
Average	32.8 ± 7.0		

Sample Size Calculations

In order to obtain an acceptable power level of .95, MiniTab's 14.1 power and sample size calculator was utilized to determine the appropriate size to reach the pre-specified power level. Upon completing the initial fifteen participants for the Phase II study a sample size calculation was performed to determine if more participants were necessary. Variables used in the calculation included the maximum difference between

factor level means and standard deviation. The standard deviation for performing subsequent ANOVA analysis was the square root of the mean square error (MS error). Using MiniTab's power and sample size calculator, provided the minimum factor level means differences, it was determined that 13 participants would sufficient in reaching the predetermined power level of .95. Table 9 includes the power and sample size data calculations.

Table 9. Power and Sample Size Statistical Data

Alpha = 0.05
Assumed standard deviation = 0.252837
Number of Levels = 3

	Sample	Target		Maximum	
SS Means	Size	Power	Actual Power	Difference
0.0396774	26*	0.95	0.950703	0.2817
0.0012350	801*	0.95	0.950161	0.0497
0.0269120	38*	0.95	0.951577	0.2320

* 13 participants measured at center and right, total of N=26

Reaction Time Analysis

Table 10 provides descriptive statistics of the reaction times by the modality factor. No outlier data was removed. The mean reaction time for the auditory center warning was 1.238 ± 0.298 and right warning was 1.137 ± 0.310; mean reaction time for the haptic center warning was 0.922 ± 0.223 and right warning 0.890 ± 0.210, and; mean reaction time for combo center warning was 1.044 ± 0.274 and right warning 1.232 ± 0.333.

Table 10. Descriptive Statistics of Reaction Times

	Reaction Times (seconds)					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	1.238	0.298	0.922	0.223	1.044	0.274
Right Warning	1.137	0.310	0.890	0.210	1.232	0.333

Figure 30 is a box plot of reaction time for each modality at each warning location (center and right). The slowest reaction time was the auditory warning at the center location at 1.24 seconds. The fastest reaction time was the haptic warning at the right location at 0.89 seconds. The slowest reaction time was 1.536 seconds in the auditory condition and the quickest was 0.68 seconds occurred in the haptic condition, a difference of 0.856 seconds. Driving a speed of 55 mph, a 0.856 second reduction would be equal

to a 69 foot reduction. If the driver is traveling at a speed of 75 mph this time reduction amounts to approximately 94 feet. The greatest variability in reaction time was the right warning combination of haptic and auditory warning at ± 0.333 seconds, least amount of variability was the haptic condition at the right location at ± 0.210 seconds.

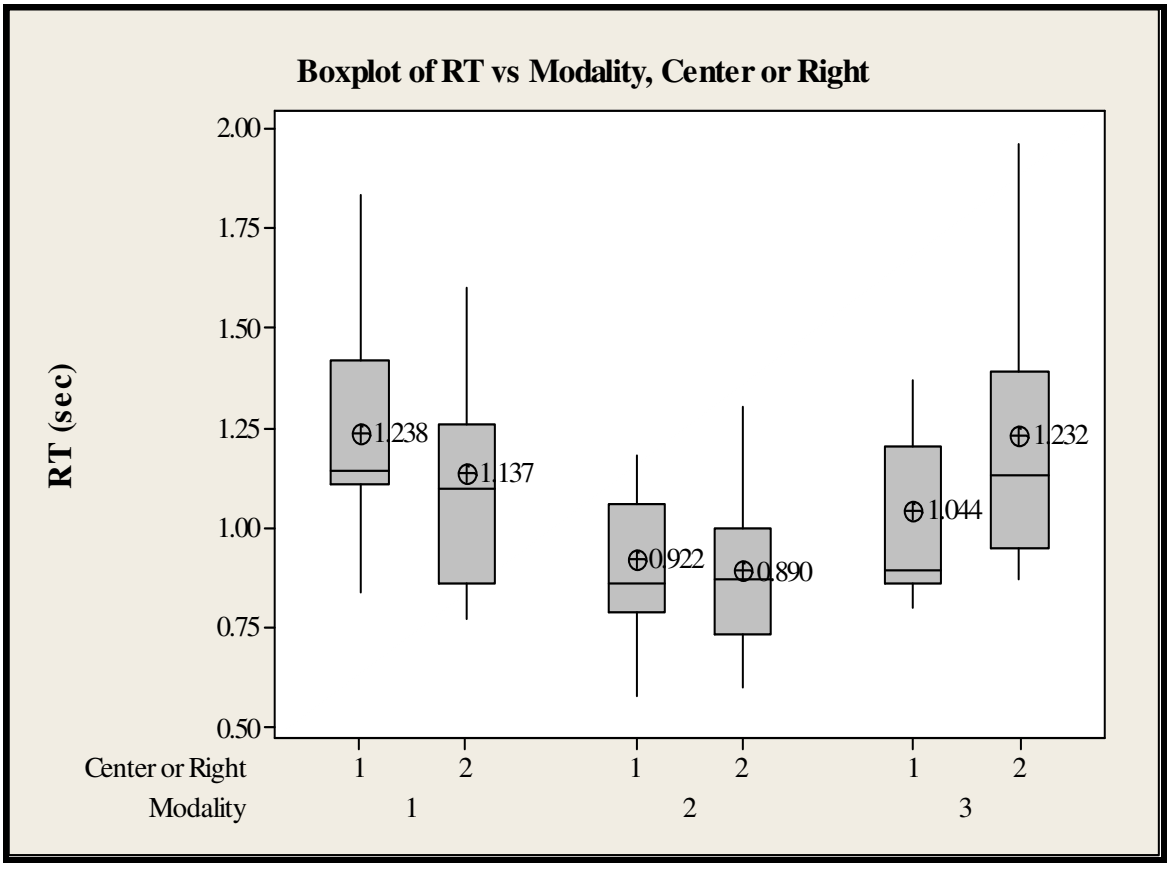


Figure 30. Box plot of Reaction Time
Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Individual reaction time data for each modality location is provided in Figure 31.

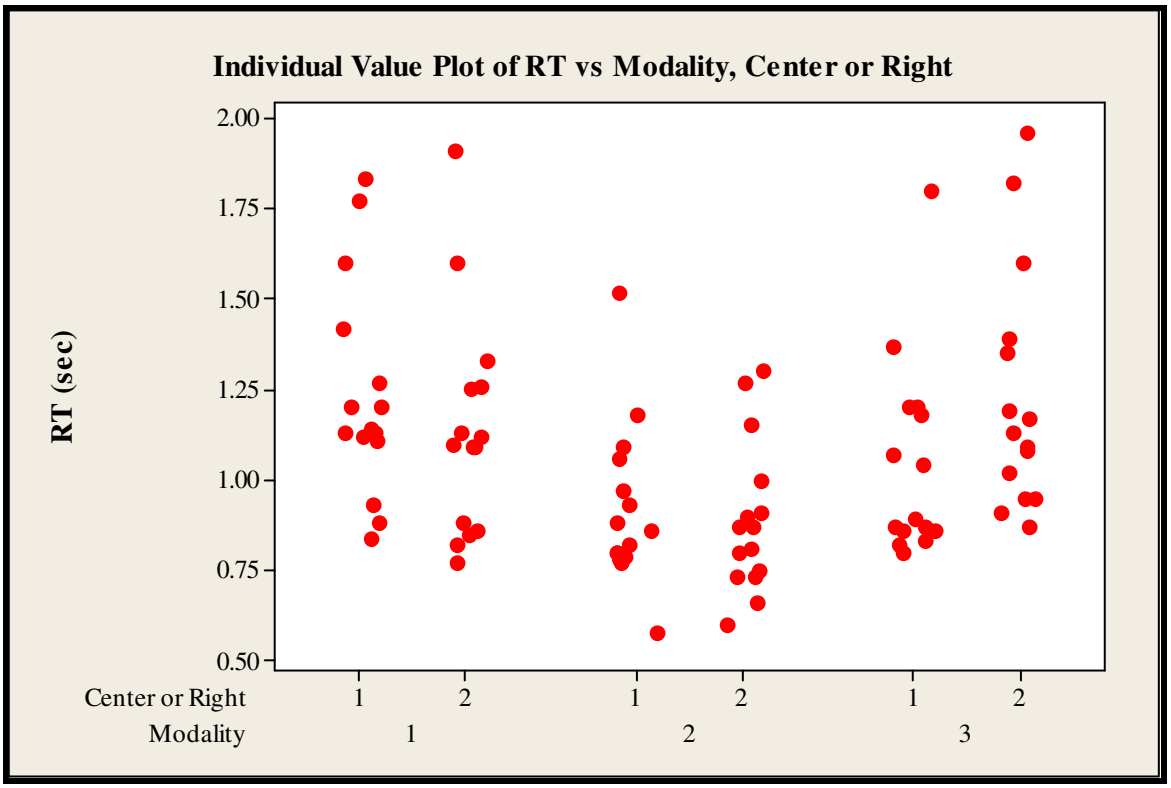


Figure 31. Participant Data of Reaction Time
Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

No significant differences were found in the location of warning (center or right) factor, $F_{1,70} = 0.12$, $p = 0.730$ significant differences were found among the modality factor $F_{2,70} = 10.61$, $p = 0.000$. Tukey's post-hoc pairwise comparison among levels of modality determined that the haptic condition was significantly faster than both the auditory $p = 0.0002$ and combination $p = 0.002$ treatment. The haptic condition reduction in reaction time over the auditory and combination at the center location was 0.316 seconds and 0.122 seconds, respectively. The haptic condition reduced reaction time over the auditory and combination by 0.247 seconds and 0.342 seconds, respectively.

The greatest reduction in reaction time, provided the means and standard deviation, occurred between the combination modality at right location and haptic modality at the right at .885 seconds. No significant differences were found between auditory and the combination treatment, $p = 0.7281$.

Table 11 has been provided to summarize the statistical calculations.

Table 11. General Linear Model Statistics for Reaction Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	2.02912	2.02912	0.14494	2.27	0.013
Modality	2	1.35627	1.35627	0.67818	10.61	0.000
Center or Right	1	0.00765	0.00765	0.00765	0.12	0.730
Modality*Center or Right	2	0.34111	0.34111	0.17055	2.67	0.076
Error	70	4.47485	4.47485	0.06393		
Total	89	8.20901				

Main effects and interaction plots are shown in Figures 32 and 33, respectively. The main effects plot demonstrates the mean response time (sec) for each modality at each location. There is a significant difference between the auditory condition and the

haptic condition, with the auditory condition requiring significantly more time than the haptic condition.

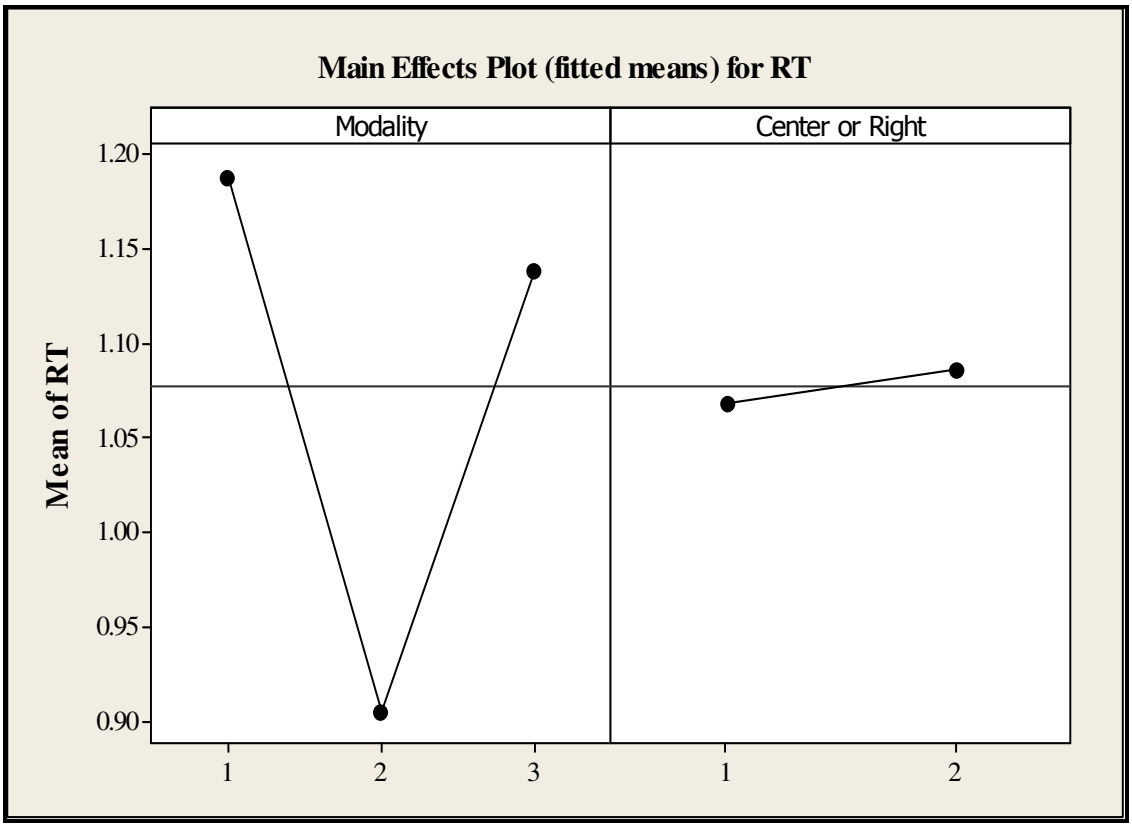


Figure 32. Main Effects Plot of Reaction Time

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

In the interaction plot the lines for auditory and haptic modality are near parallel, while the line for combination modality is not parallel with the auditory or haptic modality. However, the statistical analysis indicates there are no significant interactions between modality and location of warning (center or right), $p = 0.076$.

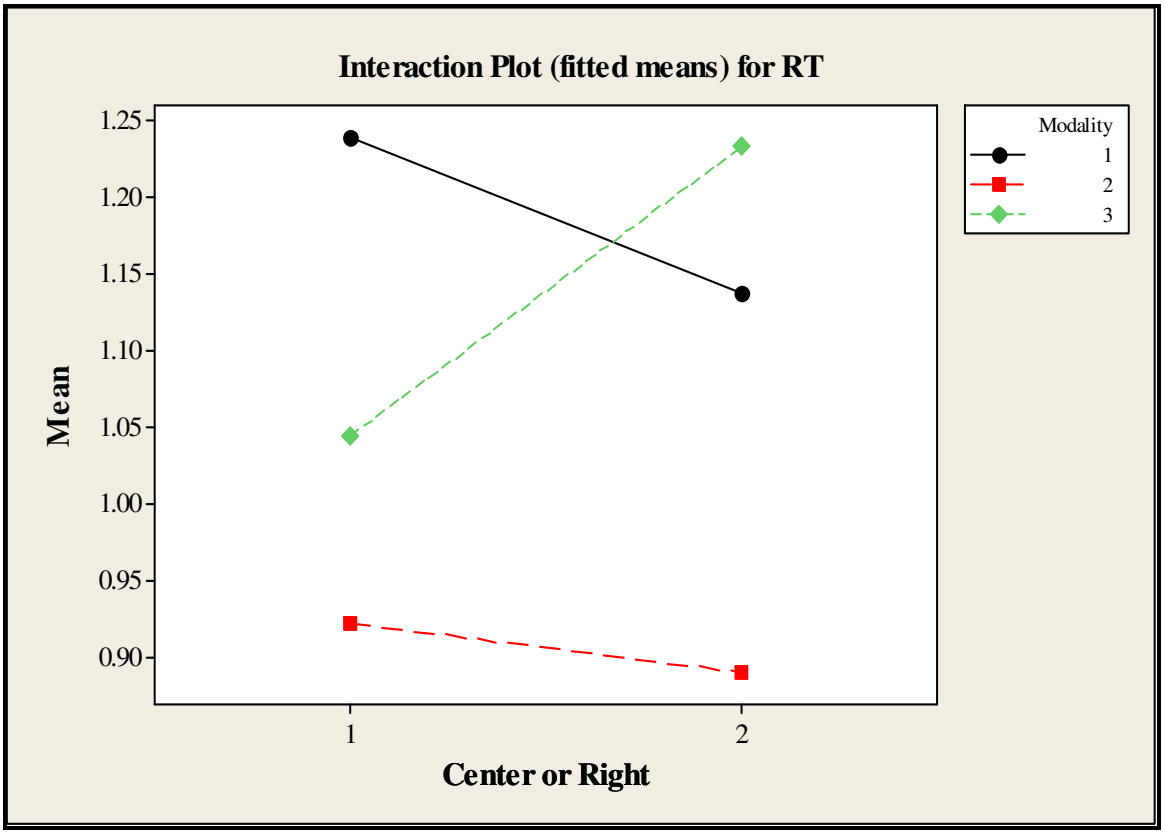


Figure 33. Interaction Plot of Reaction Time

Where, Location 1 = Center, 2 = Right

Time to Return to Lane

Descriptive statistics have been provided for the time to return to lane measurement in Table 12. One participant's data was removed due to participant's confusion regarding the task of returning to lane. The mean time to return to lane for auditory modality was 2.548 ± 0.489 seconds for center warning and 4.299 ± 0.917 for right warning. Mean time to return to lane for haptic modality was 2.506 ± 0.655 seconds center warning and 4.076 ± 1.053 for right warning; and, mean time to return to lane for

combination was 2.297 ± 0.749 seconds center warning and 4.147 ± 0.995 for right warning. Auditory modality at the right had the highest mean return to lane with 4.299 seconds. The fastest return to lane recorded was the combination condition at the center location at 2.297 seconds. The largest standard deviation in recorded reaction time was the haptic condition at the right location.

Table 12. Descriptive Statistics Return to Lane

	Return to Lane (seconds)					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	2.548	0.489	2.506	0.655	2.297	0.749
Right Warning	4.299	0.917	4.076	1.053	4.147	0.995

The analysis of variance found no significant difference among modalities $F_{2,69} = 0.51$, $p > 0.05$. Significant differences were found for the location factor $F_{1,69} = 100.21$, $p = 0.000$, in which significantly more time was required to return to lane when exiting the roadway to the right than at the center warning. Figure 34 demonstrates the time to return to lane for each modality at each location.

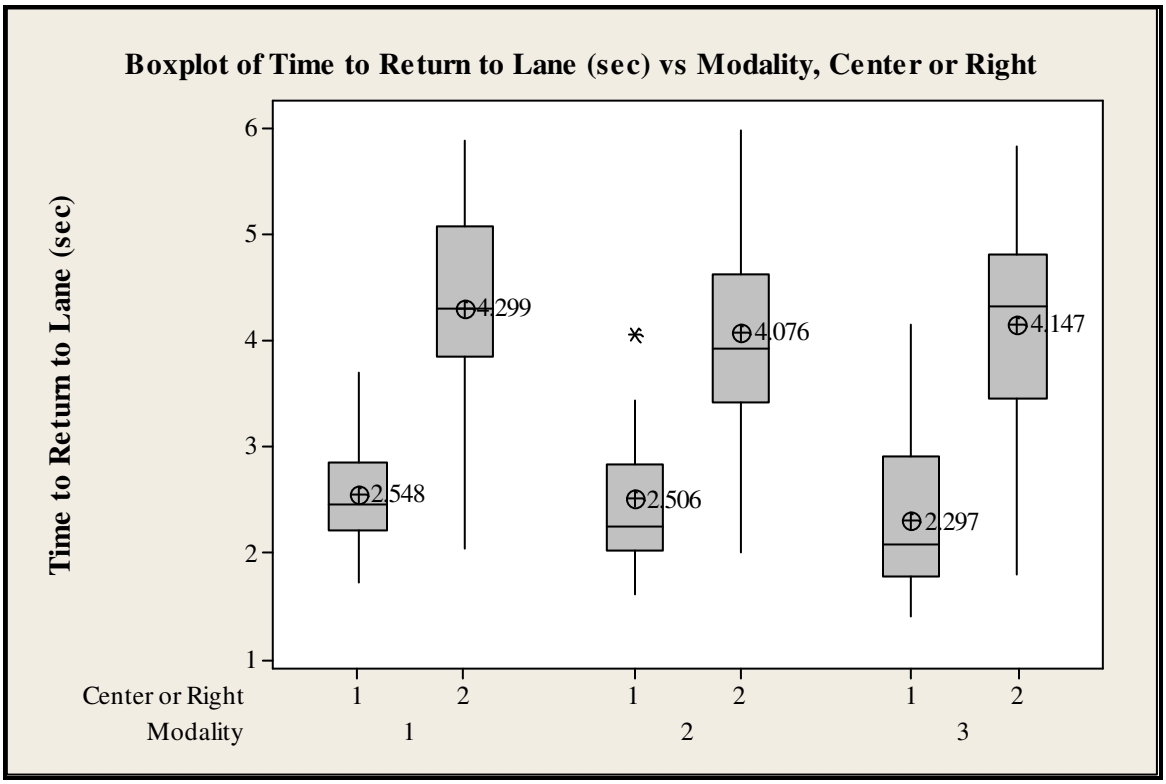


Figure 34. Time to Return to Lane

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Statistical analysis has been provided for the time to return to lane measurement in Table 13.

Table 13. General Linear Model Statistics for Return to Lane

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	13.475	12.561	0.897	1.380	0.184
Modality	2	0.739	0.658	0.329	0.510	0.604
Center or Right	1	65.131	64.917	64.917	100.210	0.000
Modality*Center or Right	2	0.386	0.386	0.193	0.300	0.744
Error	69	44.700	44.700	0.648		
Total	88	124.440				

When outlier data was removed (N=82), significant main effects ($p<0.05$) were discovered. Many researchers consider an outlier if the data point is different than the sample mean by more than twice its pooled standard deviation. For this data set, values that were between 1.5 and 3 times away from the middle 50% of the data were considered outliers, hence removed (MiniTAB™ documentation). The descriptive statistics of the new data set, outliers removed, are shown in Table 14. The longest time to return to lane occurred at the right location under the auditory condition at 4.461 ± 0.694 seconds. The shortest time to return to lane occurred at the center location under the combination condition at 2.165 ± 0.567 seconds. The greatest recorded time variability occurred at the right warning under the combination condition at ± 0.78 seconds.

Table 14. Descriptive Statistics of Return to Lane Outliers Removed

	Return to Lane (seconds)					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	2.548	0.489	2.396	0.138	2.165	0.567
Right Warning	4.461	0.694	3.931	0.557	4.315	0.78

Tukey's pairwise comparison test revealed that significant main effects of location $F_{1,62}$ =206.36 and main effects of modality were significant $F_{2,62}$ = 3.14 where auditory condition required more time to return to lane than the haptic condition ($p<0.05$). It can be hypothesized that the extended time to return to lane is a function of the reaction time. The auditory condition had the longest reaction time leading to longer

time out of the lane, therefore it is expected to require more time to return to lane. No significant differences were found between combination and haptic or combination and auditory ($p>0.05$). A box plot of return to lane times versus modalities and location of warning in Figure 35 is shown. As shown the time to return to the lane was consistently longer for the right location than the left location. This is likely because the warning location threshold was closer to the lane on the center (i.e. centerline warning) than the right warning threshold which had an offset of six inches.

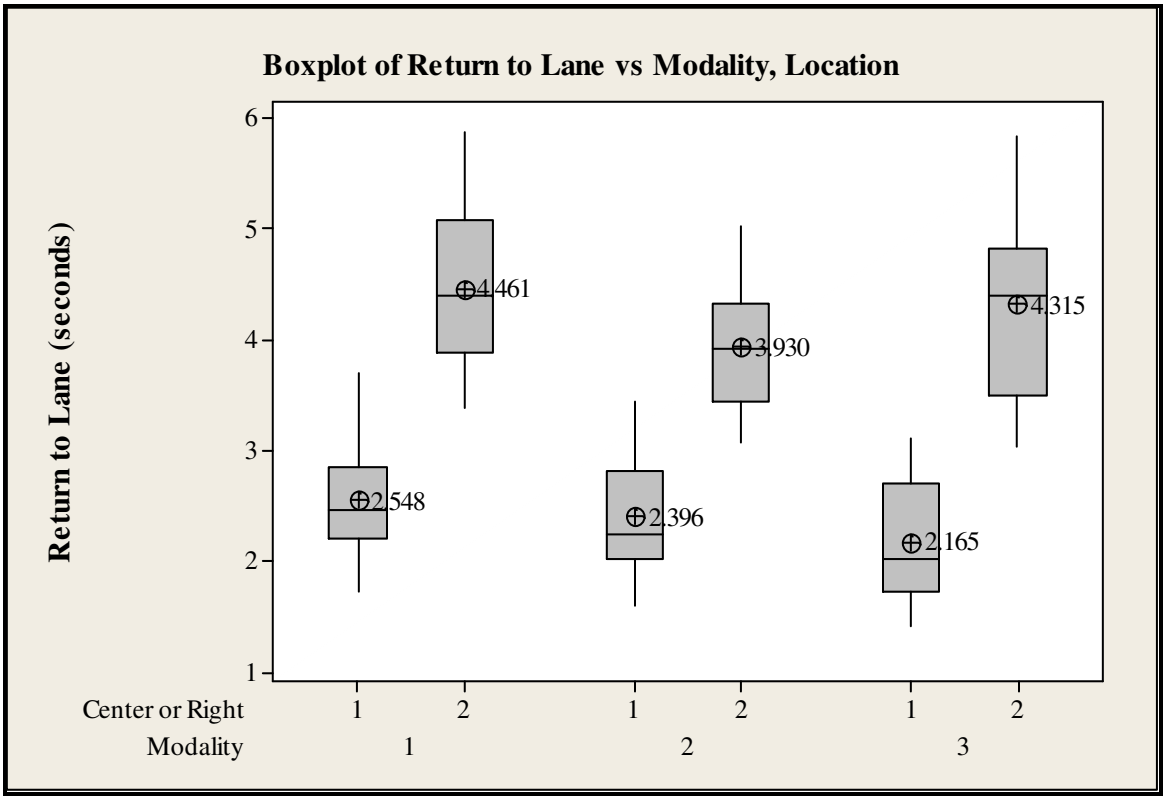


Figure 35. Time to Return to Lane (sec) Outliers Removed

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Statistical analysis from the ANOVA is provided in Table 15.

Table 15. General Linear Model: Return to Lane Outliers Removed

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	9.198	7.810	0.558	1.690	0.080
Modality	2	2.440	2.072	1.036	3.140	0.050
Center or Right	1	69.977	68.037	68.037	206.360	0.000
Modality*Center or Right	2	1.752	1.752	0.876	2.660	0.078
Error	62	20.441	20.441	0.330		
Total	81	103.808				

Main effects and interaction plots are shown in Figures 36 and 37, respectively. The main effect plot demonstrates the mean time to return lane for each modality. The haptic and combination modality were more similar in time in comparison to the auditory modality. As can bee seen in the main effects plot the auditory required more time to return to lane than that require of the haptic (P=0.05). There were no significant difference between the auditory and combination condition, though a trend (p=0.162) of auditory requiring more time that than of the combination condition.

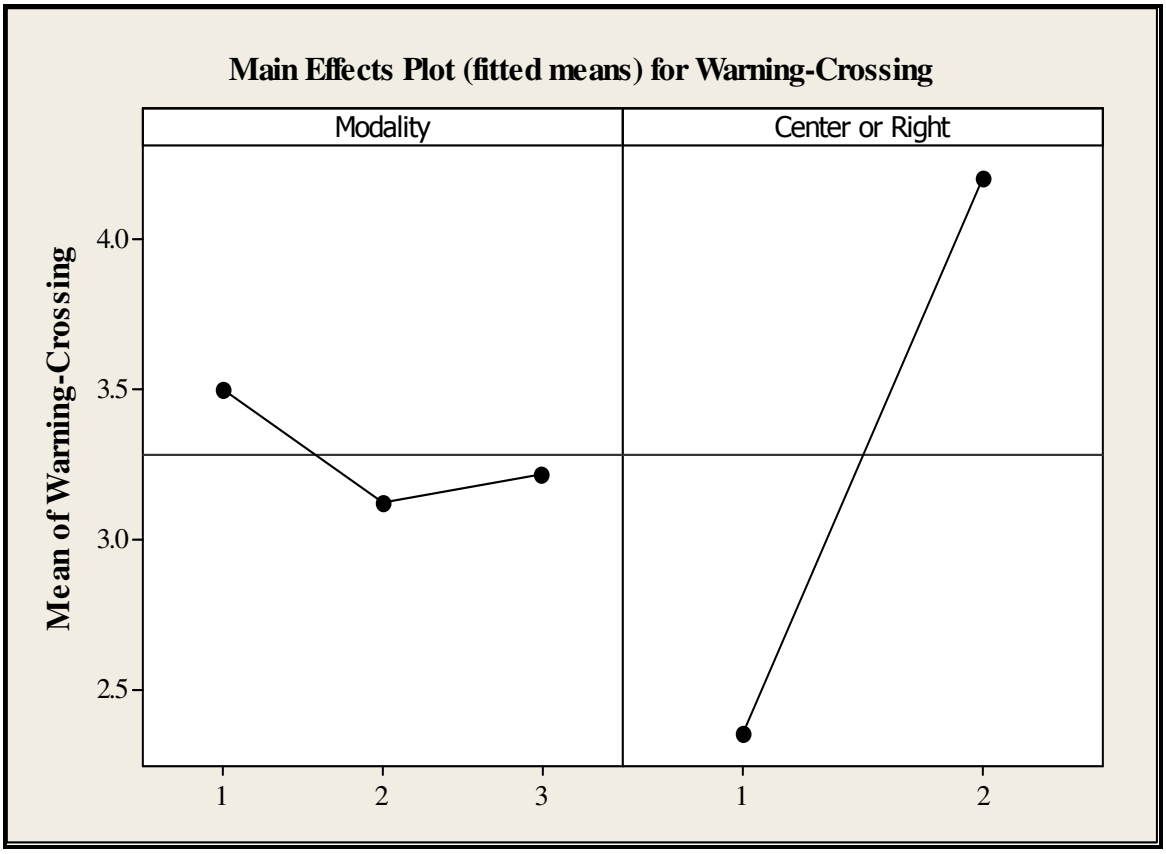


Figure 36. Main Effects Plot of Time to Return to Lane

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

In the interaction plot the lines for auditory and haptic modality are near parallel, while the line for combination modality is not parallel with the auditory or haptic modality. However, the statistical analysis indicates there are no significant interactions between modality and location of warning (center or right), $p = 0.078$.

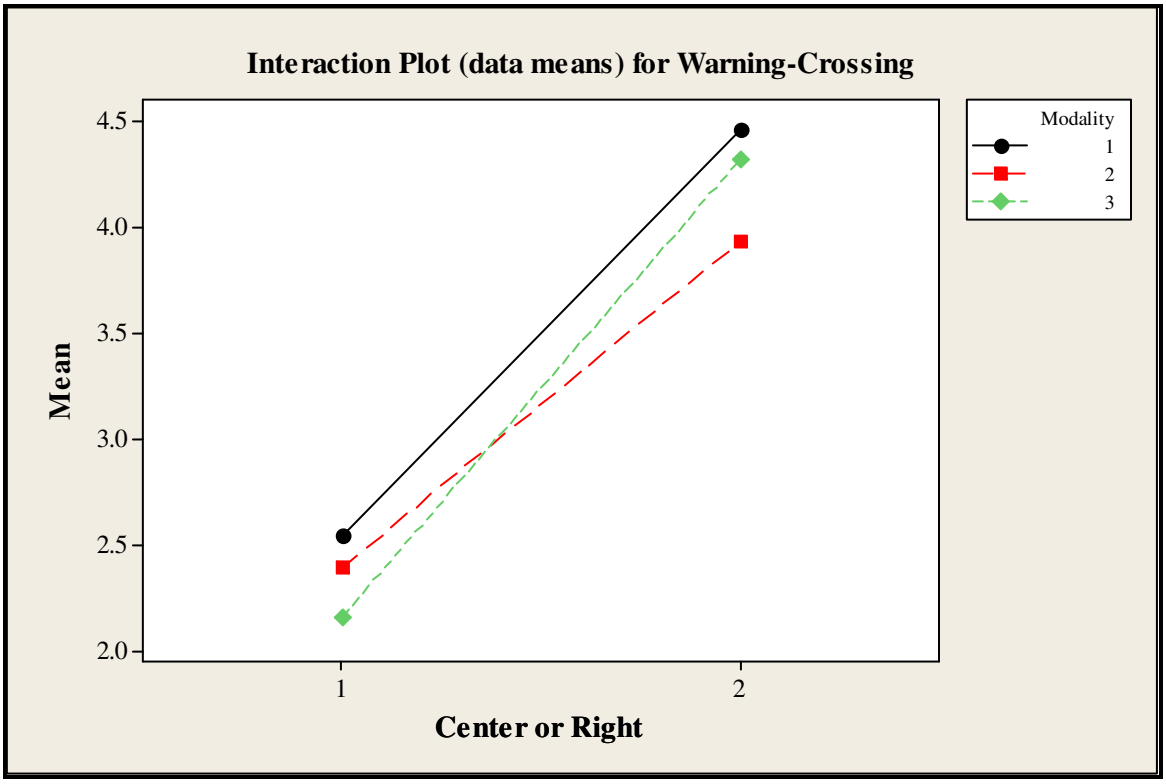


Figure 37. Interaction Plot for Return to Lane

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Return to Steady State

Descriptive statistics have been provided for the time to return to steady state are in Table 16. Both the fastest and slowest time to return to steady occurred in the haptic condition at right location with 5.04 ± 1.17 seconds and 5.79 ± 1.18 seconds at the center location. The greatest standard deviation of time to return to steady state occurred in the combination condition at ± 3.68 seconds.

Table 16. Descriptive Statistics of Time to Return to Steady State

	Time to Return to Steady State (seconds)					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	5.655	1.108	5.79	1.183	5.577	0.97
Right Warning	5.324	0.199	5.038	1.166	5.258	3.68

The graph in Figure 38 is a box plot of time to return to steady state for each modality at each location.

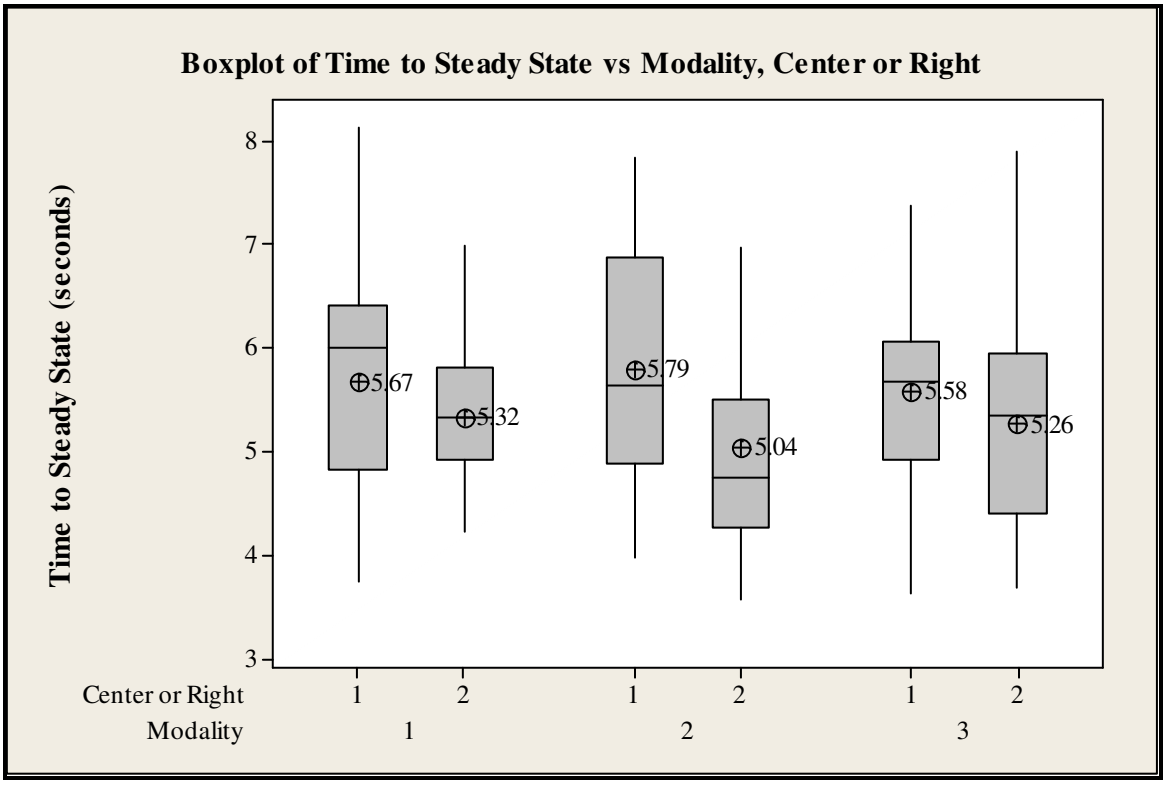


Figure 38. Time to Steady State (sec)

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Significantly more time was needed to return to steady state at the center location than the right $F_{1,69} = 5.57$, p=0.02. This may be due to the number of incorrect maneuvers needed to return to lane. It has been hypothesized that participants may have been more confused to location presence at the center than the right location, leading to more time required to reach steady state. No significant effects were found among modality and time to return to steady state $F2_{,69} = 0.08$, p = 0.919. It should be noted perhaps the cause for slower times for returning the steady state was function of steering response, in that "time to return to steady state" is defined at the point where the steering was less than five degrees of deflection in the positive or negative direction. Statistical results have been provided in Table 17.

Table 17. General Linear Model: Time to Return to Steady State

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	27.714	28.056	2.004	2.17	0.018
Modality	2	0.124	0.155	0.078	0.080	0.919
Center or Right	1	5.052	5.140	5.140	5.570	0.021
Modality*Center or Right	2	1.004	1.004	0.502	0.540	0.583
Error	69	63.675	63.675	0.923		
Total	88	97.570				

Main effects and interaction plots are shown in Figures 39 and 40, respectively. The main effect plot demonstrates the mean time to return to steady state for each

modality. The haptic and combination modality were more similar in time in comparison to the auditory modality.

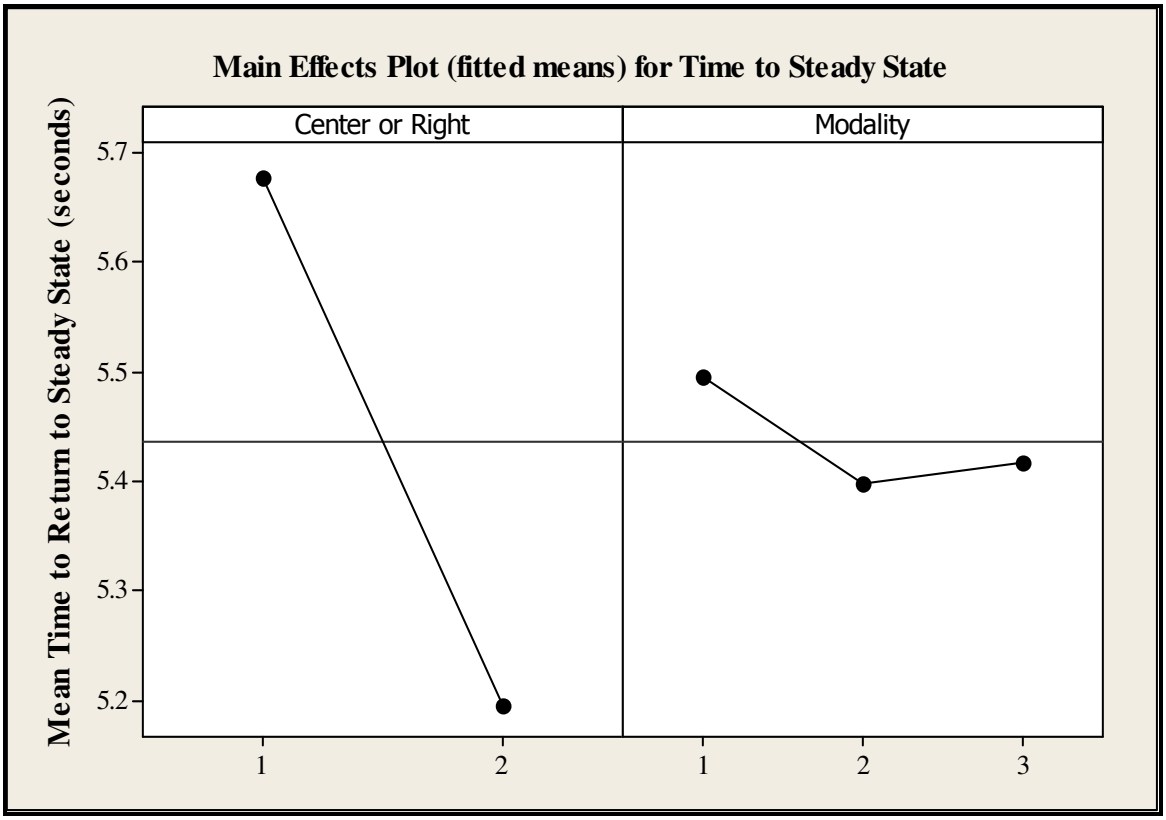


Figure 39. Main Effects Plot of Time to Return to Steady State
Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

In the interaction plot the lines for auditory and combination modality are near parallel, while the line for haptic modality is not parallel with the auditory or combination modality. However, the statistical analysis indicates there are no significant interactions between modality and location of warning (center or right), $p = 0.583$.

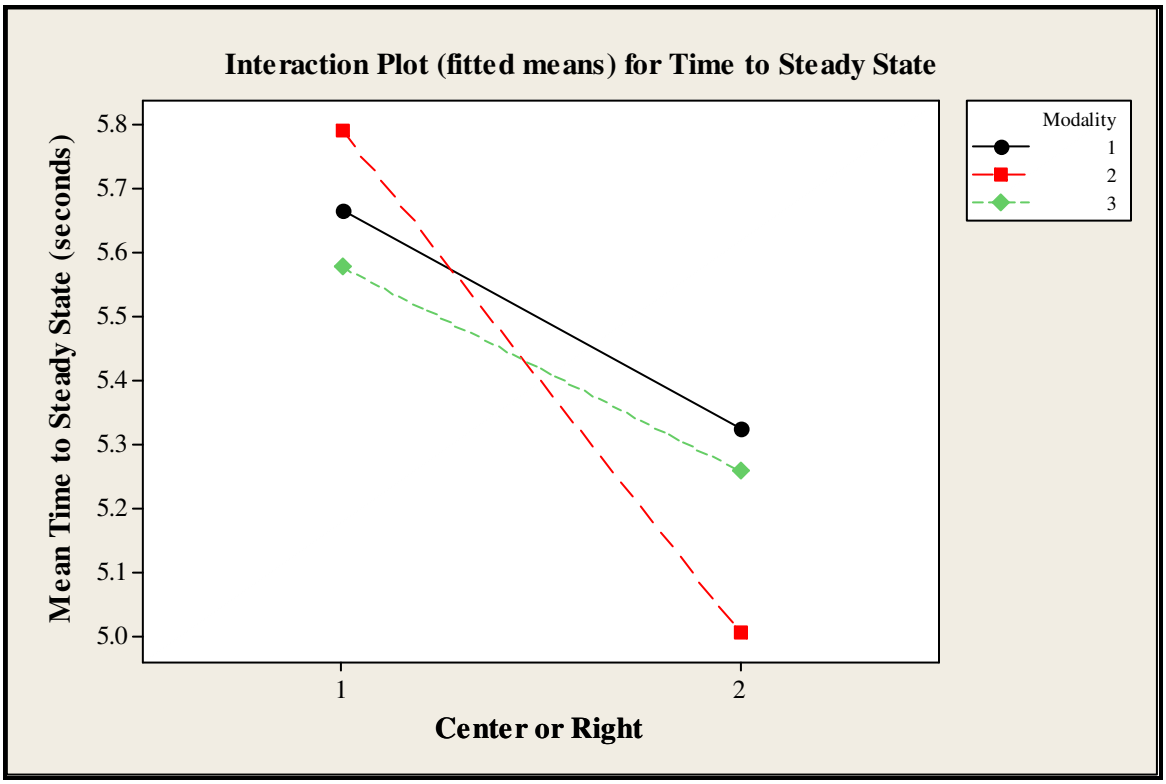


Figure 40. Interaction Plot for Time to Steady State

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Number of Steering Reversals

Table 18 presents descriptive statistics for the number steering reversals per participant under each condition. The greatest mean number of steering reversals occurred at the at the center warning under the combination condition, with 3.53 ± 1.36 steering reversals. The least amount of steering reversals also took place under the combination condition except at the right location, with 2.33 ± 0.62 steering reversals.

Table 18. Descriptive Statistics of Number of Steering Reversals

	Number of Steering Reversals (≥ 5 degree)					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	3.27	1.11	2.80	0.68	3.53	1.36
Right Warning	2.80	1.01	2.670	0.82	2.33	0.62

The bar chart in Figure 41 reveals the total number of steering reversals for all participants by modality at each location. The combination condition had 53 steering reversals the most number of steering reversals, while the haptic condition had the fewest with 40 steering reversals.

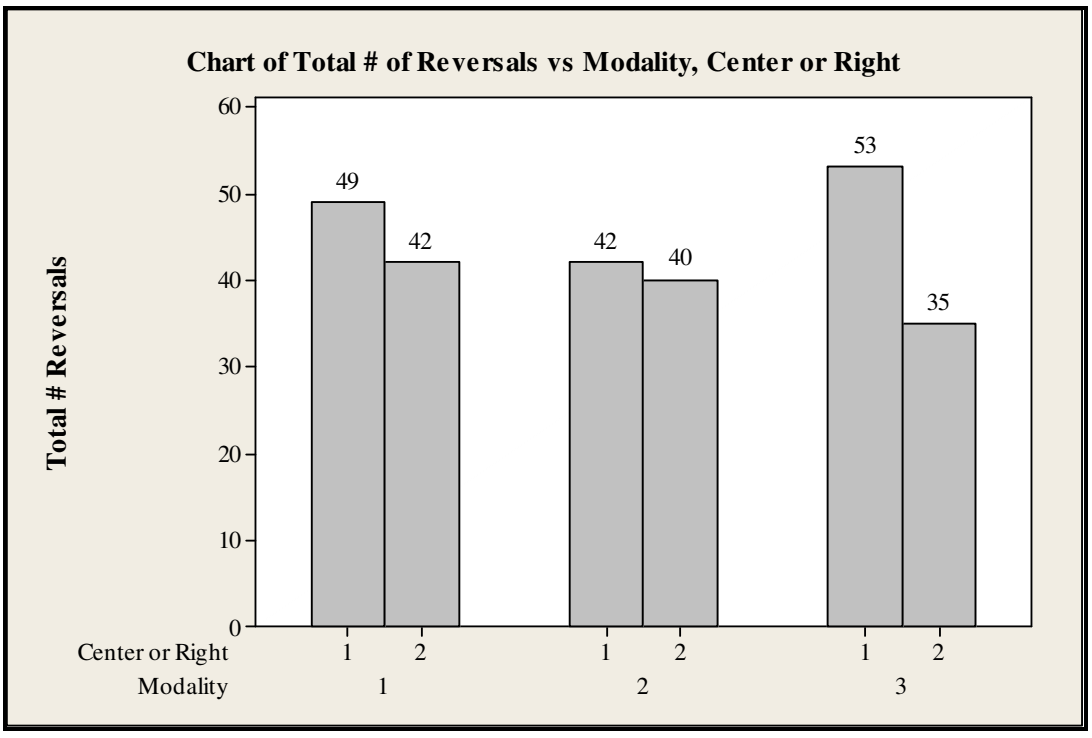


Figure 41. Number of Steering Reversals

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

The non-parametric Chi-Square test found no significant differences among the modalities and the number of steering reversals ($p>0.05$). A further analysis into the number of steering wheel reversals was investigated. This was done by classifying steering reversal behavior, where a severe steering reversals was considered a response to the warning that included more than three reversals in response to the warning. In order to properly return to the lane in a safe manner two steering reversals were required. Therefore studying severe steering reversals may shed light on driver steering responses to the modalities. A bar chart in Figure 42 demonstrates the number of severe steering reversals versus modality and location. The statistical analysis found no significant ($p<0.05$) differences among modalities.

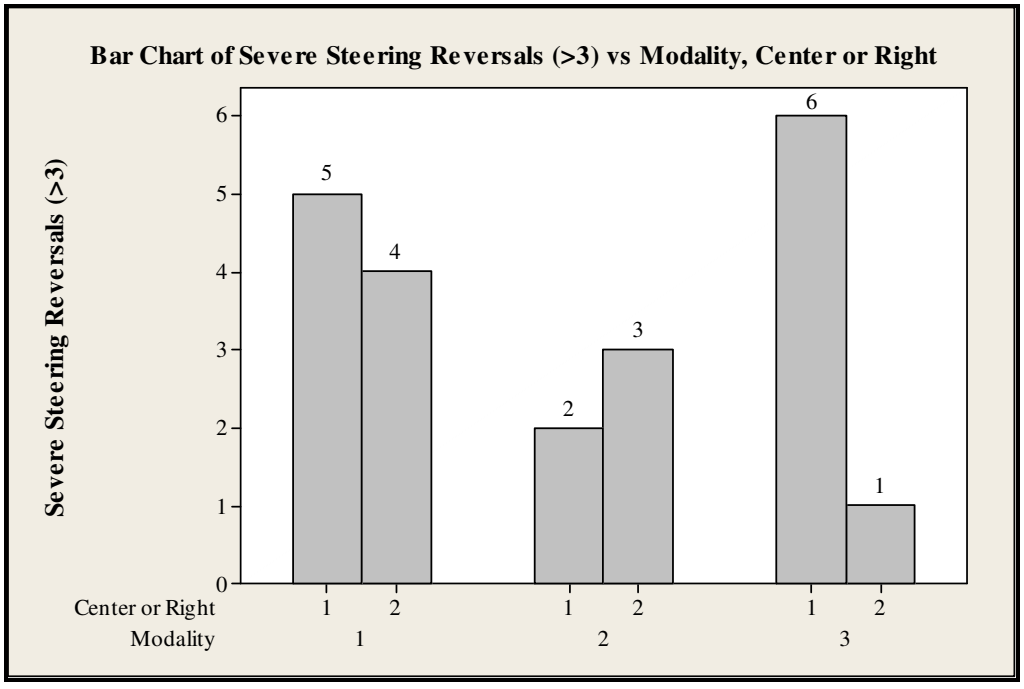


Figure 42. Number of Severe Steering Reversal

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Incorrect Maneuvers

The number of correct and incorrect responses to the warning for each modality at center and right location is shown in Table 19. The most incorrect number of steering maneuvers occurred consistently at the center location

Table 19. Descriptive Statistics of Number of Correct/Incorrect Maneuvers

	Number of Correct/Incorrect Steering Maneuvers	
	Center	Right
	Incorrect	Incorrect
Auditory	11	2
Haptic	11	5
Combination	14	1

The bar chart in Figure 43 displays the number of incorrect steering maneuvers based upon lane position under each modality. This data leads to the percentage of incorrect maneuvers at the center warning location for the auditory, haptic, and combination treatment to include 24.4%, 24.4%, and 31.1% (Mean = 26.6%), respectively. For the percentage of incorrect maneuvers at the right location for the auditory, haptic, and combination condition was 4%, 11%, and 2.2% (Mean = 5.7%), respectively.

This number of incorrect steering maneuvers coincides with research by Noyce and Elango (2004) where they performed a simulation study to study driver behavior at shoulder and centerline rumble strips. Their results determined that approximately between 20 and 23 percent of drivers corrected left (versus right) on the straight roadway segments. In concurrence with Noyce and Elango (2004) experimenter observations

determined that participants were more comfortable when they encountered shoulder warnings than centerline warnings. As it seemed participants were startled or more alarmed when encountering centerline warnings. This data may support the notion that based upon a previous driving experiences drivers will make proportional more incorrect maneuvers on the centerline than the shoulder. The higher percentage shown in this study (~27% versus 20-23%) as compared to Noyce and Elango (2004) may be attributed to the demographic of the participant population. Few of the participants had any experience with centerline rumble strips, only 5% indicated ever experiencing centerline rumble strips in their lifetime. Perhaps this is because the demographic was mostly Montana drivers, where Montana has limited use of centerline rumble strips.

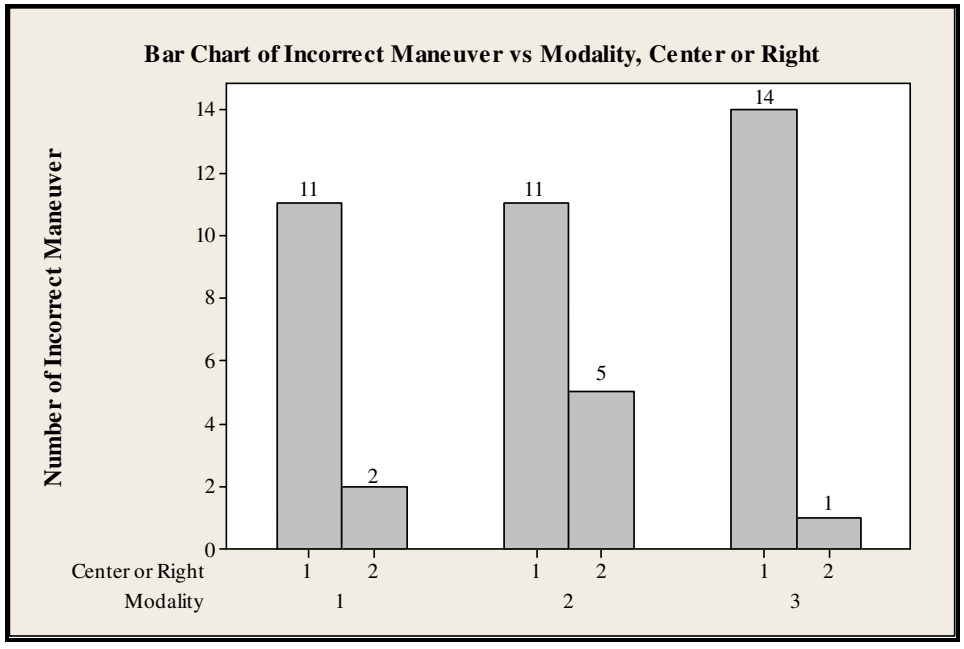


Figure 43. Number of Incorrect Steering Maneuvers

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

The nonparametric chi-square test found no significant differences among modalities ($p>0.05$). However, significantly more participants turned into the oncoming lane into traffic upon receiving the warning of a left departure ($p<0.05$). The bar chart in Figure 44 better demonstrates the magnitude of the number of incorrect maneuvers at the center with a total of 36 incorrect steering maneuvers and only eight at the right location. Clearly more participants responded to the center lane warning by consistently turning left into the oncoming lane.

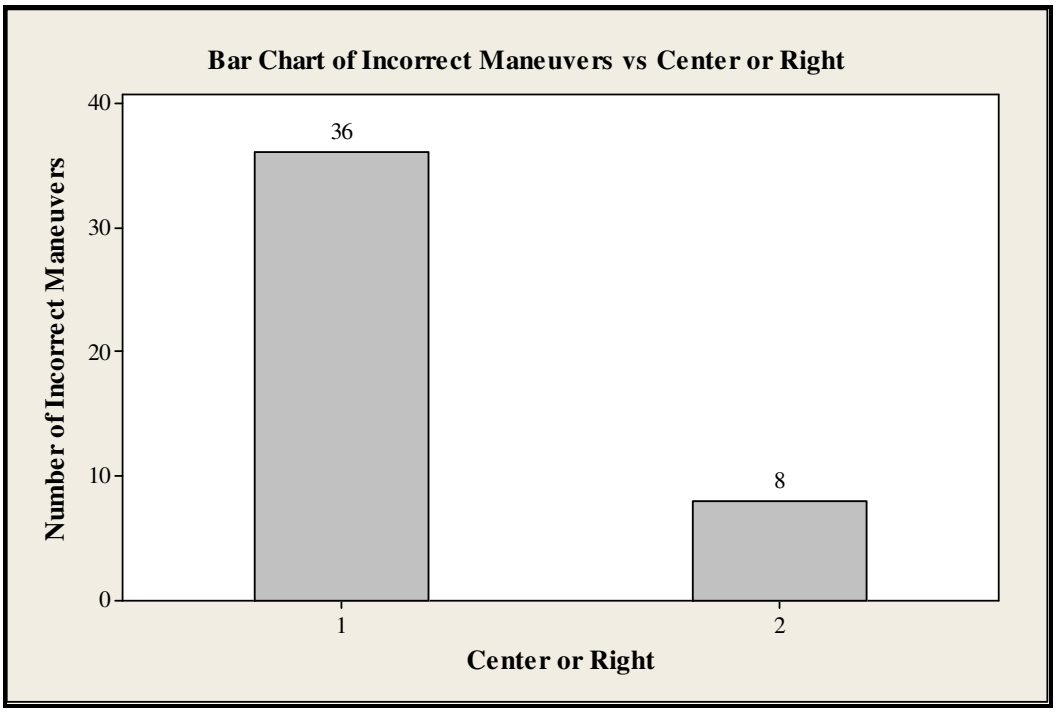


Figure 44. Number of Incorrect Steering Maneuvers

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Steering Response

Maximum Steering Response. Table 20 is the mean values of the maximum steering response. The greatest mean recorded steering response occurred at the auditory condition at the right location, with 27.37 degrees. The least amount of maximum steering response occurred in the combination condition at the center location, at 14.41 degrees. The center location had consistently lower maximum steering responses than the right location.

Table 20. Descriptive Statistics of Maximum Steering Response

	Maximum Steering Response (degrees)					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	18.66	10.60	14.41	11.16	14.25	8.76
Right Warning	27.37	13.05	21.89	12.41	21.96	9.74

A box plot of the maximum recorded steering response is found in Figure 45. Significant main effects were found in location of warning (center or right) and in warning modality. A Tukey's test found that auditory modality had significantly higher recorded maximum steering responses than haptic or the combination warning modality ($p<0.05$).

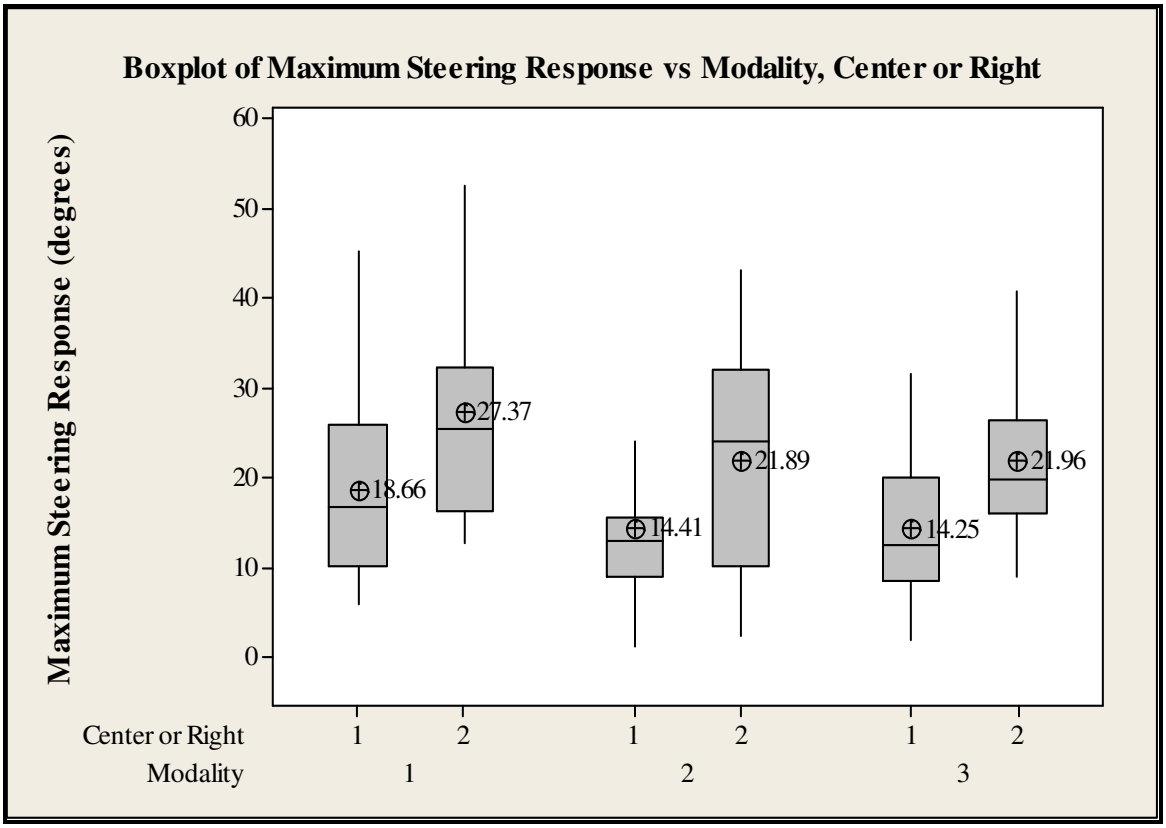


Figure 45. Maximum Steering Response

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Mean Root Mean Square (RMS) of Steering Response. Descriptive statistics for the root mean square values of the steering response are found in Table 21. The greatest steering response behavior occurred in the auditory condition at the center location. The least amount of steering response behavior occurred in the haptic condition at the right location.

Table 21. Descriptive Statistics of Root Mean Square of Steering Response

	Maximum RMS Steering Response (degrees)					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	211.0	199.4	148.3	196.5	120.5	111.8
Right Warning	148.1	134.9	113.7	113.7	130.6	116.6

A box plot of the mean root mean square steering response for each modality at each location is shown in Figure 46.

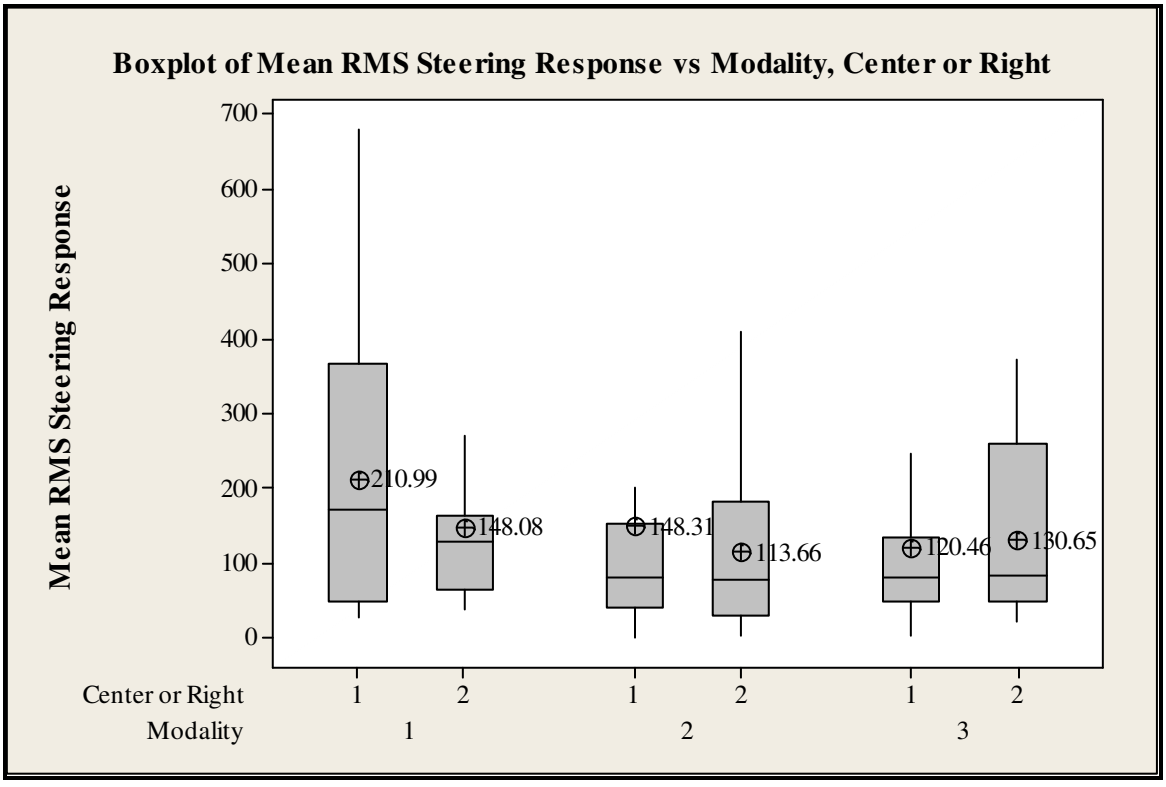


Figure 46. Mean RMS Steering Response

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Table 22 indicates the statistical results from the analysis of variance of RMS steering.

Table 22. General Linear Model: RMS Steering

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	876492	876492	62607	4.29	0.000
Modality	2	53009	53009	26505	1.82	0.170
Center or Right	1	19083	19083	19083	1.31	0.257
Modality*Center or Right	2	20380	20380	10190	0.70	0.501
Error	70	1021616	1021616	14595		
Total	89	1990580				

When outliers were removed (N=83, 7 removed), significant main effects for modality at a p-level of 0.042 were found. The Tukey's test found that the auditory condition had a significantly higher recorded mean root mean square than the haptic condition ($p<.05$). The graph in Figure 47 demonstrates the data when outliers were removed.

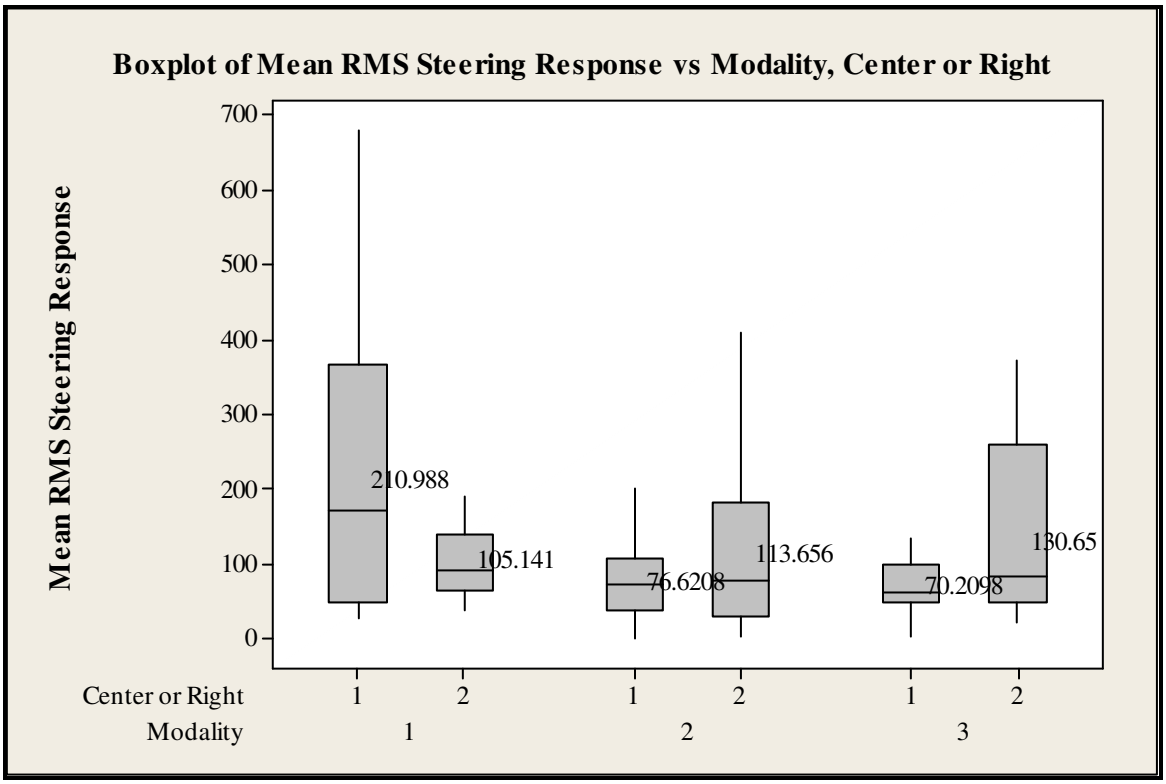


Figure 47. Mean RMS Steering Response Outliers Removed

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Table 23 is the results from the ANOVA when outliers were removed of the RMS steering response.

Table 23. General Linear Model Statistics Outliers Removed RMS Steering

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	353878	315759	22554	2.06	0.027
Modality	2	77173	73113	36556	3.34	0.042
Center or Right	1	1003	573	573	0.05	0.820
Modality*Center or Right	2	67209	67209	67209	3.07	0.053
Error	63	689889	689889	10951		
Total	82	1189151				

Maximum Braking Response

Descriptive statistics for maximum braking response are shown in Table 24. No statistical differences were fond among modality or location of warning. However, the greatest braking response occurred in the auditory condition for both right (Mean = 0.025) and center (Mean = 0.032) warning. The least amount of maximum braking response was found in the haptic condition at the center (Mean = 0.016) and right (Mean = 0.016) warning locations. It has been hypothesized by minimizing severe braking response will allow drivers to maintain better vehicular control (i.e. reducing roll-overs, minimizing erratic lane deviations as a result of severe braking).

Table 24. Descriptive Statistics of Maximum Braking Responses

	Maximum Braking Response					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	0.032	0.059	0.016	0.001	0.029	0.049
Right Warning	0.025	0.039	0.016	0.004	0.023	0.032

Figure 48 is a box plot of the maximum braking response versus modality and location. Outliers are shown in the graph as asterisks to demonstrate only four occurrences of severe braking behavior upon receiving the warning. When outliers were removed no significant differences were found in either factor.

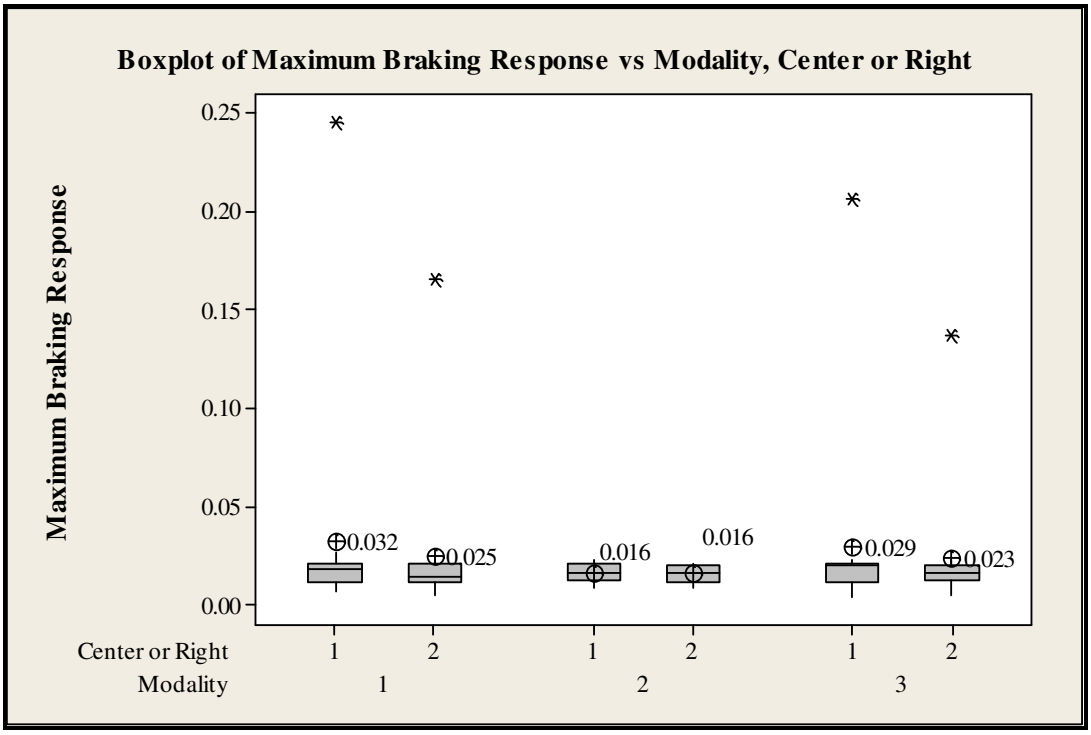


Figure 48. Maximum Braking Response

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Table 25 is the statistical results from the ANOVA of the maximum braking response behavior.

Table 25. General Linear Model: Maximum Braking

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	0.0779038	0.0779038	0.0055646	9.38	0.000
Modality	2	0.0025920	0.0025920	0.0012960	2.18	0.120
Center or Right	1	0.0004096	0.0004096	0.0004096	0.69	0.409
Modality*Center or Right	2	0.0002129	0.0002129	0.0001064	0.18	0.836
Error	70	0.0415442	0.0415442	0.0005935		
Total	89	0.1226625				

Minimum Acceleration Response

Descriptive statistics for minimum acceleration response are shown in Table 26. No statistical differences were fond among modality or location of warning. The least amount of acceleration response occurred in the haptic condition at the center location (Mean = 0.098), the most amount of acceleration response occurred in the auditory condition at the right location (Mean = 0.149). Measuring the minimum acceleration response was to determine if participants completely removed their foot from the accelerator pedal. By controlling speed via deceleration, without severely braking, it is hypothesized will better assist drivers in returning to lane in a safer manner.

Table 26. Descriptive Statistics of Minimum Acceleration Responses

	Minimum Acceleration Response					
	Auditory		Haptic		Combo	
	Mean	StDev	Mean	StDev	Mean	StDev
Center Warning	0.123	0.087	0.098	0.0906	0.080	0.084
Right Warning	0.149	0.060	0.131	0.0846	0.111	0.106

Figure 49 is a box plot of the minimum acceleration response versus modality and location.

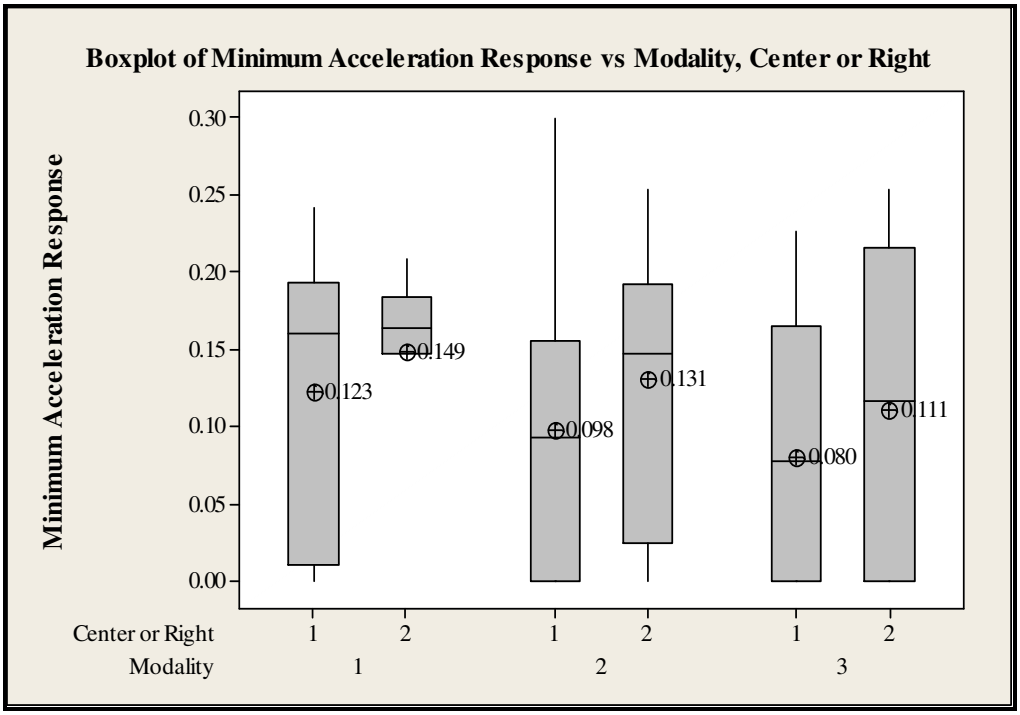


Figure 49. Box plot of Minimum Acceleration Response

Where, Modality 1 = Auditory, 2 = Haptic, 3 = Combination,
Location 1 = Center, 2 = Right

Statistical results for the minimum acceleration data is found in Table 27.

Table 27. General Linear Model Statistics for Minimum Acceleration

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Participant	14	0.26242	0.26242	0.01874	3.6	0
Modality	2	0.02407	0.02407	0.01204	2.3	0.11
Center or Right	1	0.02013	0.02013	0.02013	3.9	0.05
Modality*Center or Right	2	0.00022	0.00022	0.00011	0	0.98
Error	70	0.36293	0.36293	0.00519		
Total	89	0.66978				

Driver Attitude Results

The Friedman nonparametric test was performed on the driver attitude results, significant differences were found among modality condition ($p<0.05$). Participant's ranked combination modality as the most favored warning interface modality for benefit of driving, most likely to purchase, level of trust, level of appropriateness, level of urgency, and overall preference. The haptic interface was ranked first for the least annoying and having the least interference. Table 28 indicates the mean and median of ranked preference for the warning interface modalities based upon the state criterion.

Table 28. Driver Attitude Mean and Median Rankings of the Modalities

		Warning Interface Modality		
Question		Auditory	Haptic	Combination
Benefit to Driving	Mean	2.47	2.33	1.20
	Median	3	2	1
Most Likely to Purchase	Mean	2.47	2.13	1.40
	Median	3	2	1
Level of Trust	Mean	2.67	2.07	1.30
	Median	3	2	1
Level of Annoyance	Mean	2.2	1.87	1.93
	Median	3	1	2
Level of Interference	Mean	2.13	1.67	2.20
	Median	2	1	3
Level of Appropriateness	Mean	2.60	1.93	1.47
	Median	3	2	1
Level of Urgency	Mean	2.47	2.33	1.20
	Median	3	2	1
Overall Preference	Mean	2.33	2.07	1.60
	Median	3	2	1

The percentage of participants ranking the given modality as the most preferred based upon the stated criterion is found in Table 29, where: (1) benefit to driving criterion with 41% ranking the combination modality as the most preferred, 39% preferred the haptic, and 20% preferred the auditory, (2) 41% said they would most likely purchase the combination, 36% chose the haptic, and 23% reported most likely to purchase the auditory modality, (3) 44% preferred the combination modality, haptic 34% and auditory 22%, reported most likely to trust, (4) 36% ranked the haptic modality as the least annoying, 34% for the combination, and 30% thought the auditory was least annoying., (5) 41% percent of participants thought the haptic interfered the least with their ability to drive safely, 31% chose the auditory, and 28% thought the combination had the least amount of interference, it may be hypothesized that drivers felt the combination interfered with their driving the most because it required two sensory modalities, where the driver had to process and conduct sensory discretion between the auditory and haptic warnings, perhaps leading to driver confusion and more interference with their ability to drive safely, (6) 44% of drivers felt the combination modality had the greatest level of appropriateness for warning of a lane departure, haptic and auditory reported 32% and 24%, respectively, (7) 41%t of drivers felt the combination group had the greatest level of urgency (i.e. quickest reaction time), while 39% felt the haptic warned them with greatest level of urgency, and 20% preferred the auditory. The driver performance dependent variable of reaction time was found to be the fastest with the haptic modality, this did not coincide with the perception of many of the participants. Perhaps drivers felt having two sensory modalities would provide a great level of urgency, but the driving performance

data indicates otherwise, (8) 39%of drivers preferred the combination modality as the overall preference, 34% preferred haptic, and 27% preferred the auditory.

Table 29. Percentage of Participants Preferred Modality

Criterion	Auditory	Haptic	Combination
Benefit to Driving	20	39	41
Most Likely to Purchase	23	36	41
Level of Trust	22	34	44
Least Annoyance	30	36	34
Least Interference	31	41	28
Level of Appropriateness	24	32	44
Level of Urgency	20	39	41
Overall Preference	27	34	39

The auditory modality was the consistent under performer under all criterions. Haptic and the combination modality were more similar in driver responses to the criterion. Many of the participants reported having a difficult time distinguishing between the three modalities having reported “they felt the same to me”. This may be due to the cross-modality matching goal of reaching similar perceived levels of intensity, which may have led to a lack of discretion among the modalities.

These findings coincide with Lee and Hoffman (2004) findings were they reported that drivers found using a vibrating seat was perceived as less annoying and more appropriate than auditory.

Note: Results for Phase I IVIBE™ Console, Phase I accelerometer, Phase II driver performance, steering response, acceleration response, steering RMS response, driver attitudes response, and participant history questionnaire may be found in Appendices R through Y, respectively.

CHAPTER 5

DISCUSSION

In this simulator-based study, fifteen participants received alerting cues in three sensory modalities; haptic (seat vibration), auditory ("rumble strip" sound), and combined auditory and haptic sensory warnings. Major findings include that haptic modality produced significantly faster reaction times than both the auditory and combination modalities. The faster reactions times allowed for 0.86 seconds in additional time to correct and return to the lane. This time reduction equated to a 69 foot reduction when traveling at a speed of 55mph and 94 foot reduction at a speed of 75 mph. This additional time may provide drivers the additional leeway time needed for returning to lane in a safer manner, i.e. reducing a roadway departure, than that of the auditory and combination modalities. Furthermore, the auditory modality produced significantly greater maximum steering response than the haptic and combination condition. Erratic steering responses often may lead to the driver losing control of their vehicle, causing run-off-road accidents and vehicle roll-overs. Drivers rated the haptic modality to be the least annoying with least interference, while the combination modality was the most preferred in benefit of driving, most likely to purchase, level of trust, level of appropriateness, level of urgency, and overall preference.

A summary table of each dependent variable with the corresponding statistical method used, significance among modality, point of statistical significance, and whether the null hypothesis was accepted is found in Table 30.

Table 30. Statistical Analysis Summary

Dependent Variable	Statistical Method	Modality Significance	Where Significant	Null Hypothesis Accepted
Reaction Time	GLM/Tukey's	Yes	Haptic significantly reduced reaction time over auditory & combined modalities	No
Time to Return to Lane	GLM/Tukey's	No, with outliers removed Yes	Auditory required significantly more time than haptic condition	No
Time to Steady State	GLM/Tukey's	No	-	Yes
Number of Steering Reversals	Chi-Square	No	-	Yes
Number of Incorrect steering Maneuvers	Chi-Square	No	-	Yes
RMS Steering Response	GLM/Tukey's	No, with outliers removed Yes	Auditory significantly higher RMS steering response than haptic condition	No
Braking Response	GLM/Tukey's	No	-	Yes
Acceleration Response	GLM/Tukey's	No	-	Yes
Driver Preferences	Friedman's	Yes	-	No

Many of the findings of this research coincide with past research, for example Lee and Hoffman (2004) found in reference to longitudinal haptic warnings that when using a vibrating seat drivers perceived the warning as less annoying and more appropriate than auditory warnings. Also, studies have shown that haptic feedback may improve reaction time (Janssen & Nilsson, 1993) as was found in this study. However, this research also

contrasted past research, where Lee and Hoffman (2004) reported that drivers performed similarly when presented with longitudinal haptic warnings (whole seat vibration) and auditory warnings. Perhaps this is due to the arena of presentation, this study focused on lateral warnings versus longitudinal warnings. These inconsistencies of findings among the arena of presentation need further research. It appears that drivers may require a different set of inputs based upon the objective of the warning. In that drivers responded more quickly to haptic warnings in the lateral warning setting, whereas there was no difference in the haptic and auditory modality in longitudinal warnings (i.e. rear end collisions with following a vehicle). It is unclear at this point why drivers respond differently under different warning strategies.

None of the warning modalities were superior in presenting location cues. Many participants turned in the wrong direction and into oncoming traffic. Therefore, further research is needed in the area of warning strategies that will reduce inappropriate steering response patterns to minimize incorrect steering responses and reduce number of steering reversals. The findings that many participants turned in the incorrect during the centerline may be due to the driver's ad hoc expectancies with shoulder rumble strips. Shoulder rumble strips were installed on the New Jersey Garden State Parkway in 1955 and today many more states have implemented shoulder rumble strips than centerline rumble strips, hence drivers are more than likely more familiar with shoulder rumble strips. As a result, it is hypothesized that drivers first instinct when hearing and/or feeling a rumble strip is to correct the trajectory of the vehicle by turning left to return to the roadway. As the results from this study indicate none of the modalities were superior

in assisting drivers of where they were relative to the roadway. Further research may include a better understanding of effective location cues to assist drivers. Maybe a different sound is generated on the right, in this case maybe a rumble strip sound due to ad hoc expectation and distinctly different sound for the centerline warning. Possibly having more directional auditory cues when the driver is at the right location a sound from the right (at ear level) is generated, when on the left a sound from the left location is emitted. Further studies may include testing algorithms that warn the driver sooner at the centerline than the shoulder. This would be similar to having static rumble strips placed on both sides of the centerline, rather than on the centerline, which would lead to an earlier lane departure warning. The question remains as how to properly present warning cues to drivers of their location in the roadway.

Another explanation that may have exacerbated the number of incorrect maneuvers that was witnessed predominately at the centerline, but also on the shoulder might have been due to the laboratory conditions. The scenarios lacked ambient traffic, specifically on-coming traffic during the warnings. Also, the experimental nature of this research where participants cannot be immersed 100%, lacking consequences of an incorrect maneuver. Additionally, the scenarios were straight roads with larger than normal shoulders for rural roads. Regardless, it should be noted an interesting phenomenon is occurring with regards to driver behavior at center versus shoulder locations, whether it is confusion or poor instinctive (possibly due to ad hoc expectations) behaviors at differing locations.

The premise of this study was to better understand the basic human factors principles as they relate to interface design for advance avoidance collision systems during roadway departures. Vehicles of the future may include an unpredictable combination of in-vehicle crash avoidance systems in the form of vehicle displays, controls, and informational devices. Lane-departure warning systems are not the only device being considered in reducing crashes. Other examples include: headway warning devices, blind spot warning devices, backup warning devices, driver alertness monitors, intersection collision warnings, impending rollover warnings, low road friction warnings, approaching emergency vehicles, lane closures, weather warnings, and rail-highway grade crossings. Most of these devices have been studied in an isolated fashion, rather than from a systems perspective. Future in-vehicle devices will need to be developed in harmony with other in-vehicle devices to ensure that ultimate goal of reducing accidents is actually reached. For example, will longitudinal warnings require a different set of parameters than that of lateral warnings? The potential for proliferation of warning devices may ultimately lead to an increase in driver workload and confusion leading to increased reaction time and inaccurate driver responses.

Furthermore, it should be noted that many of these devices may be add-ons rather than OEM's which may lead to even greater inconsistencies. Additionally, not all car manufacturers, at this time, plan to have similar safety devices on all models of their vehicles. Human factors designers will need to integrate a systems perspective in evaluating and designing safety devices for the automobile. These systems will need to work in an optimal complimentary fashion in order to be effective in the driving

environment; otherwise, unwanted driver workload may increase resulting in safety problems of their own. Ultimately, these systems must lead the driver to quick and accurate responses to imminent dangers, minimize distraction from the primary task of driving, and be acceptable and usable to the whole driving population. In this study, the finding that the haptic modality shows promise in effectively warning drivers perhaps leads to the integration of devices that use the haptic sensory modality that has yet to be used by automobile manufacturers.

The goal of this study was to better understand the driver behavior in response to modalities as a means to warn of imminent dangers. A major objective of human factors engineering is to apply knowledge about human abilities and limitations to the design of equipment, tasks, and jobs. According to the Intelligent Transportation Institute U.S. Department of Transportation Intelligent Vehicle Initiative the primary goals of human factors research in intelligent vehicle initiative is to:

To assess and enhance compatibility between operating features of advanced driver assistance systems and the capabilities of the driving population.

1. *To minimize the degradation of driving performance that could be caused by driver distraction from using advanced in-vehicle information systems* (http://www.its.dot.gov/ivi/ivihf/index.html, Accessed March 5, 2006).

Three major steps in researching in-vehicle information systems as stated by the Intelligent Vehicle Initiative include:

1.) Identify the safety issue

2.) Identify safe and effective designs.

3.) Evaluate system acceptance, effectiveness, and safe use

4.) Deployment technology to decrease crashes.

This study adds to the body of knowledge in the steps 2 and 4, in better identifying safe and effective designs and evaluates system acceptance, effectiveness, and safe usage. This study helps researchers to better understand driver behavior and performance to various warning cues as a crash avoidance countermeasure.

Many products in use today are designed for the "average" user or for a range of the population. Product design for the driving population does not have the convenience of designing for the "average" or for a range of users, these systems are designed with the goal of saving lives of all. Saving lives of all means all users, young, old, hearing disorders, etc. Hence, these systems will be integrated into vehicles that will be used by a population with much variation. Unlike pilots, air traffic controllers, medical technicians, etc. where users are highly trained, relatively homogenous, the driving population receives minimal training and only requires a drivers license in order to operate. Training will be nonexistent, in that drivers will purchase these systems and drive off the car lot without any formal training. With this in mind these systems must be designed with human responses that are in the form of natural mapping requiring natural thought and instincts. Additionally, much of the driving population may have some type or a combination of physical, sensory, or cognitive deficiencies. In order to be usable for the 100^{th} percentile driver, designing for extremes or designing for adjustable guidelines will need to be performed. Further questions remained unanswered with regards to designing

in-vehicle collision avoidance systems; what is the proper intensity to warn the driver using one or a combination of modality? Will the system be adjustable? How will the driver know what level of intensity is effective?

Phase I study indicated the need for adjustability of the warning interface, as gender and age may play a key role in adjustability needs of the user. Phase I study determined statistically significant differences in the order of trials during the cross-modality matching, where participants consistently reported a higher measurement during descending trials and a lower measurement during ascending trials. This may be a limitation of the study, perhaps future research may include having random treatments of varying intensities of the haptic signal. Where the experimenter would present a haptic intensity and the participant would record if the intensity is perceived to be higher or lower than the auditory signal. At that point the experimenter would begin to ascend or descend until the participant perceives equal intensities of both modalities. Another potential limitation of the study was the variation in vibration energy among the four quadrants. The effects of lack in uniformity of vibration energy within the seat are unknown. The Phase I study attempted to answer some of these questions, however many questions remain unanswered.

It is unknown if the design of the vibration seat attributed to the quicker reaction time in the haptic condition. Past studies have used vibration seats, where attenuators are placed under the seat causing the whole seat to vibrate during warning activation. The IVIBE® seat in this study was a more acute sensation of vibration than the whole seat vibrating, which may have a less intense feeling as the IVIBE® seat. The vibration

energy used in past research remains unknown as no quantitative data has been reported. Additional research is needed to better understand on-road effects of seat vibration. It is possible that the seat vibration (either non-acute or acute) on the road may be difficult for drivers to discriminate the warning of the seat vibration warning versus natural road vibrations. Ideally it can be hypothesized that the driver would need a more acute more sensitized sensation of the vibration in order to effectively warn the driver. Moreover, having differing placement of the vibration may be beneficial in assisting drivers in location cues to assist in making the correct maneuver, i.e. if a driver experiences a right departure then a vibration sensation to the right leg may assist the driver to turn away from the vibration and vice versa. Here again natural mapping is necessary for site specific warning thresholds. It is unknown if placing vibration warning cues at specific locations within the seat would produce the natural mapping needed to effectively warn the driver to make the remedial action.

As with all systems where human interaction exists, the user must understand the system and ultimately trust the system to behave the manner it was intended. In this study participants perceived the haptic modality to be the least annoying with least interference, while the combination modality was the most preferred in benefit of driving, most likely to purchase, level of trust, level of appropriateness, level of urgency, and overall preference. It may be hypothesized that drivers felt the combination interfered with their driving the most because it required two sensory modalities. In that the driver had to process and conduct sensory discretion between the auditory and haptic warnings, possibly leading to driver confusion (i.e. longer reaction times) and more interference

with their ability to drive safely. Drivers may have had an inherent preference that perceptually seemed to be the better modality, but their preferences for the most part did not coincide with their driving performance. Each user has their own measure of interference, annoyance and tolerance for the modalities. The design of the warning algorithm and interface will be critical in the driver acceptance of the system. A system that has too many false alarms and/or one with an interface that perceptually is not tolerable will be an unsuccessful system.

An additional concern will be the incorporation of the collision avoidance system within the social context of driving. A driver may prefer a system that does not alert them in addition to the passenger, in this case a haptic sensation to the driver would be the preferred modality. Auditory or combination warning modalities, auditory and haptic, means that the warning is heard by all passengers. If warnings are issued the driver may feel influenced by the social context in that they may feel a sense of embarrassment, or feelings of incompetence, or a need to feel superior to those in the vehicle. On the positive side, this may make drivers more aware of their driving behaviors and habits; leading to a transformation of the driver's poor driver behaviors into safer driver ones. A haptic warning may be more beneficial in terms of social context since only the driver experiences the sensation.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to (1) determine appropriate and comparable intensities for the auditory ("rumble strip" sound) and haptic signal (seat vibration), (2) compare driver responses to variations in haptic, auditory, and combined modalities of auditory and haptic, and (3) determine driver attitudes in response to the presented modalities as a collision avoidance warning technique during roadway departures. This study concluded that the haptic seat vibration modality demonstrated significantly faster reaction times in comparison to the auditory and combination modality. The haptic condition recorded significantly faster return to lane times in comparison to the auditory condition; this is likely in response to the faster reaction times. The auditory modality revealed significantly higher recorded maximum steering responses than haptic and the combination conditions. The auditory condition had significantly higher recorded root-mean-square steering response than the haptic condition. Participants perceived the haptic modality to be the least annoying with least interference, while the combination modality was the most preferred in benefit of driving, most likely to purchase, level of trust, level of appropriateness, level of urgency, and overall preference. Drivers may have had an inherent preference to the combination modality because it perceptually seemed to be the better modality, but their preferences did not coincide with their driving performance.

Driver drowsiness and driver inattention account for 20.1% and 12.7%, respectively, of all roadway departures. Haptic (seat vibration) warnings demonstrate

promise as an alerting strategy over auditory and combination modalities in reducing these types of roadway departures. With a decrease in reaction time and less erratic steering responses, haptic warnings have the potential to better assist drivers in returning to the lane more quickly and safely. More erratic steering maneuvers could lead to a higher probability of losing vehicular control. The combination modality did not demonstrate the same positive effect as the haptic alone. This may be due to a startling effect or confusion of the participant. Having two modalities may overwhelm the driver resulting in higher workloads or higher need for sensory discretion.

None of the warning modalities were superior in presenting location cues. Many participants turned in the wrong direction and into oncoming traffic. Therefore, further research is needed in the area of warning strategies that will reduce inappropriate steering response patterns to minimize incorrect steering responses and reducing number of steering reversals. Based upon the findings of this study, a summary of future research questions and recommendations are provided below:

(1) Some studies have shown longitudinal haptic feedback may improve reaction time (Janssen & Nilsson, 1993) as was found with lateral warnings such as the present study. However, this past research has also found that drivers performed similarly when presented with longitudinal haptic warnings and auditory warnings. These inconsistencies of findings among the arena of presentation need further research. It appears that drivers may require a different set of inputs based upon the objective of the warning. It is unclear at this point why drivers respond differently under different warning strategies.

(2) None of the warning modalities were superior in presenting location cues. Therefore, further research is needed in the area of warning strategies that will reduce inappropriate steering response patterns to minimize incorrect steering responses and reducing number of steering reversals. Further research may include a better understanding of effective location cues to assist drivers i.e. perhaps a different sound generated on the right ("rumble strip" sound) due to ad hoc expectations and distinctly different sound for the centerline warning ("beeping"). Or possibly having more directional auditory cues when the driver is at the right location a sound from the right (at ear level) is generated, when on the left a sound from the left location is emitted. Moreover, having differing placement of the vibration may be beneficial in assisting drivers in location cues to assist in making the correct maneuver, i.e. if a driver experiences a right departure then a vibration sensation to the right leg may assist the driver to turn away from the vibration and vice versa. It is unknown if placing vibration warning cues at specific locations within the seat would produce the natural mapping needed to effectively warn the driver to make the corrective action.

(3) Further studies may include testing algorithms that warn the driver sooner at the centerline than the shoulder, i.e. more dynamic predictive algorithms. This would be similar to having static rumble strips placed on both sides of the centerline, rather than on the centerline, which would lead to an earlier lane departure warning.

(4) Many in-vehicle devices have been studied in an isolated fashion, rather than from an all inclusive ("systems") perspective. Future in-vehicle devices will need to be developed in harmony with other in-vehicle devices to ensure that ultimate goal of

reducing accidents is actually reached. The question remains as to whether longitudinal warnings require a different set of parameters than that of lateral warnings. The potential for proliferation of warning devices may ultimately lead to an increase in driver workload and confusion leading to increased reaction time and inaccurate driver responses.

(5) Further questions remained unanswered with regards to designing in-vehicle collision avoidance systems; what is the proper intensity to warn the driver using one or a combination of modality? Will the system be adjustable? How will the driver know what level of intensity is effective? What age and or gender effects exist in determining the proper level of intensity to effectively warn a driver?

(6) Phase I study determined statistically significant differences in the order of trials during the cross-modality matching, where participants consistently reported a higher measurement during descending trials and a lower measurement during ascending trials. This may be a limitation, perhaps future research may include having random treatments of varying intensities of the haptic signal. Where the experimenter would present a random haptic intensity, the participant would determine if the intensity is perceived to be higher or lower than the auditory signal. At that point the experimenter would begin to ascend or descend until the participant perceives equal intensities of both modalities.

(7) A potential limitation of the Phase I study was the variation in vibration energy among the four quadrants, with one quadrant having significantly less vibration energy than the other three quadrants. The effects of lack in uniformity of vibration

energy within the seat is unknown, perhaps future studies may study these effects on drivers.

(8) It is unknown if the particular design of the vibration seat attributed to the quicker reaction time in the haptic condition. Past studies have used vibration seats, where attenuators are placed under the seat causing the whole seat to vibrate during warning activation. The IVIBE® seat in this study was a more acute sensation of vibration than the whole seat vibrating, which may have a more intense feeling than those with attenuators vibration the seat which may lead to a "dulling" sensation. The vibration energy used in past research remains unknown as no quantitative data has been reported.

(9) Additional research is needed to better understand on-road effects of seat vibration. It is possible that the seat vibration (either non-acute or acute) on the road may be difficult for drivers to detect the warning of the seat vibration versus natural road vibrations. Ideally it can be hypothesized that the driver would need a more acute, more sensitized sensation of the vibration in order to effectively warn the driver, however this remains unknown.

(10) It may be hypothesized that drivers felt the combination interfered with their driving the most because it required two sensory modalities, though this is unknown. Additionally, drivers may have had an inherent preference that perceptually seemed to be the better modality, but their preferences for the most part did not coincide with their driving performance. It is unknown if the combination modality created increased driver

workload that may have lead to less advantageous reaction times than that of the haptic modality.

(11) Outside of the realm of driver interface, the actual design of the warning algorithm will be critical in the driver acceptance of the system. A system that has too many false alarms and/or one with an interface that perceptually is not tolerable will be an unsuccessful system. These algorithms will need to follow signal detection theory principles of minimizing false alarms while maximizing "true-positive" feedback.

(12) When warnings are issued drivers may feel influenced by their social context, this possible influence has not been studied to date. However, this may make drivers more aware of their driving behaviors and habits leading safer driving behaviors. A haptic warning may be more beneficial in terms of social context because only the driver would experience the stimuli, this would need further research to confirm.

It must be noted that the conclusions from this study are based on driving in a simulated environment in which participants may behave in a different manner than in the field. Therefore, simulated studies should naturally be field tested where appropriate (i.e. maintaining safety). Long term, on-road testing is ultimately needed to gain the appropriate level of driver acceptance and effectiveness of these systems.

This study has shown that several basic human factors principles and guidelines

should be considered when developing advanced collision warning systems. These include:

1.) The need for cross-modality matching.

2.) Designing from a systems perspective.

3.) Design according to the signal detection theory.

4.) Minimize driver workload.

5.) Consideration of social context.

6.) Acute or non-acute sensitization requirements.

7.) Objective of warning and corresponding human needs based upon those objectives.

8.) Effective assistance of location cues.

LITERATURE CITED

Alm, H., & Nilsson, L. (1995). The effects of a mobile telephone task on driver behavior in a car following situation. *Accident Analysis and Prevention*, *Vol 27 No. 5* pp 707-715.

Ashley, S. (2001). Driving the info highway Scientific American, 2001. Lee, J.D., McGehee, D.V., Brown, T.L. and Reyes, M.L. Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors, 44 (2)* pp. 314-334.

Ben-Yaacov, A., Maltz, M., & Shinar, D. (2002). Effects of an invehicle collision avoidance warning system on short and longterm driving performance. *Human Factors, 44,* pp. 335–342.

Benson, A. J. (1978). Motion sickness. In G. Dhenin & J. Ernsting (Eds.), *Aviation Medicine,* pp. 468-493. London: Tri-Med Books.

Bliss, J. and Acton, S.A (2003). Alarm mistrust in automobiles: how collision alarm reliability affects driving. *Applied Ergonomics, 34*. pp. 499-509.

Burns, P. C., Knabe, E., & Tevell, M. (2000). Driver behavioral adaptation to collision warning and avoidance information [Abstract]. In *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society* (Vol. 3, p. 315). Santa Monica, CA: Human Factors and Ergonomics Society.

Chaudoin, J. H. and G. Nelson (1985). *Interstate Routes 15 and 40 Shoulder Rumble Strips*. Report No. 08-85-1, California Department of Transportation, Sacramento, Ca.

ComCare Alliance (2001). 911 – America's Universal Emergency Phone Number, *Comcare Alliance, 888 17th St.NW. 12th Floor, Washington DC.*

Diederich (1995). A. Intersensory facilitation of reaction-time: Evaluation of counter and diffusion coactivation models. *Journal of Mathematical Psychology, 39 (2).* pp. 197-215.

Dingus, T. A., Hulse, M. C., Mollenhauer, M. A., Fleischman, R. N., Mcgehee, D. V. and Manakkal, N. (1997). Effects of age, system experience, and navigation technique on driving with an Advanced Traveler Information Systems, *Human Factors, 39*, pp. 177 - 199.

Dingus, T. A., McGehee, D. V., Manakkal, N., Jahns, S. K., Carney, C., & Hankey, J. M. (1997). Human factors field evaluation of automotive headway maintenance/collision warning devices. *Human Factors, 39*, pp. 216–229.

Fatality Accident Reporting System (FARS). http://www-fars.nhtsa.dot.gov/

Federal Highway Administration (FHWA) – Wyoming Divisions Office, *Shoulder Rumble Strips - Effectiveness and Current Practice.* http://safety.fhwa.dot.gov/fourthlevel/rumble/state_wyom.htm.

Federal Highway Administration (FHWA), *Safety - Run-off-the-Road Rumble Strips.* http://safety.fhwa.dot.gov/programs/ rumble.htm. Accessed November 15, 2000.

Fernandez, J.E. and Marley, R.J. (1998). *Applied Occupational Ergonomics: A Textbook*. Kendall/Hunt Publishing.

Garder, P., and J. Alexander. *Fatigue Related Accidents and Continuous Shoulder Rumble Strips.* http://www.umeciv.maine.edu/ce/research/rumbles.htm.

Glaijan, R., Gilkey, J., and Turner, R. (1994). Carrier phase GPS for AHS control SRI, Menlo Park, CA, SRI Rep. 5074-94-FR-253.

Gielen, S.C.A.M. and Schnidt, R.A (2004). On the nature of intersensory facilitation of reaction time. *Perception and Psychophysics, 34*. pp. 161-168.

Griffith, M. S. (1999). Safety Evaluation of Rolled-In Continuous Shoulder Rumble Strips Installed on Freeways. In *Transportation Research Record 1665,* TRB, National Research Council, Washington, D.C., pp. 28–34.

Harwood, D.W. (1993). *NCHRP Synthesis 191: Use of Rumble Strips to Enhance Safety*. TRB, National Research Council, Washington, D.C., 1993.

Janssen, W. and Nilsson, L. (1993). Behavioral effects of driver support. in Parkes, A.M. and Franzen, S. eds. *Driving Future Vehicles*, Taylor & Francis, Washington, D.C., pp. 147-155.

Kennedy, R. S., & Frank, L. H. (1985). *A review of motion sickness with special reference to simulator sickness* (Tech. Rep. NAVTRAEQUIPCEN 81-C-0105-16). Orlando, FL: Naval Training Equipment Center.

Kiefer, R., LeBlanc, D., Palmer, M., Salinger, J., Deering, R. and Shulman, M. (1992). Development and validation of functional definitions and evaluation procedures for collision warning/avoidance systems, *Crash Avoidance Metrics Partnership*, Washington DC, 72

Kiefer, R. J. (2000). Developing a forward collision warning system timing and interface approach by placing drivers in realistic rear-end crash situations. In *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society Vol. 3*, pp. 308–311). Santa Monica, CA: Human Factors and Ergonomics Society.

Labiale, G. (1990). In-car road information: comparisons of auditory and visual presentations, in *Proceedings of the Human Factors Society 34th Annual Meeting* (Santa Monica:Human Factors Society), pp. 623-627.

Lansdown, T. C. (1997). Visual allocation and the availability of driver information, in T. Gothengater and E. Carbonell (eds), *TraYc & Transport Psychology: Theory and Application* (Amsterdam: Pergamon), pp. 215-223.

Lee, J. D., McGehee, D. V., & Brown, T. L. (2000). Prior exposure, warning algorithm parameters, and driver response to imminent rear-end collisions on a high fidelity simulator. In *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society Vol. 3*, pp. 316–319). Santa Monica, CA:

Lee, J.D., McGehee, D.V., Brown, T.L. and Reyes, M.L. (2002). Driver Distraction, Warning Algorithm Parameters, and Driver Response to Imminent Rear-end Collisions in a High-Fidelity Driving Simulator, National Highway Traffic Safety Administration, Washington, DC.

Lee, H. C., Cameron, D., Lee, A. H. (2003). *Assessing the Driving Performance of Older Adult Drivers: On-road versus Simulated Driving*. *Accident Analysis and Prevention. Volume 5, Number 5*, pp. 797-803.

Lee, J.D., Hoffman, J.D. (2004). Collision Warning Design to Mitigate Driver Distraction. CHI, Vienna, Austria. http://www.engineering.uiowa.edu/~csl/publications/ pdf/leehoffmanhayes04.pdf Accessed December 7, 2004.

Lee, H. C., Cameron, D., Lee, A. H. (2003). Assessing the Driving Performance of Older Adult Drivers: On-road versus Simulated Driving. *Accident Analysis and Prevention. Volume 5, Number 5.* pp. 797-803.

Lee, J.D., Caven, B., Haake, S. and Brown, T.L. (2001) Speech-based interaction with in-vehicle computers: The effect of speechbased e-mail on drivers' attention to the road. *Human Factors, 43 (4).* pp. 631-640.

Lee, J.D. and See, K.A (2004). Trust in technology: Designing for appropriate reliance. *Human Factors*.

Ligon, C. M., E. C. Carter, D. B. Joost, and W. F. Wolman (1985). Effects of Shoulder Textured Treatments on Safety. Report No. FHWA-RD-85-027, Federal Highway Administration, Washington, D.C.

Liu, Y.C., (2001). Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveler information systems. *Ergonomics, 2001, Vol. 44, No. 4,* pp. 425-442.

Fernandez, J. and Marley, R. (1998). *Applied Occupational Ergonomics*: Kendall/Hunt Publishing Company.

McGehee, D.V., Lee, J., Matthew, R., Dawson, J., Bateman, K. Quantitative analysis of steering adaptation on a high performance driving simulator. November 4, 2003. http://www.engineering.uiowa.edu/~csl/publications/ppt/mcgeheeleerizzodawsonbatemanp.ppt#1. Accessed December, 2005.

McGehee, D. V., Mazzae, E. N., & Baldwin, G. H. S. (2000). Driver reaction time in crash avoidance research: Validation of a driving simulator study on a test track. In *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society Vol. 3,* pp. 320–323. Santa Monica, CA: Human Factors and Ergonomics Society.

Naatanen, R., & Summala, H. (1976). Road-user behavior and traffic accidents. Amsterdam: North-Holland.

National Highway Traffic Safety Administration (NHTSA) (2003). Crash Information Web Site. Traffic Safety Facts. Early Edition. http://www-nrd.nhtsa.dot.gov/pdf/nrd30/NCSA/TSFAnn/TSF2002EE.pdf. Accessed December 7, 2004.

Nickerson, R.S (1973). Intersensory facilitation of reaction time: Energy summation or preparation enhancement. *Psychological Review, 80*. pp. 489-509.

Noyce, D.A. and Elango, V.V. (2004). Safety Evaluation of Centerline Rumble Strips: a Crash and Driver Behavior Analysis. *Transportation Research Board 2004 Annual Meeting Proceedings*.

Outcalt, W. (2001). *Centerline Rumble Strips. Report No.* CDOT-DTD-R-2001-8, Colorado Department of Transportation, Denver, Co.

Parasuraman, R., Hancock, P. A., & Olofinboba, O. (1997). Alarm effectiveness in driver-centred collision-warning systems. *Ergonomics, 40,* pp. 390–399.

Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, and abuse. *Human Factors, 39*, pp. 230–253.

Pilutti, T. and Ulsoy, G. (2003). Fuzzy-Logic-Based Virtual Rumble Strip for Road Departure Warning Systems. *IEEE Transactions on Intelligent Transportation Systems, Vol. 4, No. 1*.

Reason, J. T., & Brand, J. J. (1975). *Motion sickness*. London: Academic.

Schladover, S. (2005). Preparing the Way for Vehicle-Infrastructure Integration (Retrieved on August 2005, http://www.path.berkeley.edu/PATH/Research/current/safety/5213.html)

Shaldover, S., Desoer, C., Hedrick, K.J., Tomizuka, M. Walrand, J., Zhang, W.B., Mcmahon, D.H., Peng, H., Sheikholeslam, S., Mckeown, N. (1991). Automated Vehicle Control Developments in the PATH Program, *IEEE Trans. Veh. Technol., Vol. 40,* pp. 114-120.

Sklar, A.E. and Sarter, N.B. (1999). Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event-driven domains. *Human Factors, 41 (4).* pp. 543-552.

Stanley, L.M., Kelly, M.J., Lassacher, S.(2005). Driver Performance While Interacting with the 511 Travel Information System in Urban and Rural Traffic. *Third International Driving Symposium on Human Factors in Driver Assessment Training and Vehicle Design*, Rockport, MA.

Stevens , S.S. (1960). *Psychophysics: Introduction to its perceptual, neural, and social prospects.* New York: John Wiley & Sons.

Walker, J., Alicandri, Sedney, C. and Roberts, K. (1991). In-vehicle navigation devices: Effects on the safety of driver performance, in *Vehicle Navigation and Information Systems Conference Proceedings* (Warrendale: Society of Automotive Engineers), pp. 499

Wheatley, D.J. & Hurwitz, J.B. (2001). The use of a multi-modal interface to integrate in-vehicle information presentation. In: *Proceedings of Driving Assessment Conference*, Aspen, Colorado. University of Iowa, Iowa City.

Wickens, C. D., Sandry, D. and Vidulich, M. (1983).Compatibility and resource competition between modalities of input, central processing, and output, *Human Factors, 25*, pp. 227-248.

Peters, G.A. and Peters, B.J. (2001). The distracted driver. *Journal of the Royal Society For the Promotion of Health, 121 (1).* pp. 23-28.

Peterson, A. (1995). *Run-Off Road Collision Avoidance Using IVHS Countermeasures: Task 3 Report - Volume II,* U.S. Department of Transportation, Washington, D.C.

Outcalt, W. (2001). *Centerline Rumble Strips.* Report No. CDOT-DTD-R-2001-8 Interim Report, Colorado Department of Transportation, Denver, CO.

Tijerina, L., Jackson, J.L, Pomerleau, D.A., Romano, R.A., Perterson, A. (1995, 1999). *Run-Off-Raod Collision Avoidance Countermeasures Using IVHS Countermeasures Task 3-Volume 2-3.* National Highway Traffic Safety Administration. U.S. Department of Transportation Final Report DOT HS 808 502.

Turochy, R.E. (2004). Shoulder Rumble Strips: Evolution, Current Practice, and Research Needs. *Transportation Research Board Annual Meeting Proceedings*

APPENDICES

APPENDIX A

PARTICIPANT CONSENT FORM PHASE I

PARTICIPANT CONSENT FORM
FOR PARTICIPATION IN HUMAN PARTICIPANT RESEARCH AT
MONTANA STATE UNIVERSITY

HAPTIC VIBRATION WARNING VERSUS AUDITORY WARNING

You are being invited to take part in a study of driver behavior during roadway departures. The study is being conducted by the Western Transportation Institute at Montana State University and is sponsored by the U.S. Department of Transportation.

The purpose of the study is to explore what haptic (seat vibration) warning intensity that is in equal magnitude to an auditory warning used in warning drivers of roadway departures.

Procedures: If you agree to take part in the study, you will take part in one experimental session. This session will last approximately one hour.

At the start of the session, to ensure you meet criteria to participate a short hearing test will be administered. You will then be seated on a haptic vibration seat, where you will be given an auditory signal and will be asked to respond to the experimenter on how the seat vibration feels in response to the auditory signal. The experimenter will prompt you through two trials of haptic vibration and auditory warnings.

Risks: No known risks.

Benefits: There may be no immediate benefits to you. Future benefits of the research may include better guidelines for advanced collision avoidance systems for use during roadway departures.

Participation is voluntary. You do not have to take part in this research and you may withdraw your consent and leave the study at any time without penalty.

Confidentiality: Your confidentiality will be fully protected. You will be assigned a code number and all measures will be recorded under that number. All records by which a given participant can be related to the code number will be kept in a locked file and will be destroyed at the conclusion of their participation. Your driving performance scores will only be reported as group averages.

Questions:

Questions or complaints about the research should be directed to Dr. Michael Kelly, Western Transportation Institute, Montana State University – Bozeman, MT 59717-4250. Phone: 406-994-7377.

You have certain rights as a participant in this research. Questions about these rights should be directed to Dr. Mark Quinn, Chair of the Human Participants Committee, Montana State University – Bozeman, MT. Phone: 406-994-5721.

Please feel free to ask the researchers any questions that you may have before signing this consent form.

AUTHORIZATION: I have read the above consent form and it has been explained to me. A copy of this consent form has been given to me. All of my questions have been answered to my satisfaction. I agree to participate in this study. I understand that I am free to withdraw at any time without penalty.

Name (Print): _____ Date:_____

Signature: _____

Investigator: _____

APPENDIX B

MONTANA STATE UNIVERSITY HUMAN PARTICIPANTS COMMITTEE APPLICATION FORM

Montana State University Human Participants Committee Application Form
MONTANA STATE UNIVERSITY

Institutional Review Board Application for Review
(revised 3/28/03)

THIS AREA IS FOR INSTITUTIONAL REVIEW BOARD USE ONLY. DO NOT WRITE IN THIS AREA.

Approval Date:
Application Number:

SUBMIT 14 COPIES OF THIS APPLICATION (INCLUDING THE SIGNATURE COPY), ALONG WITH 14 COPIES OF THE PARTICIPANT CONSENT FORM AND 14 COPIES OF ALL OTHER RELEVANT MATERIALS, TO INSTITUTIONAL REVIEW BOARD, 308 LEON JOHNSON HALL, MONTANA STATE UNIVERSITY, BOZEMAN, MT 59717. (PLEASE STAPLE, BIND OR CLIP TOGETHER THE APPLICATION FORM, SURVEYS, ETC. AS 14 INDIVIDUAL PACKETS; ONE COMPLETE PACKET FOR EACH BOARD MEMBER.) SUBMIT ONE COPY OF GRANT CONTRACT PROPOSAL FOR THE OFFICE FILE. FOR INFORMATION AND ASSISTANCE, CALL 994-4411 OR CONTACT THE INSTITUTIONAL REVIEW BOARD CHAIR, MARK QUINN, 994-5721 or STEPHEN GUGGENHEIM, ADMINISTRATOR, 994-4411.

PLEASE TYPE YOUR RESPONSES IN BOLD

Date: 10/05/05

I. Investigators and Associates (list all investigators involved; application will be filed under name of first person listed)
NAME: Michael J. Kelly
TITLE: Research Director

DEPT: Western Transportation Institute
ADDRESS: Box 174250
PHONE #: 7377
DATE TRAINING COMPLETED: 6/12/02

NAME: Laura M. Stanley
TITLE: Research Fellow
DEPT: Western Transportation Institute
ADDRESS: Box 174250
PHONE #: 6994
DATE TRAINING COMPLETED: 3/22/04

II. Title of Proposal: Haptic and Auditory Interfaces As A Collision Avoidance Technique During Run-Off Road and Head-On Collisions and Driver Perception of Modalities Project

III. Beginning Date for Use of Human Participants: 11/01/05

IV. Type of Grant and/or Project (if applicable)

Research Grant: W0767
Contract:
Training Grant:
Classroom Experiments/Projects:
Thesis Project:
Other (Specify):

V. Name of Funding Agency to which Proposal is Being Submitted (if applicable): United States Federal Highway Administration

VI. Signatures

Submitted by Investigator
Typed Name: Michael J. Kelly
Signature:
Date: 10/05/05

Faculty sponsor (for student)
Typed Name:
Signature:
Date:

THIS AREA IS FOR INSTITUTIONAL REVIEW BOARD USE ONLY. DO NOT WRITE IN THIS AREA.

Approved:
Disapproved:
HSC Chairman's Signature and Date:
Participant to the following conditions:

VII. Summary of Activity. Provide answers to each section and add space as needed. Do not refer to an accompanying grant or contract proposal.

A. RATIONALE AND PURPOSE OF RESEARCH (What question is being asked?)

The objectives of the driver simulator study are as follows: 1) to quantify driver responses to haptic, auditory and combined auditory and haptic modality warnings of roadway departures; 2) to quantify whether driver preference exists among the haptic, auditory, and combined warnings as a collision avoidance technique.

B. RESEARCH PROCEDURES INVOLVED. Provide a short description of sequence and methods of procedures that will be performed with human participants. Include details of painful or uncomfortable procedures, frequency of procedures, time involved, names of psychological tests, questionnaires, restrictions on usual life patterns, and follow up procedures.
WTI is using the Driving Simulation Laboratory to test driver simulator participants in three simulated scenarios having varying modalities of warning presentation:

1) Straight road ~ 10 minutes in length, receive haptic warning.
2) Straight road ~ 10 minutes in length, receive auditory warning.
3) Straight road ~ 10 minutes in length, receive combined haptic and auditory warning.

14 participants will drive the three simulated scenarios. Each scenario will be presented on separate days. Participants will have the study explained to them and complete the consent process. They will then complete a brief screening questionaire to determine

their susceptibility to simulator discomfort. Participants will then be trained on driving the simulator by driving a series of "gentle" scenarios with limited maneuvering and traffic.

After initial training, participants will drive a ~ 10 minute simulation. All groups will cover the same stretch of road and containing the same events. The simulation is straight two-lane rural highway with no ambient traffic. After three minutes of driving, participants will be presented with a distracter task where they will look over their shoulder and read an index card of letters, at this time the experimenter will issue a gradual wind gust (East to West, or West to East), to take them out of the lane. Once out of lane, participants will be issued a warning, in the form of haptic seat vibration, auditory, or haptic/auditory combined. At this time a record of driver response will be gathered. Eight minutes into the drive the participant will do the same distracter task and a wind gust will be generated from the opposite direction to gradually take them out of the lane, warning signal will be issued at this time. Driver response to the wind gust will be recorded.

Differences in driving behaviors when presented with the varying warning modalities are measured in each of the three treatments. The observed speeds, lane position, steering angles, braking, acceleration, of all drivers in all scenarios, allow us to determine if one modality produces a more advantageous response than another. After the participants have completed their driving test, we ask them to fill out a driver preference survey to gather additional information regarding their preferences in warning modalities. One survey question, for example, asks test participants which modality they would most likely purchase.

C. DECEPTION - If any deception (withholding of complete information) is required for the validity of this activity, explain why this is necessary and attach debriefing statement. No deception will be employed.

D. PARTICIPANTS

1. Approximate number and ages
   How Many Participants: 14
   Age Range of Participants: 18-65
   How Many Normal/Control:
   Age Range of Normal/Control:

2. Criteria for selection: Licensed drivers, normal hearing, normal vision, not susceptible to motion discomfort

3. Criteria for exclusion: Participants with a significant history of motion sickness, migraine headaches, or physical conditions that create limitations on their driving will be excluded. Pregnant females will be excluded.

4. Source of Participants (including patients): Announcements, advertising, word-of-mouth.

5. Who will approach participants and how? Explain steps taken to avoid coercion. They will respond to announcements and advertising.

6. Will participants receive payments, service without charge, or extra course credit? (Yes or No. If yes, what amount and how? Are there other ways to receive similar benefits?) Participants will receive payment of $10 per hour.

7. Location(s) where procedures will be carried out. Research will be conducted in the WTI Driving Simulator Laboratory in the Molecular Bioscience Building on the MSU campus (or wherever WTI relocates during summer '05).

E. RISKS AND BENEFITS (ADVERSE EFFECTS)

1. Describe nature and amount of risk and/or adverse effects (including side effects), substantial stress, discomfort, or invasion of privacy involved.
The study requires participants to drive a high-fidelity driving simulator through a realistic driving scenario on computer-generated rural highways. Studies have found that approximately 8% of participants will experience some symptoms of motion sickness (sweating, dizziness, abdominal discomfort) during simulator testing. A smaller number may experience headaches. In our recently completed study involving 36 participants, two participants reported abdominal discomfort and one reported a headache; all participants were able to complete the study.

2. Will this study preclude standard procedures (e.g., medical or psychological care, school attendance, etc.)? If yes, explain. NO

3. Describe the expected benefits for individual participants and/or society. Roadway departure fatalities, which includes run-off-road and head-on collisions accounted for 55 percent of all roadway fatalities in the United States in 2003. The primary goal of this research is to better understand basic human factors principles to haptic and auditory interfaces as a collision avoidance technique during run-off-road and head-on collisions and driver perception of these modalities.

F. ADVERSE EFFECTS

1. How will possible adverse effects be handled? The only anticipated adverse effect is simulator discomfort consisting of dizziness, sweating, or abdominal discomfort lasting no more than 15 minutes.

The prevalence of these symptoms will be minimized by (a) prescreening participants using a standardized history questionnaire, (b) pretraining participants using low speed driving scenarios, (c) using relatively short testing periods, (d) maintaining a cool room temperature, and (e) maintaining a low level of background illumination so that participants don't become completely immersed in the virtual world.

A standard published protocol will be used for managing simulator discomfort during training and testing. It is reproduced below:

Watching for Simulator Discomfort

The investigator is to watch for any symptoms of simulator discomfort during the training phase and during the experimental phases. These include: uneasiness, flushed skin, pallor, increased temperature, dizziness, abdominal pains, sweating, mild nausea, participant commenting on any of these symptoms, etc.

Protocol for Participants with Simulator Discomfort

Protocol: Simulator Sickness

- Mild Simulator Sickness (uneasiness, flush, pallor, increased temperature)
    - Determine whether participant can continue experiment.
    - If no, end scenario
    - Turn on room lights

- Escort participant to the chair in the Driving Simulation Laboratory.
- Offer the participant a beverage or saltines.
- Allow participant to sit and return to normal
- Indicate to participant that these feelings will pass soon.
- When participant indicates that they have returned to normal, administer the simulator discomfort scale. Release the participant when all measures are below "slight" on the scale.

- Medium Simulator Sickness (uneasiness, flush, pallor, increased temperature, dizziness, mild nausea)
  - Determine whether participant can continue experiment.
  - If no, end scenario
  - Turn on room lights
  - Escort participant to the chair in the Driving Simulation Laboratory.
  - Offer the participant a beverage or saltines.
  - Allow participant to sit and return to normal
  - Indicate to participant that these feelings will pass soon.
  - When participant indicates that they have returned to normal, administer the simulator discomfort scale. Release the participant when all measures are below "slight" on the scale.

2. Are facilities/equipment adequate to handle possible adverse effects?
(Yes or No. If no, explain.) Yes

3. Describe arrangements for financial responsibility for any possible adverse effects.
N/A

MSU compensation (explain):
Sponsoring agency insurance:
Participant is responsible:
Other (explain):

G. CONFIDENTIALITY OF RESEARCH DATA

1. Will data be coded? (Yes or No) Yes

2. Will master code be kept separate from data? (Yes or No) Yes

3. Will any other agency have access to identifiable data? (Yes or No. If yes, explain.) No

4. How will documents, data be stored and protected?

Locked file: Participant name/address/email/SSN and identity code will be stored in locked file. Identity code will be removed from participant identity record and destroyed at the completion of participation.

Computer with restricted password: Data will be stored on a password protected computer under identity codes.

Other (explain):

VIII. Checklist to be Completed by Investigator(s)

A. Will any group, agency, or organization be involved? (Yes or No. If yes, please confirm that appropriate permissions have been obtained.) No

B. Will materials with potential radiation risk be used (e.g. x-rays, radioisotopes)? (Yes or No) No

1. Status of annual review by MSU Radiation Sources Committee (RSC).

(Pending or Approved. If approved, attach one copy of approval notice.)

2. Title of application submitted to MSU RSC (if different).

C. Will human blood be utilized in your proposal? (Yes or No. If yes, please answer the following:)

1. Will blood be drawn? (Yes or No. If yes, who will draw the blood and how is the individual qualified to draw blood? What procedure will be utilized?) No

2. Will the blood be tested for HIV? (Yes or No)

3. What disposition will be made of unused blood?

4. Has the Biosafety Committee been contacted? (Yes or No)

D. Will non-investigational drugs or other substances be used for purposes of the research? (Yes or No.) No

Name:
Dose:
Source:
How Administered:
Side effects:

E. Will any investigational new drug or other investigational substance be used? (Yes or No.) No If yes, provide information requested below and one copy of:

1) available toxicity data; 2) reports of animal studies; 3) description of studies done in humans; 4) concise review of the literature prepared by the investigator(s); and 5) the drug protocol.)

Name:
Dose:
Source:
How Administered:
IND Number:
Phase of Testing:

F. Will an investigational device be used? (Yes or No. If yes, provide name, source description of purpose, how used, and status with the U.S. Food and Drug Administration FDA). Include a statement as to whether or not device poses a significant risk. Attach any relevant material.) No

G. Will academic records be used? (Yes or No.) No

H. Will this research involve the use of:
Medical, psychiatric and/or psychological records (Yes or No) No

Health insurance records (Yes or No) No
Any other records containing information regarding personal health and illness (Yes or No)No

If you answered "Yes" to any of the items under "H.", you must complete the HIPAA worksheet.

I. Will audio-visual or tape recordings or photographs be made? (Yes or No.) No

J. Will written consent form(s) be used? (Yes or No. If no, explain.) Yes

APPENDIX C

PARTICIPANT COMPENSATION FORM



REQUEST FOR RESEARCH PARTICIPANT COMPENSATION

Project # 4W0767
Investigator

Investigator Signature: _____

Sum paid: _____

Payment to:

PLEASE PRINT LEGIBLY

Name _____

Signature _____

Social Security Number _____

Mailing Address:

_____

_____

_____

Phone # _____

Email _____

PARTICIPANT #:____

APPENDIX D

PHASE I ORDER OF PRESENTATION

ORDER OF PRESENTATION

Participant Number	Order
1	Initially A-Ascending
2	Initially A-Ascending
3	Initially A-Ascending
4	Initially A-Ascending
5	Initially A-Ascending
6	Initially A-Ascending
7	Initially A-Ascending
8	Initially A-Ascending
9	Initially D-Descending
10	Initially D-Descending
11	Initially D-Descending
12	Initially D-Descending
13	Initially D-Descending
14	Initially D-Descending
15	Initially D-Descending

APPENDIX E

FLYER FOR RECRUITMENT OF PARTICIPANTS

Driver's Needed - Get Paid $$ to Drive

Driving Simulation Study Conducted by Western Transportation Institute at MSU

Requirements:

***Must be between 18-65 years of age**
***Must have valid driver's license**
***Commitment of 2 hours**
***Must not be susceptible to motion sickness**

Western Transportation Institute
Montana State University-Bozeman



Contact Information

Contact WTI Office
994-6114
wtioffice@coe.montana.edu

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994-6114
wtioffice@coe.montana.edu

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994-6114
wtioffice@coe.montana.edu

APPENDIX F

PARTICIPANT CONSENT FORM PHASE II

PARTICIPANT CONSENT FORM
FOR PARTICIPATION IN HUMAN PARTICIPANT RESEARCH AT
MONTANA STATE UNIVERSITY

DRIVER BEHAVIOR TO ROADWAY DEPARTURE WARNINGS

You are being invited to take part in a study of driver behavior during roadway departures. The study is being conducted by the Western Transportation Institute at Montana State University and is sponsored by the U.S. Department of Transportation.

The purpose of the study is to explore how drivers respond to roadway departures upon receiving a warning signal of the departure.

Procedures: If you agree to take part in the study, you will take part in a three experimental sessions. The first session will last approximately one hour; the second and third session will last approximately one hour.

At the start of the session, you will complete a questionnaire to determine whether you are eligible to participate. To ensure you meet criteria to participate a short vision and hearing test will be administered. You will then practice driving a high-fidelity driving simulator on rural roads by driving two short trips. After a rest period, you will participate in a 10-minute drive where you will be given two tasks to perform and will continue driving as you normally would. After the first session you will return for two more sessions at the same time of day (on different days) where you will drive two more 10-minute scenarios given similar tasks as before. You will finish the session by completing a questionnaire about your experience.

Risks: The research requires you to drive a high fidelity driving simulator through a series of realistic driving scenarios on computer-generated urban and rural roads. Studies have found that approximately one person in twelve will experience some form of motion discomfort (sweating, dizziness, abdominal discomfort) during simulator testing. A much smaller number may experience headaches. These effects are temporary and may last for up to 15 minutes.

We will use standard published procedures for minimizing your exposure to motion discomfort, identifying early stages of motion discomfort, and responding to it. These include a standardized procedure for conducting the research, for determining whether you can continue, and for terminating the simulation if you cannot continue. All research will employ these standardized and recognized procedures and staff members involved in participant testing are trained on their use.

Benefits: There may be no immediate benefits to you. Future benefits of the research may include better guidelines for advanced collision avoidance systems for use during roadway departures.

Participation is voluntary. You do not have to take part in this research and you may withdraw your consent and leave the study at any time without penalty.

Confidentiality: Your confidentiality will be fully protected. You will be assigned a code number and all measures will be recorded under that number. All records by which a given participant can be related to the code number will be kept in a locked file and will be destroyed at the conclusion of their participation. Your driving performance scores will only be reported as group averages.

Questions:

Questions or complaints about the research should be directed to Dr. Michael Kelly, Western Transportation Institute, Montana State University – Bozeman, MT 59717-4250. Phone: 406-994-7377.

You have certain rights as a participant in this research. Questions about these rights should be directed to Dr. Mark Quinn, Chair of the Human Participants Committee, Montana State University – Bozeman, MT. Phone: 406-994-5721.

Please feel free to ask the researchers any questions that you may have before signing this consent form.

_____

AUTHORIZATION: I have read the above consent form and it has been explained to me. A copy of this consent form has been given to me. All of my questions have been answered to my satisfaction. I agree to participate in this study. I understand that I am free to withdraw at any time without penalty.

Name (Print): _____ Date:_____

Signature: _____

Investigator: _____

APPENDIX G

SIMULATOR SICKNESS PRE-SCREENING QUESTIONNAIRE

This study will require you to drive in a simulator. In the past, some participants have felt uneasy after participating in studies using the simulator. To help identify people who might be prone to this feeling, we would like to ask the following questions.

- Do you or have you had a history of migraine headaches? □ yes □ no
  If yes, please describe: _____
- Do you or have you had a history of claustrophobia? □ yes □ no
  If yes, please describe: _____
- Do you or have you had a history of frequent or severe motion sickness? □ yes □ no
  If yes, please describe: _____
- Do you or have you had a history of any health problems (e.g., seizures, diabetes, heart problems, vertigo) that affect your ability to drive? □ yes □ no
  If yes, please describe: _____
- If you are a female, are you or is there a possibility that you might be pregnant? □ yes □ no

If a participant answered Yes to any of these questions, indicate to them they may be at a higher risk for problems resulting from simulator exposure (may trigger migraines for migraine sufferers, the confined space may be a challenge for claustrophobics, and motion sickness may be exacerbated.) If a participant answered Yes to two or more questions, they will not be eligible to participate. Ask participant to initial and date this form. Attach to signed consent form.

The investigator has explained to me that I may be at a higher risk for problems related to simulator exposure.

| --- | --- | --- |
| Participant Initials | Date | Investigator Initials |

Please tell us how you feel right now. Are you experiencing any of the following?

Eye Strain:		❑ none	❑ slight	❑ moderate	❑ severe
Temperature increase:		❑ none	❑ slight	❑ moderate	❑ severe
Dizziness:	❑ none	❑ unsteady	❑ slight	❑ moderate	❑ severe
Headache:	❑ none	❑ lightheaded	❑ slight	❑ moderate	❑ severe
Nausea:	❑ none	❑ uneasy	❑ slight	❑ moderate	❑ severe

If a participant answers Slight or higher to two or more questions, they should not participate today.

APPENDIX H

POST-EXPERIMENT SIMULATOR INDUCED DISCOMFORT QUESTIONNAIRE

There is a small risk associated with driving in the driving environment simulator. The driver may experience feelings of dizziness and increased body temperature, which are symptoms of a temporary condition called 'Simulator Induced Discomfort' (SID).

To verify the extent of SID occurrence, we are tracking the severity of any discomfort felt by those who drive in the driving environment simulator.

Sex:
❑ male
❑ female

Age: _____

Are you wearing prescription glasses or contact lenses?
❑ no
❑ glasses
❑ contact lenses

What is your exposure to the driving environment simulator?
❑ first time
❑ second time
❑ more than two times

During this most recent experience in the driving environment simulator did you experience any feelings of discomfort?

Eye Strain:		❑ none	❑ slight	❑ moderate	❑ severe
Temperature increase:		❑ none	❑ slight	❑ moderate	❑ severe
Dizziness:	❑ none	❑ unsteady	❑ slight	❑ moderate	❑ severe
Headache:	❑ none	❑ lightheaded	❑ slight	❑ moderate	❑ severe
Nausea:	❑ none	❑ uneasy	❑ slight	❑ moderate	❑ severe

APPENDIX I

PARTICIPANT HISTORY QUESTIONNAIRE

1. AGE: _____
2. GENDER:_____
3. HOW MANY MILES DO YOU DRIVE ANNUALLY?:_____
4. NUMBER OF YEARS OF DRIVING EXPERIENCE?:_____
5. HOW MANY TRIPS PER YEAR DO YOU DRIVE MORE THAN 500 MILES AT A TIME?:_____
6. HOW MANY ACCIDENTS HAVE YOU BEEN INVOLVED IN WHILE YOU WERE THE DRIVER?:_____
7. WHAT IS YOUR OCCUPATION?:_____
8. HAVE YOU EVER HAD YOUR LICENSE REVOKED?:_____
9. HAVE YOU EVER TAKEN A DRIVER EDUCATION PROGRAM?:_____
10. ARE YOU ON ANY MEDICATIONS?:_____
    a. If yes, what are they?_____
11. DO YOU HAVE ANY MEDICAL CONDITIONS?:_____

APPENDIX J

INDEX LETTERS FOR DISTRACTOR TASK

L H D R I F V

#1

M H M T W X

#2

J O P Q R G A

#3

Q U M S Z P C

#4

U I X D G V B

#5

I U T Y V E Q

#6

E I Y T N K M

#7

Z V H J K L I

#8

A S C V J P O

#9

APPENDIX K

HYPERDRIVE® SCRIPTING FOR ENABLING WIND GUST AND AUDITORY WARNING SIGNAL

Rumble Strip Sound Generation

```
set rumble false

TimerProcCreate tpDonerumble {

set rumble false
}
VTriggerCreate vtRumbleStrip {

if { ($::LanePos > 1.1744 || $::LanePos < -1.022) &&

$rumble == "false" } {

set rumble true

TimerProcAdd tpDonerumble 2

AudioPlaySample rumble 0 Immediate
}

VTriggerAdd vtRumbleStrip 60 Hz
```

Wind Gust Generation

```
TimerProcCreate tpCheckForAButton {

 VTriggerAdd vtCheckForAButton 10 Hz
}

VTriggerCreate vtCheckForAButton {

 if { [string index $DigitalInputs2 15] == 1} {

 DynamicsSetExternalForce 1 1000 0 0 0 0 0

 VTriggerRemove vtCheckForAButton
```

```
 TimerProcAdd tpCheckForAButton 1
 }


VTriggerAdd vtCheckForAButton 10 Hz

TimerProcCreate tpCheckForAButton2 {
 VTriggerAdd vtCheckForAButton2 10 Hz
}

VTriggerCreate vtCheckForAButton2 {

 if { [string index $DigitalInputs2 14] == 1} {

 DynamicsSetExternalForce 1 -1000 0 0 0 0 0

 VTriggerRemove vtCheckForAButton2

 TimerProcAdd tpCheckForAButton2 1
}
VTriggerAdd vtCheckForAButton2 10 Hz
```

Data Collection Generation

```
SimCollectData On 60 NONE

SimSelectDataCollectionElements ALL
```

APPENDIX L

DRIVER PERCEPTION QUESTIONNAIRE

Rank your experience to the presented warnings:

1. Vibration Only
2. Auditory Only
3. Combination of Auditory and Vibration

	RANKING
1. Benefit to Driving	
2. Most Likely Purchase	
3. Level of Trust	
4. Level of Annoyance	
5. Level of Interference	
6. Level of Appropriateness	
7. Level of Urgency	
8. Overall Preference	

APPENDIX M

SAS STATISTICAL DATA FILTERING PROGRAM CODE

```
options ls=78 ps = 66;
dm "log;clear;out;clear;";
* only need one FILENAME DATAIN file as shown below;
FILENAME DATAIN
'C:Research\Dissertation_Auditory\Participant_1\Participant_1.sas';

DATA ENTIREDATASET;
   * INNAME stores the name of the external files to be read;
   * Remember that "-" is an alphanumeric character therefore you must treat
     it with the "$" as shown below;
        LENGTH INNAME $ 75;  * long enough to hold the entire file name;
        LENGTH NAME $ 15;
        LENGTH NOTES $ 5;
        LENGTH TIME $ 20;
        LENGTH ZONENAME $ 10;
        LENGTH LANENAME $ 15;
        LENGTH LANEPOS $ 10;
        LENGTH SPEEDLIMIT $ 10;
        LENGTH GEAR $ 10;
        LENGTH SIGNAL $10;
        LENGTH HORN $ 10;
        LENGTH COLLISION $ 10;
        LENGTH COLLISIONANG $ 10;
        LENGTH COLLISIONVEL $ 10;
        LENGTH VEHAHEAD $ 10;
        LENGTH HEADWAYTIME $10;
        LENGTH HEADWAYDIST $ 10;
        LENGTH TTC $ 10;
        LENGTH TERRAIN $ 20;
        LENGTH CULTURE $ 15;
        LENGTH SLIP $ 5;
   LENGTH ACTIVETRIGGER $ 15;
        LENGTH ENTITYNAME $ 15;
        LENGTH DISTOENTITY $ 15;
        LENGTH TIMETOENTITY $ 15;
        LENGTH ENTITYVEL $ 15;
        LENGTH ENTITYACCEL $ 15;
        LENGTH ENTITYHEAD $ 15;
        LENGTH ENTITYX $ 15;
        LENGTH ENTITYY $ 15;
        LENGTH ENTITYZ $ 15;
        LENGTH USERDATA $ 15;
        * this statement reads the names of the external files from the CARDS;
```

```
        * section of the program;
        INPUT INNAME $;    * tell SAS that it is a string;
    * the following infile statement reads from each of the raw data
      files;
    * listed after the cards statement until end of file (EOF) is
      reached;
        * DLM is the type of deliminter, '09'x indicates that the orginal SAS
          files are diliminted by TAB;
        INFILE DATAIN FILEVAR = INNAME END = EOF DLM = '09'x DSD
FIRSTOBS = 2
       MISSOVER;  * specify delimiter;
        * run the input statement in a loop until all files specified in CARDS
        * section is done;

        DO UNTIL (EOF);
         INPUT NAME $ NOTES $ TIME $ ZONENAME $ TIME SYSTEMTIME
FRAME VELOCITY
        LANENAME $ LANEPOS LANEINDEX $ LANECOUNT LANEHEADING $
SPEEDLIMIT STEER ACCEL BRAKE
        GEAR $ HORN $ ENGINERPM PARTICIPANTHEADING $
PARTICIPANTPITCH PARTICIPANTROLL $
        PARTICIPANTX PARTICIPANTY PARTICIPANTZ SIGNAL $ LATACCEL
LONGACCEL
        COLLISION $ COLLISIONANG $ COLLISIONVEL $ VEHAHEAD $
HEADWAYTIME $ HEADWAYDIST $
                        TTC $ TERRAIN $ CULTURE $ SLIP $ DIGIINPUTS
DIGIINPUTS2 ACTIVETRIGGER $ ENTITYNAME $ DISTOENTITY $
                        TIMETOENTITY $ ENTITYVEL $ ENTITYACCEL $
ENTITYHEAD $ ENTITYX $ ENTITYY $ ENTITYZ $ USERDATA $;

    IF COLLISION = "-" THEN COLLISION = .;
    IF COLLISIONANG = "-" THEN COLLISIONANG = .;
         IF COLLISIONVEL = "-" THEN COLLISIONVELOCITY = .;
         IF VEHAHEAD = "-" THEN VEHAHEAD = .;
         IF HEADWAYDIST = "-" THEN HEADWAYDIST = .;
         IF TTC = "-" THEN TTC = .;
         IF ACTIVETRIGGER = "-" THEN ACTIVETRIGGER = .;
         IF ENTITYNAME = "-" THEN ENTITYNAME = .;
         IF TIMETOENTITY = "-" THEN TIMETOENTITY = .;
         IF ENTITYVELOCITY = "-" THEN ENTITYVELOCITY = .;
         IF LANEINDEX = "-" THEN LANEINDEX = .;
         IF LANEHEADING = "-" THEN LANEHEADING = .;
         IF PARTICIPANTHEADING = "-" THEN PARTICIPANTHEADING = .;
```

```
          IF PARTICIPANTROLL = "-" THEN PARTICIPANTROLL = .;

          STEERING = STEER**2;

       * the output statements forces the SAS to append the
         information to
                  * the ATR data set created by this program;
            OUTPUT;
         END;  * end of DO loop;

* put the names of all the input files after the CARDS statement;
* make sure sas files are placed in the same directory not by participant folder
        as shown below, all files are in the Bzn_Pass_Standard folder;
CARDS;

C:\Research\Dissertation_Auditory\Participant_1\Participant_1.sas

;
RUN;
/*

PROC PRINT DATA = ENTIREDATASET;
   TITLE ' VELOCITY MEANS';
        VAR STEER ;
RUN;

*/
/******************  STEERING DATA BETWEEN TIME @ WARNING TO
STEADY STATE (<5 degree deviation)  *****************/

DATA BEHAVIORS;
   SET ENTIREDATASET;
        IF SYSTEMTIME LE 102.21 AND SYSTEMTIME GE 95.7;
RUN;

PROC MEANS DATA = BEHAVIORS;
   TITLE 'STEERING BRAKING ACCELERATION DATA AT TIME OF WARNING
- STEADY STATE';
        VAR STEER BRAKE ACCEL STEERING SYSTEMTIME;
RUN;

PROC TABULATE DATA = BEHAVIORS;
        TITLE 'OBTAINING RMS FOR STEERING';
```

```
        CLASS NAME;
        VAR STEERING;
        TABLE NAME,
                STEERING*F = 16.3 STEERING*MEAN*F = 16.3 STEERING*N*F =
16.0;

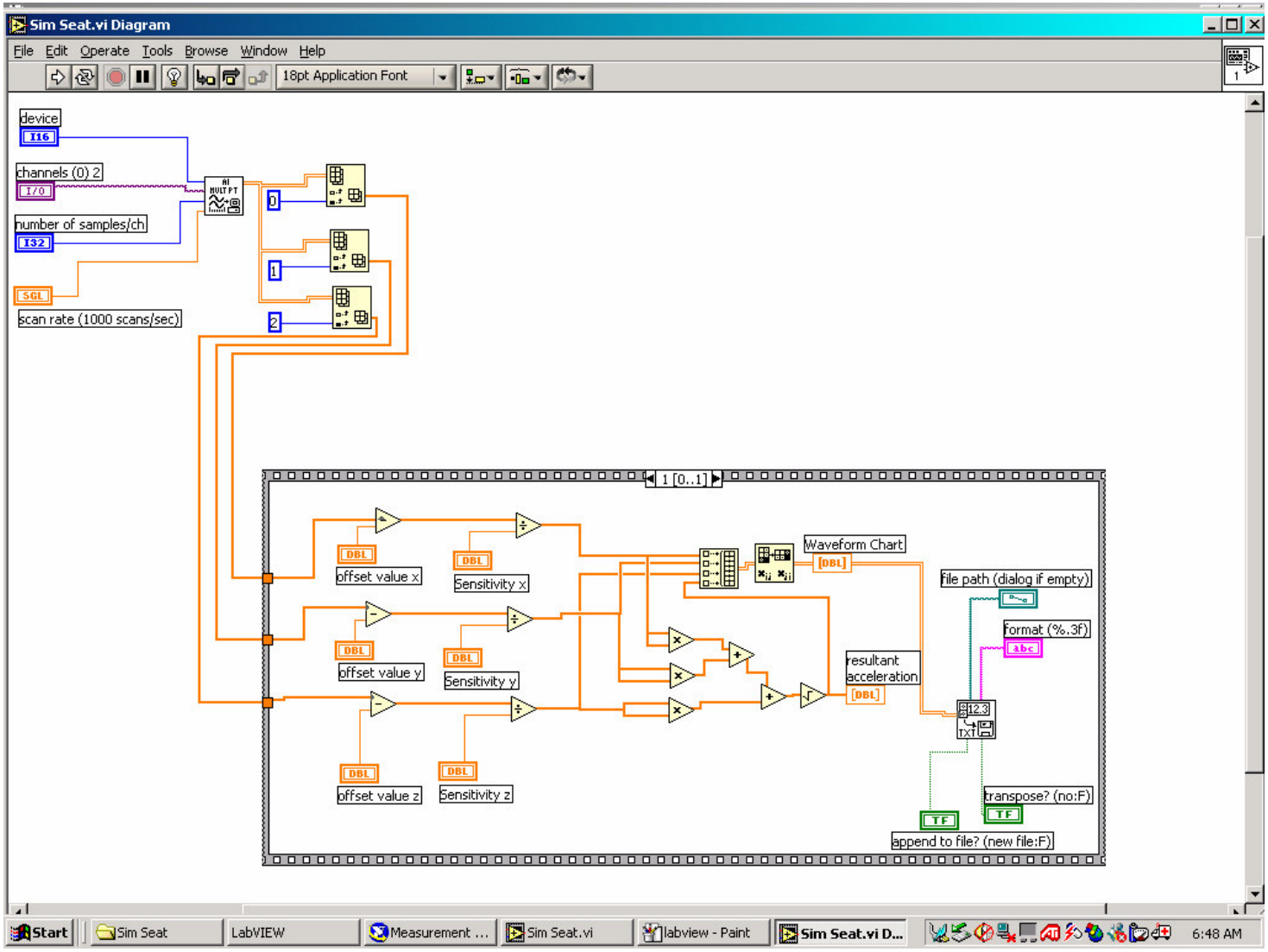
RUN;



QUIT;
```

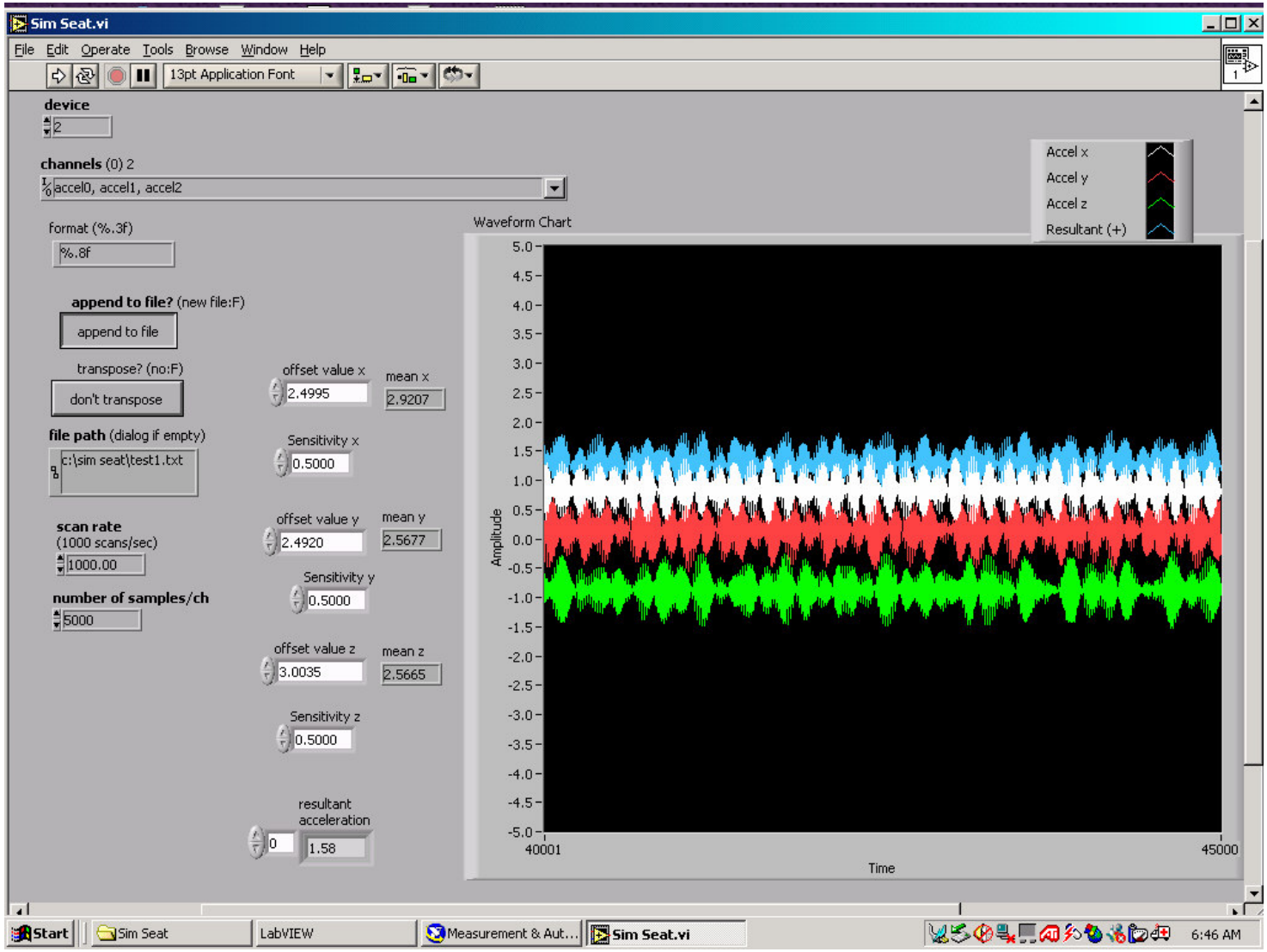
APPENDIX N

LABVIEW™ DIAGRAM FOR OBTAINING ACCELEROMETER MEASUREMENTS


Sim Seat.vi Diagram
File Edit Operate Tools Browse Window Help
18pt Application Font
device
I16
channels (0) 2
I/O
number of samples/ch
I32
SGL
scan rate (1000 scans/sec)
0
1
2
1 [0..1]
DBL
offset value x
Sensitivity x
offset value y
Sensitivity y
offset value z
Sensitivity z
Waveform Chart
resultant acceleration
File path (dialog if empty)
format (%.3f)
transpose? (no:F)
append to file? (new file:F)
Start
Sim Seat
LabVIEW
Measurement ...
Sim Seat.vi
labview - Paint
Sim Seat.vi D...
6:48 AM

APPENDIX O

LABVIEW™ USER INTERFACE FOR OBTAINING ACCELEROMETER MEASUREMENTS


Sim Seat.vi
File Edit Operate Tools Browse Window Help
13pt Application Font
device
2
channels (0) 2
accel0, accel1, accel2
format (%.3f)
%.8f
append to file? (new file:F)
append to file
transpose? (no:F)
don't transpose
file path (dialog if empty)
c:\sim seat\test1.txt
scan rate
(1000 scans/sec)
1000.00
number of samples/ch
5000
offset value x
2.4995
mean x
2.9207
Sensitivity x
0.5000
offset value y
2.4920
mean y
2.5677
Sensitivity y
0.5000
offset value z
3.0035
mean z
2.5665
Sensitivity z
0.5000
resultant acceleration
0
1.58
Waveform Chart
Accel x
Accel y
Accel z
Resultant (+)
Amplitude
Time
40001
45000
Start
Sim Seat
LabVIEW
Measurement & Aut...
Sim Seat.vi
6:46 AM

APPENDIX P

IVIBE® HYPERDRIVE® INTEGRATION TCL SCRIPT

```
#############################################################################
##
#
#  RumbleSeat.tcl
#
#  This include script is designed to work with custom programming added
#  to the driver of the IVIBE vibrating seat.
#
#----------------------------------------------------------------------

#
#  There are three things that need to be done is the user's InitScript in
#  order to use this socket communication library.
#
#  1. The IP address of the 'host' machine needs to be set:
#    SetHostIPAddress 192.168.10.xxx
#    (This will be set to 192.168.10.140 as a default.)
#
#  2. The communication port needs to be set:
#    SetHostPort xxxx
#    (The port must be greater than 1024. It will be set to 5050
#     as a default.)
#
#  3. Turn on the data transmission:
#    RumbleSeat ON
#
#  Turning on the data tranmission will establish the socket connection,
#  send the initial 'Ready to send' message, receive the 'Ready to
#  receive' message and start sending the data across the socket.
#
#----------------------------------------------------------------------

#
#  The socket data transmission should be turned off and the socket should
#  be closed before the scenario comes to an end. This can be done either
#  in a trigger at the end of the drive, but would be best done in the
#  ExitScript.
#
#  1. Turn off the data transmission:
#    RumbleSeat OFF
#
#  Turning off the data transmission will cause the data to no longer
#  be sent and close the socket.
```

```
#
##############################################################################
##
SimOutputMessage "Loading RumbleSeat.tcl..."

#-----------------------------------------------------------------------

#  The global variables...
#-----------------------------------------------------------------------
set ::RSHostIP 192.168.10.29
set ::RSHostPort 5050
set ::RSSocket 0
set ::RSSendData False



#-----------------------------------------------------------------------
#  The utility functions...
#-----------------------------------------------------------------------

proc SetHostIPAddress { ip } {
  set ipList [split $ip .]
  if { [llength $ipList] == 4 } {
    SimOutputMessage "Setting host IP Address to $ip"
    set ::RSHostIP $ip
  } else {
    SimOutputMessage "The IP address $ip does not appear to be valid"
    SimOutputMessage "Using the default IP Address of 192.168.10.140"
  }
}

proc SetHostPort { port } {
  if { $port > 1024 } {
    SimOutputMessage "Setting host port to $port"
    set ::RSHostPort $port
  } else {
    SimOutputMessage "The chosen port, $port, is not allowed"
    SimOutputMessage "Using the default port of 5050"
  }
}

proc RumbleSeat { status } {
  switch [string toupper $status] {
```

```
   "ON" {
     SimOutputMessage "Connecting to the external PC: $::RSHostIP:$::RSHostPort"
     if { [catch { set ::RSSocket [socket $::RSHostIP $::RSHostPort] } results] } {
       SimOutputMessage "                                    "
       SimOutputMessage "****************************************"
       SimOutputMessage "Couldn't connect to remote machine:"
       SimOutputMessage "  $results"
       SimOutputMessage "                                    "
       SimOutputMessage "The socket was not made and there is no"
       SimOutputMessage "communication with the remote machine."
       SimOutputMessage "****************************************"
       SimOutputMessage "                                    "
     } else {
       fconfigure $::RSSocket -blocking false
       SimOutputMessage "Connection made with remote machine."
       SimOutputMessage "Starting to monitor socket."
       puts $::RSSocket "k"
       flush $::RSSocket
       VTriggerAdd vtSocketWatcher 60 Hz
     }
   }


   "OFF" {
     VTriggerRemove vtSocketWatcher
     close $::RSSocket
   }
  }
}




#--------------------------------------------------------------------------
#  The virtual triggers...
#--------------------------------------------------------------------------


VTriggerCreate vtSocketWatcher {
  readFromSocket
  writeToSocket
}
```

```
#-------------------------------------------------------------------------
#  The internal functions...
#-------------------------------------------------------------------------
proc packData { } {
  set laneName [EntityGetInfo Participant LaneName]
  if { $laneName == "None" } {
    set laneWidth 3.6
  } else {
    set laneWidth [LaneGetWidth $laneName]
  }

  set lengthToFront [EntityGetInfo Participant LengthToFront]
  set lengthToBack [EntityGetInfo Participant LengthToBack]
  set participantLength [expr $lengthToFront + $lengthToBack]

  set participantWidth [EntityGetInfo Participant Width]

  set rsWidth 1.0
  set rsCenter [expr ($laneWidth/2) + ($rsWidth/2)]

  set laneCount [EntityGetInfo Participant LaneCount]
  set laneIndex [EntityGetInfo Participant LaneIndex]

  set onRumbleStrip False
  set encroachPoint [expr ($laneWidth/2) - ($participantWidth/2)]
  if { $::LanePos != "-" && abs($::LanePos) > $encroachPoint } {
    if { $::LanePos < 0 } {
      set onRumbleStrip True
    } elseif { $::LanePos > [expr $encroachPoint + 0.1524] } {
      set onRumbleStrip True
    }
  }

  set rumbleStatus 0
  if { $laneCount != 0 } {
    if { $laneCount == 1 } {
      if { $laneIndex != 0 && $onRumbleStrip } {
        if { $::LanePos > 0 } {
          set rumbleStatus 2
```

```
      } else {
        set rumbleStatus 1
      }
    }
  } else {
    if { $laneIndex == 1 && $onRumbleStrip } {
      if { $::LanePos < 0 } {
        set rumbleStatus 1
      }
    } elseif { $laneIndex == $laneCount &&  $onRumbleStrip } {
      if { $::LanePos > 0 } {
        set rumbleStatus 2
      }
    }
  }
 }

 return "$::Frame;$::Velocity;$::LanePos;$rumbleStatus"
}

proc readFromSocket { } {
 set str [read $::RSSocket]

 if { $str == "" } {
  return
 } elseif { [lindex $str 0] == "q" } {
  writeData [packData]
 } elseif { [lindex $str 0] == "b" } {
  set ::RSSendData True
 } elseif { [lindex $str 0] == "e" } {
  set ::RSSendData False
 }
}

proc writeData { data } {
 puts $::RSSocket $data
 flush $::RSSocket
}

proc writeToSocket { } {
 if { $::RSSendData } {
  writeData [packData]
 }
```

APPENDIX Q

IVIBE® HYPERDRIVE® INTEGRATION TCL SCRIPT TEST OBJECT

```
SimScriptAddKeyword AddWave
SimScriptAddKeyword AddTexture
set WavPath /home/sim/vection/data/sounds/
set ImagePath /home/sim/vection/data/images/

set typeCount 0
set fltPath "/home/sim/vection/system/visdb"

DynamicEntityDef "Bobtail Gray" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Commercial"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile bob_gray.wrl
                iconFile bob_gray.gif
                visualsFile $fltPath/bob_grayt.flt
                axleHeight 0.437
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.811
                rearBumperDist 3.499
                density 1.0
                width 2.17
        }

        DynamicsInfo {
                frontAxleDist 1.966
                rearAxleDist 1.874
                trackWidth 1.78
                mass 4000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
```

```
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Bobtail Tan" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Commercial"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile bob_tan.wrl
                iconFile bob_tan.gif
                visualsFile $fltPath/bob_tant.flt
                axleHeight 0.437
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.811
                rearBumperDist 3.499
                density 1.0
                width 2.17
        }

        DynamicsInfo {
                frontAxleDist 1.966
                rearAxleDist 1.874
                trackWidth 1.78
                mass 4000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
```

```
                pitchwn 1.0
        }

}

DynamicEntityDef "Bobtail White" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Commercial"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile bob_white.wrl
                iconFile bob_white.gif
                visualsFile $fltPath/bob_whitet.flt
                axleHeight 0.437
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.811
                rearBumperDist 3.499
                density 1.0
                width 2.17
        }

        DynamicsInfo {
                frontAxleDist 1.966
                rearAxleDist 1.874
                trackWidth 1.78
                mass 4000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0

                rollwn 2.0
                pitchwn 1.0
```

```
DynamicEntityDef "Celica Purple" {
	SimInfo {
		objectType $typeCount; incr typeCount
		objectSubType 0
		capacity 0
		className "Car"
		agencyName "Vehicles"
	}

	VisualsInfo {
		authorFile celica_purple.wrl
		iconFile celica_purple.gif
		visualsFile $fltPath/celica_purple.flt
		axleHeight 0.317
	}

	ScenarioInfo {
		selectForAmbient SIM_TRUE
		frontBumperDist 2.156
		rearBumperDist 1.887
		density 1.0
		width 1.728
	}

	DynamicsInfo {
		frontAxleDist 1.231
		rearAxleDist 1.243
		trackWidth 0.739
		mass 2000
		maxAccel 3.0
		normAccel 2.0
		maxDecel -8.0
		normDecel -4.0
		pitchZeta 0.28
		rollAmpSign 1.0
		rollwn 2.0
		pitchwn 1.0
	}

}

DynamicEntityDef "Four Runner Aqua" {
	SimInfo {
```

```
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile fourrunneraqua.wrl
                iconFile run_aqua.gif
                visualsFile $fltPath/fourrunneraquat.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Four Runner Blue" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
```

```
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile fourrunnerblue.wrl
                iconFile run_blue.gif
                visualsFile $fltPath/fourrunnerbluet.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Four Runner Green" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
```

```
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile fourrunnergreen.wrl
                iconFile run_green.gif
                visualsFile $fltPath/fourrunnergreent.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Four Runner Red" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }
```

```
        VisualsInfo {
                authorFile fourrunnerred.wrl
                iconFile run_red.gif
                visualsFile $fltPath/fourrunnerredt.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0

                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Four Runner White" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }
```

```
        VisualsInfo {
                authorFile fourrunnerwhite.wrl
                iconFile run_white.gif
                visualsFile $fltPath/fourrunnerwhitet.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Grand Prix Blue" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Car"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile gp_blue.wrl
```

```
            iconFile gp_blue.gif
            visualsFile $fltPath/gp_bluet.flt
            axleHeight 0.33
        }

        ScenarioInfo {
            selectForAmbient SIM_TRUE
            frontBumperDist 2.3595
            rearBumperDist 2.3595
            density 1.0
            width 1.556
        }

        DynamicsInfo {
            frontAxleDist 1.411
            rearAxleDist 1.411
            trackWidth 1.3
            mass 2000
            maxAccel 3.0
            normAccel 2.0
            maxDecel -8.0
            normDecel -4.0
            pitchZeta 0.28
            rollAmpSign 1.0
            rollwn 2.0
            pitchwn 1.0
        }

}

DynamicEntityDef "Grand Prix Green" {
        SimInfo {
            objectType $typeCount; incr typeCount
            objectSubType 0
            capacity 0
            className "Car"
            agencyName "Vehicles"
        }

        VisualsInfo {
            authorFile gp_green.wrl
            iconFile gp_green.gif
            visualsFile $fltPath/gp_greent.flt
```

```
                axleHeight 0.33
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.3595
                rearBumperDist 2.3595
                density 1.0
                width 1.556
        }

        DynamicsInfo {
                frontAxleDist 1.411
                rearAxleDist 1.411
                trackWidth 1.3
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Grand Prix Red" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Car"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile gp_red.wrl
                iconFile gp_red.gif
                visualsFile $fltPath/gp_redt.flt
                axleHeight 0.33
        }
```

```
        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.3595
                rearBumperDist 2.3595
                density 1.0
                width 1.556
        }

        DynamicsInfo {
                frontAxleDist 1.411
                rearAxleDist 1.411
                trackWidth 1.3
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Grand Prix Tan" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Car"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile gp_tan.wrl
                iconFile gp_tan.gif
                visualsFile $fltPath/gp_tant.flt
                axleHeight 0.33
        }

        ScenarioInfo {
```

```
                selectForAmbient SIM_TRUE
                frontBumperDist 2.3595
                rearBumperDist 2.3595
                density 1.0
                width 1.556
        }

        DynamicsInfo {
                frontAxleDist 1.411
                rearAxleDist 1.411
                trackWidth 1.3
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Grand Prix White" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Car"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile gp_white.wrl
                iconFile gp_white.gif
                visualsFile $fltPath/gp_whitet.flt
                axleHeight 0.33
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.3595
```

```
                rearBumperDist 2.3595
                density 1.0
                width 1.556
        }

        DynamicsInfo {
                frontAxleDist 1.411
                rearAxleDist 1.411
                trackWidth 1.3
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Land Cruiser Black" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile cruiser_black.wrl
                iconFile land_black.gif
                visualsFile $fltPath/cruiser_black.flt
                axleHeight 0.388
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.19
                rearBumperDist 2.473
                density 1.0
```

```
                width 1.834
        }

        DynamicsInfo {
                frontAxleDist 1.456
                rearAxleDist 1.339
                trackWidth 0.792
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Land Cruiser White" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile cruiser_white.wrl
                iconFile land_white.gif
                visualsFile $fltPath/cruiser_white.flt
                axleHeight 0.388
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.19
                rearBumperDist 2.473
                density 1.0
                width 1.834
        }
```

```
        DynamicsInfo {
                frontAxleDist 1.456
                rearAxleDist 1.339
                trackWidth 0.792
                mass 2000
                maxAccel 3.0

                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Lexus Blue" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Car"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile lexus_blue.wrl
                iconFile lex_blue.gif
                visualsFile $fltPath/lexus_bluet.flt
                axleHeight 0.33
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.4055
                rearBumperDist 2.4055
                density 1.0
                width 1.762
        }
```

```
        DynamicsInfo {
                frontAxleDist 1.385
                rearAxleDist 1.385
                trackWidth 1.54
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Lexus Gray" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Car"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile lexus_gray.wrl
                iconFile lex_gray.gif
                visualsFile $fltPath/lexus_grayt.flt
                axleHeight 0.33
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.4055
                rearBumperDist 2.4055
                density 1.0
                width 1.762
        }

        DynamicsInfo {
                frontAxleDist 1.385
```

```
                rearAxleDist 1.385
                trackWidth 1.54
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Montero Aqua" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile monteroaqua.wrl
                iconFile mont_aqua.gif
                visualsFile $fltPath/monteroaquat.flt
                axleHeight 0.4
        }

        ScenarioInfo {

                selectForAmbient SIM_TRUE
                frontBumperDist 2.25
                rearBumperDist 2.25
                density 1.0
                width 2.0
        }

        DynamicsInfo {
                frontAxleDist 1.342
                rearAxleDist 1.158
```

```
                trackWidth 1.8
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Montero Dark Blue" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile monterodarkblue.wrl
                iconFile mont_blue.gif
                visualsFile $fltPath/monterodarkbluet.flt
                axleHeight 0.4
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.25
                rearBumperDist 2.25
                density 1.0
                width 2.0
        }

        DynamicsInfo {
                frontAxleDist 1.342
                rearAxleDist 1.158
                trackWidth 1.8
                mass 3000
```

```
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Montero Green" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile monterogreen.wrl
                iconFile mont_green.gif
                visualsFile $fltPath/monterogreent.flt
                axleHeight 0.4
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.25
                rearBumperDist 2.25
                density 1.0
                width 2.0
        }

        DynamicsInfo {
                frontAxleDist 1.342
                rearAxleDist 1.158
                trackWidth 1.8
                mass 3000
                maxAccel 3.0
                normAccel 2.0
```

```
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Montero Red" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile monterored.wrl
                iconFile mont_red.gif
                visualsFile $fltPath/monteroredt.flt
                axleHeight 0.4
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.25
                rearBumperDist 2.25
                density 1.0
                width 2.0
        }

        DynamicsInfo {
                frontAxleDist 1.342
                rearAxleDist 1.158
                trackWidth 1.8
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
```

```
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Montero White" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile monterowhite.wrl
                iconFile mont_white.gif
                visualsFile $fltPath/monterowhitet.flt
                axleHeight 0.4
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.25
                rearBumperDist 2.25
                density 1.0
                width 2.0
        }

        DynamicsInfo {
                frontAxleDist 1.342
                rearAxleDist 1.158
                trackWidth 1.8
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
```

```
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Montero Yellow" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "SUV"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile monteroyellow.wrl
                iconFile mont_yellow.gif
                visualsFile $fltPath/monteroyellowt.flt
                axleHeight 0.4
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.25
                rearBumperDist 2.25
                density 1.0
                width 2.0
        }

        DynamicsInfo {
                frontAxleDist 1.342
                rearAxleDist 1.158
                trackWidth 1.8
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
```

```
        }

}

DynamicEntityDef "Motorcycle" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Motorcycle"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile mcycle.wrl
                iconFile motorcycle.gif
                visualsFile $fltPath/mcycle.flt
                axleHeight 0.296
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 1.0
                rearBumperDist 1.0
                density 0.1
                width 0.6
        }

        DynamicsInfo {
                frontAxleDist 0.6
                rearAxleDist 1.2
                trackWidth 0.7
                mass 500
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign -1.0
                rollwn 2.0
                pitchwn 3.0
        }
```

```
}

DynamicEntityDef "Police Car" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Emergency"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile police.wrl
                iconFile police.gif
                visualsFile $fltPath/policet.flt
                axleHeight 0.4
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.491
                rearBumperDist 2.678
                density 0.1
                width 2.0
        }

        DynamicsInfo {
                frontAxleDist 1.665
                rearAxleDist 1.661
                trackWidth 1.73
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}
```

```
DynamicEntityDef "Police Car (B&W)" {
	SimInfo {
		objectType $typeCount; incr typeCount
		objectSubType 0
		capacity 0
		className "Emergency"
		agencyName "Vehicles"
	}

	VisualsInfo {
		authorFile policebw.wrl
		iconFile policebw.gif
		visualsFile $fltPath/police.flt
		axleHeight 0.316
	}

	ScenarioInfo {
		selectForAmbient SIM_TRUE
		frontBumperDist 2.128
		rearBumperDist 2.355
		density 0.1
		width 1.8
	}

	DynamicsInfo {
		frontAxleDist 1.535
		rearAxleDist 1.544
		trackWidth 1.541
		mass 2000
		maxAccel 3.0
		normAccel 2.0
		maxDecel -8.0
		normDecel -4.0
		pitchZeta 0.28
		rollAmpSign 1.0
		rollwn 2.0
		pitchwn 1.0
	}

}

DynamicEntityDef "Tacoma Aqua" {
	SimInfo {
```

```
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Pickup"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile tacomaaqua.wrl
                iconFile tacoma_aqua.gif
                visualsFile $fltPath/tacomaaquat.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Tacoma Blue" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
```

```
            capacity 0
            className "Pickup"
            agencyName "Vehicles"
        }

        VisualsInfo {
            authorFile tacomablue.wrl
            iconFile tacoma_blue.gif
            visualsFile $fltPath/tacomabluet.flt
            axleHeight 0.382
        }

        ScenarioInfo {
            selectForAmbient SIM_TRUE
            frontBumperDist 2.5
            rearBumperDist 2.5
            density 1.0
            width 1.8
        }

        DynamicsInfo {
            frontAxleDist 1.488
            rearAxleDist 1.291
            trackWidth 1.344
            mass 3000
            maxAccel 3.0
            normAccel 2.0
            maxDecel -8.0
            normDecel -4.0
            pitchZeta 0.28
            rollAmpSign 1.0
            rollwn 2.0
            pitchwn 1.0
        }

}

DynamicEntityDef "Tacoma Green" {
        SimInfo {
            objectType $typeCount; incr typeCount
            objectSubType 0
            capacity 0
            className "Pickup"
```

```
            agencyName "Vehicles"
        }

        VisualsInfo {
            authorFile tacomagreen.wrl
            iconFile tacoma_green.gif
            visualsFile $fltPath/tacomagreent.flt
            axleHeight 0.382
        }

        ScenarioInfo {
            selectForAmbient SIM_TRUE
            frontBumperDist 2.5
            rearBumperDist 2.5
            density 1.0
            width 1.8
        }

        DynamicsInfo {
            frontAxleDist 1.488
            rearAxleDist 1.291
            trackWidth 1.344
            mass 3000
            maxAccel 3.0
            normAccel 2.0
            maxDecel -8.0
            normDecel -4.0
            pitchZeta 0.28
            rollAmpSign 1.0
            rollwn 2.0
            pitchwn 1.0
        }

}

DynamicEntityDef "Tacoma Red" {
        SimInfo {
            objectType $typeCount; incr typeCount
            objectSubType 0
            capacity 0
            className "Pickup"
            agencyName "Vehicles"
        }
```

```
        VisualsInfo {
                authorFile tacomared.wrl
                iconFile tacoma_red.gif
                visualsFile $fltPath/tacomaredt.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "Tacoma White" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Pickup"
                agencyName "Vehicles"
        }

        VisualsInfo {
```

```
                authorFile tacomawhite.wrl
                iconFile tacoma_white.gif
                visualsFile $fltPath/tacomawhitet.flt
                axleHeight 0.382
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 2.5
                rearBumperDist 2.5
                density 1.0
                width 1.8
        }

        DynamicsInfo {
                frontAxleDist 1.488
                rearAxleDist 1.291
                trackWidth 1.344
                mass 3000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0
                pitchwn 1.0
        }

}

DynamicEntityDef "VW Golf Yellow" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                capacity 0
                className "Car"
                agencyName "Vehicles"
        }

        VisualsInfo {
                authorFile vwgulf_yellow.wrl
                iconFile gulf_yellow.gif
```

```
                visualsFile $fltPath/vwgulf_yellow.flt
                axleHeight 0.303
        }

        ScenarioInfo {
                selectForAmbient SIM_TRUE
                frontBumperDist 1.917
                rearBumperDist 1.666
                density 1.0
                width 1.554
        }

        DynamicsInfo {
                frontAxleDist 1.246
                rearAxleDist 1.246
                trackWidth 0.652
                mass 2000
                maxAccel 3.0
                normAccel 2.0
                maxDecel -8.0
                normDecel -4.0
                pitchZeta 0.28
                rollAmpSign 1.0
                rollwn 2.0

                pitchwn 1.0
        }

}

ScenarioToolDef "Start Point" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                className "Marker"
                agencyName "Scenario Tool"
        }

        VisualsInfo {
                authorFile green.wrl
                iconFile startpt.gif
                visualsFile $fltPath/start.flt
        }
```

```
}

TileDef "rur2p002.tile" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                culture "Rural"
                signage "Pass"
                laneConfig "2 Lane"
        }

        VisualsInfo {
                authorFile rur2p002.wrl
                iconFile rur2lpass.jpg
                visualsFile $fltPath/rur2p002.flt
        }

        ScenarioInfo {
                width 200.0
                length 200.0
                center 100.0 100.0
                occlusionCode 0
        }

}

TileDef "fwy6p002.tile" {
        SimInfo {
                objectType $typeCount; incr typeCount
                objectSubType 0
                culture "Freeway"
                signage "Pass"
                laneConfig "6 Lane"
        }

        VisualsInfo {
                authorFile fwylanes800.wrl
                iconFile fwylanes800.jpg
                visualsFile $fltPath/fwylanes800.flt
        }

        ScenarioInfo {
```

```
        width 800.0
        length 200.0
        center 100.0 100.0
        occlusionCode 0
}
```

APPENDIX R

PHASE I STUDY IVIBE® CONSOLE RESULTS

	IVIBE Seat Setting	Age		IVIBE Seat Setting	Age	
Subject 1	33.0		Subject 9	36.20		**Total Average =** **43.62**
	39.8	31		45.10	28	
	36.2			46.00		
	40.5			56.60		
	40.7			54.80		**Average Age =** **34.5**
	47.5			58.10		
Avg	39.6		Avg	49.47		
Subject 2	50.4		Subject 10	33.60	35	
	43.2	28		29.10		
	45.0			43.30		
	45.2			40.70		
	46.0			43.30		
	41.5			47.20		
Avg	45.2		Avg	39.53		
Subject 3	26.1		Subject 11	47.00	46	
	39.8	41		27.40		
	27.4			51.30		
	40.7			30.90		
	48.4			53.50		
	42.4			32.60		
Avg	37.5		Avg	40.45		
Subject 4	42.0		Subject 12	42.40	33	
	42.4	37		39.30		
	40.7			55.70		
	45.0			45.10		
	55.3			45.20		
	52.3			43.30		
Avg	46.3		Avg	45.17		

	IVIBE Seat Setting	Age		IVIBE Seat Setting	Age
Subject 5	33.2		Subject 13	34.50	35
	46.9	36		38.70	
	45.1			60.10	
	59.2			49.50	
	48.8			53.90	
	51.1			41.50	
Avg	47.4		Avg	46.37	
Subject 6	40.7		Subject 14	64.00	
	47.7	27		27.40	
	46.0			72.50	
	47.7			35.30	
	43.0			82.10	
	43.3			42.00	
Avg	44.7		Avg	53.88	
Subject 7	21.2		Subject 15	56.60	30
	29.2	49		39.80	
	28.0			46.90	
	32.7			42.40	
	35.0			62.80	
	38.0			59.20	
Avg	30.7		Avg	51.28	
Subject 8	37.1				
	45.1	27			
	26.5				
	40.7				
	28.3				
	43.3				
Avg	36.8				

APPENDIX S

PHASE I STUDY ACCELEROMETER RESULTS

Accelerometer Measurements

Upper Left Quadrant			Average			STD
x	2.921	2.922	2.921	Average X	2.925	0.008
y	2.600	2.595	2.597	Average Y	2.505	0.138
z	2.540	2.542	2.541	Average Z	2.512	0.050
Resultant	1.840	1.520	1.680	Average Resultant	1.745	0.476
Lower Left Quadrant						
x	2.922	2.921	2.922			
y	2.301	2.299	2.300			
z	2.483	2.470	2.477			
Resultant	2.670	2.200	2.435			
Upper Right Quadrant						
x	2.938	2.937	2.938			
y	2.558	2.555	2.556			
z	2.464	2.461	2.462			
Resultant	1.460	1.510	1.485			
Lower Right Quadrant						
x	2.921	2.921	2.921			
y	2.569	2.568	2.568			
z	2.567	2.567	2.567			
Resultant	1.180	1.580	1.380			

APPENDIX T

DRIVER RESPONSE DATA

Subject	Modality	Center or Right	Time @ Warning	Time @ Response	Time @ 0 Crossing	Time @ Steady State	RT	Warning-Crossing	Warning-Steady State
1	1	1	95.7	96.97	98.44	102.21	1.27	2.74	6.51
1	1	2	194.59	195.47	197.97	199.58	0.88	3.38	4.99
1	2	1	77.05	77.82	79.07	82.19	0.77	2.02	5.14
1	2	2	151.97	152.57	161.04	161.55	0.6	9.07	9.58
1	3	1	194.37	195.24	196.3	198.77	0.87	1.93	4.4
1	3	2	120.35	121.54	123.39	124.69	1.19	3.04	4.34
2	1	1	150.39	151.32	153.3	156.79	0.93	2.91	6.4
2	1	2	85.56	86.42	89.61	89.97	0.86	4.05	4.41
2	2	1	86.72	87.81	89.52	92.74	1.09	2.8	6.02
2	2	2	225.55	226.35	228.61	229.52	0.8	3.06	3.97
2	3	1	87.53	88.35	89.74	92.57	0.82	2.21	5.04
2	3	2	41.68	42.55	45.62	46.12	0.87	3.94	4.44
3	1	1	74.1	75.23	76.15	79.42	1.13	2.05	5.32
3	1	2	140.35	141.2	144.65	146.7	0.85	4.3	6.35
3	2	1	183.84	184.77	186	187.82	0.93	2.16	3.98
3	2	2	108.59	109.59	112.02	112.94	1	3.43	4.35
3	3	1	40.63	41.52	42.7	45.17	0.89	2.07	4.54
3	3	2	119.14	120.22	122.59	122.82	1.08	3.45	3.68
4	1	1	243.83	244.95	246.04	248.36	1.12	2.21	4.53
4	1	2	141.85	142.94	145.7	146.77	1.09	3.85	4.92
4	2	1	65.24	66.76	68.42	70.87	1.52	3.18	5.63
4	2	2	103.17	104.04	107.1	107.97	0.87	3.93	4.8
4	3	1	47.47	48.33	49.3	52.39	0.86	1.83	4.92
4	3	2	130.56	131.47	132.35	134.84	0.91	1.79	4.28
5	1	1	118.17	119.59	120.55	123.1	1.42	2.38	4.93
5	1	2	205.85	207.1	210.92	211.32	1.25	5.07	5.47
5	2	1	229.99	230.77	234.04	237.26	0.78	4.05	7.27
5	2	2	192.42	193.32	196.33	196.52	0.9	3.91	4.1
5	3	1	256.04	257.11	257.81	261.84	1.07	1.77	5.8
5	3	2	80.37	81.46	85	85.76	1.09	4.63	5.39
6	1	1	76.65	78.25	80.35	82.67	1.6	3.7	6.02
6	1	2	139.94	141.54	145.82	145.94	1.6	5.88	6
6	2	1	83.25	84.31	85.59	90.9	1.06	2.34	7.65
6	2	2	368.14	369.41	371.5	371.7	1.27	3.36	3.56
6	3	1	293.02	294.39	294.99	299.62	1.37	1.97	6.6
6	3	2	94.05	95.65	99.88	100.32	1.6	5.83	6.27
7	1	1	32.73	34.5	35.17	38.73	1.77	2.44	6
7	1	2	147.94	149.07	152.45	153.32	1.13	4.51	5.38
7	2	1	241.48	242.45	243.73	249.31	0.97	2.25	7.83
7	2	2	37.15	38.3	43.13	44.12	1.15	5.98	6.97
7	3	1	27.57	28.77	30.47	33.63	1.2	2.9	6.06
7	3	2	222.13	223.95	226.82	227.51	1.82	4.69	5.38
8	1	1	40.75	41.88	43.6	47.12	1.13	2.85	6.37
8	1	2	109.19	110.52	113.9	114.29	1.33	4.71	5.1
8	2	1	123.31	124.49	126.75	127.99	1.18	3.44	4.68
8	2	2	50.72	52.02	55.2	55.94	1.3	4.48	5.22
8	3	1	54.93	56.13	57.57	60.5	1.2	2.64	5.57
8	3	2	99.49	100.62	103.8	105.15	1.13	4.31	5.66

APPENDIX U

STEERING RESPONSE DATA

Participant	Modality	Center or Right	MEAN	STD	MIN	MAX
1	1	1	-0.8350	22.4900	-46.7000	45.1000
1	1	2	1.5929	24.1600	-40.0000	57.0000
1	2	1	-2.4502	25.3198	-55.3000	38.2000
1	2	2	-0.9020	2.9970	-11.6000	7.1000
1	3	1	0.3034	19.0658	-37.7000	31.2000
1	3	2	0.3590	16.8500	-29.9000	40.7000
2	1	1	-0.6310	6.9330	-10.9000	10.2000
2	1	2	3.2898	7.2240	-7.6000	13.6000
2	2	1	-1.0111	8.8985	-15.7000	12.6000
2	2	2	1.1669	16.3483	-19.1000	43.1000
2	3	1	-0.7472	15.6680	-36.6000	19.9000
2	3	2	1.0990	9.0200	-10.3000	19.8000
3	1	1	-1.5590	13.0900	-29.0000	16.8000
3	1	2	0.9819	9.3170	-8.1000	33.8000
3	2	1	-0.5410	24.2017	-40.1000	36.4000
3	2	2	1.4111	14.7562	-23.6000	32.6000
3	3	1	0.4773	18.9209	-42.5000	31.5000
3	3	2	0.6330	19.3360	-28.4000	38.1000
4	1	1	-1.3280	19.1090	-48.2000	25.9000
4	1	2	1.5395	16.3860	-17.4000	52.5000
4	2	1	-1.2920	12.2918	-37.1000	15.4000

4	2	2	0.6743	20.2378	-27.6000	37.9000
4	3	1	-0.3844	11.5993	-29.5000	22.9000
4	3	2	0.2750	16.1570	-38.8000	17.8000
5	1	1	-4.5870	25.6780	-64.2000	29.2000
5	1	2	1.3640	11.7000	-10.6000	32.2000
5	2	1	-0.2718	8.4672	-27.5000	9.1000
5	2	2	1.6927	8.5978	-8.9000	25.2000
5	3	1	-2.5280	6.4513	-13.6000	7.8000
5	3	2	1.4670	7.7490	-8.1000	22.0000
6	1	1	-0.1331	5.0910	-9.4000	10.9000
6	1	2	2.0170	7.7740	-10.3000	15.2000
6	2	1	-1.9000	0.0000	-1.9000	-1.9000
6	2	2	3.1846	4.3058	-1.1000	8.3000
6	3	1	-0.4225	1.7092	-4.4000	1.9000
6	3	2	1.6600	5.4246	-5.9000	10.9000
7	1	1	-1.3900	7.3000	-14.9000	9.0000
7	1	2	2.0500	13.6220	-17.2000	27.2000
7	2	1	-0.3087	8.0650	-17.6000	15.2000
7	2	2	-1.1974	13.4116	-22.7000	29.9000
7	3	1	-0.2297	9.4980	-17.8000	15.5000
7	3	2	0.6997	18.0470	-23.8000	37.0000
8	1	1	-0.6540	13.1126	-25.0000	20.2000
8	1	2	-0.0676	11.9000	-17.3000	27.2000
8	2	1	0.5174	14.1298	-26.0000	24.0000
8	2	2	1.7952	11.2726	-9.3000	31.9000
8	3	1	-0.5033	7.4838	-	9.9000

8	3	2	0.7255	8.9390	14.6000 - 10.7000	19.1000
9	1	1	-0.2666	6.7440	- 15.6000	10.0000
9	1	2	0.5583	12.7200	- 14.8000	32.0000
9	2	1	-0.7412	9.3240	- 20.3000	13.3000
9	2	2	1.5691	11.4506	- 11.7000	31.1000
9	3	1	-1.9980	10.7650	- 27.4000	8.5000
9	3	2	1.4140	8.3367	- 11.5000	19.4000
10	1	1	-1.6600	5.9677	- 13.7000	5.9000
10	1	2	1.4200	8.6960	-9.3000	16.3000
10	2	1	-0.9285	6.9442	- 14.9000	8.9000
10	2	2	1.3039	7.4776	-8.6000	16.5000
10	3	1	-3.3180	6.0740	- 18.5000	4.8000
10	3	2	1.7550	9.4500	-7.7000	19.7000
11	1	1	-4.1800	11.0800	- 19.8000	9.9000
11	1	2	0.4770	7.5070	- 10.1000	18.8000
11	2	1	-1.1732	5.8044	- 10.1000	6.0000
11	2	2	0.8472	4.7912	-6.3000	10.1000
11	3	1	-0.4029	6.4649	- 11.0000	8.9000
11	3	2	0.8215	4.5060	-6.4000	8.9000
12	1	1	-0.6856	13.7300	- 26.6000	26.2000
12	1	2	0.6124	9.5620	- 12.9000	25.4000
12	2	1	0.0041	9.9934	- 17.5000	12.9000
12	2	2	1.6081	8.7374	- 12.2000	23.9000
12	3	1	-0.1026	8.9964	-	14.2000

12	3	2	0.4564	9.0880	18.1000 - 11.9000	26.3000
13	1	1	-2.8900	21.0800	-51.8000	23.1000
13	1	2	2.2122	5.7220	-6.8000	12.7000
13	2	1	-0.4884	6.3590	-10.4000	9.5000
13	2	2	2.1247	6.3625	-6.6000	14.2000
13	3	1	-0.6454	10.0156	-18.4000	13.7000
13	3	2	1.5460	6.8190	-7.8000	16.1000
14	1	1	-1.0640	8.5100	-13.5000	12.1000
14	1	2	2.0392	11.2910	-16.0000	22.2000
14	2	1	-1.1772	10.5695	-17.7000	15.4000
14	2	2	2.1247	6.3625	-6.6000	14.2000
14	3	1	-0.6357	8.0302	-14.2000	10.5000
14	3	2	0.6360	6.4390	-10.6000	11.9000
15	1	1	-0.9628	14.2800	-22.2000	25.4000
15	1	2	2.9801	10.9117	-11.1000	24.5000
15	2	1	0.1571	0.5661	-1.2000	1.2000
15	2	2	0.0589	1.2502	-2.2000	2.4000
15	3	1	-1.3298	7.3908	-19.7000	12.5000
15	3	2	2.2500	10.0040	-8.9000	21.7000

APPENDIX V

ACCELERATION RESPONSE DATA

Participant	Modality	Center or Right	MEAN	STD	MIN	MAX
1	1	1	0.0156	0.0036	0.0070	0.0210
1	1	2	0.0165	0.0037	0.0070	0.0230
1	2	1	0.0156	0.0036	0.0050	0.0210
1	2	2	0.0150	0.0019	0.0120	0.0200
1	3	1	0.0104	0.0068	0.0000	0.0210
1	3	2	0.0110	0.0057	0.0000	0.0210
2	1	1	0.0142	0.0036	0.0070	0.0210
2	1	2	0.0105	0.0015	0.0070	0.0140
2	2	1	0.0092	0.0071	0.0000	0.0230
2	2	2	0.0087	0.0039	0.0000	0.0160
2	3	1	0.0084	0.0052	0.0000	0.0210
2	3	2	0.0169	0.0025	0.0110	0.0230
3	1	1	0.0645	0.0935	0.0000	0.2450
3	1	2	0.0277	0.0528	0.0000	0.1650
3	2	1	0.0111	0.0082	0.0000	0.0230
3	2	2	0.0127	0.0034	0.0070	0.0210
3	3	1	0.0535	0.0708	0.0000	0.2060
3	3	2	0.0430	0.0515	0.0000	0.1370
4	1	1	0.0150	0.0064	0.0050	0.0270
4	1	2	0.0127	0.0034	0.0050	0.0210
4	2	1	0.0172	0.0019	0.0140	0.0210
4	2	2	0.0109	0.0055	0.0000	0.0200
4	3	1	0.0055	0.0069	0.0000	0.0210
4	3	2	0.0160	0.0020	0.0110	0.0200
5	1	1	0.0116	0.0015	0.0070	0.0160
5	1	2	0.0096	0.0015	0.0050	0.0120
5	2	1	0.0080	0.0020	0.0040	0.0140
5	2	2	0.0074	0.0026	0.0020	0.0140
5	3	1	0.0075	0.0018	0.0040	0.0110
5	3	2	0.0060	0.0017	0.0020	0.0110
6	1	1	0.0072	0.0018	0.0040	0.0110
6	1	2	0.0072	0.0018	0.0040	0.0110
6	2	1	0.0067	0.0018	0.0040	0.0090
6	2	2	0.0063	0.0017	0.0020	0.0110
6	3	1	0.0103	0.0015	0.0070	0.0140
6	3	2	0.0119	0.0018	0.0070	0.0180
7	1	1	0.0120	0.0032	0.0050	0.0200
7	1	2	0.0035	0.0015	0.0000	0.0090
7	2	1	0.0128	0.0060	0.0000	0.0210
7	2	2	0.0129	0.0067	0.0000	0.0210

7	3	1	0.0105	0.0067	0.0000	0.0230
7	3	2	0.0139	0.0016	0.0110	0.0180
8	1	1	0.0076	0.0059	0.0000	0.0200
8	1	2	0.0087	0.0039	0.0020	0.0180
8	2	1	0.0095	0.0043	0.0000	0.0180
8	2	2	0.0059	0.0058	0.0000	0.0160
8	3	1	0.0071	0.0068	0.0000	0.0210
8	3	2	0.0069	0.0036	0.0000	0.0140
9	1	1	0.0031	0.0017	0.0000	0.0070
9	1	2	0.0107	0.0015	0.0070	0.0160
9	2	1	0.0112	0.0016	0.0070	0.0160
9	2	2	0.0099	0.0015	0.0070	0.0140
9	3	1	0.0015	0.0016	0.0000	0.0050
9	3	2	0.0023	0.0019	0.0000	0.0070
10	1	1	0.0055	0.0048	0.0000	0.0180
10	1	2	0.0022	0.0017	0.0000	0.0050
10	2	1	0.0040	0.0019	0.0000	0.0090
10	2	2	0.0133	0.0019	0.0090	0.0200
10	3	1	0.0069	0.0067	0.0000	0.0200
10	3	2	0.0018	0.0016	0.0000	0.0050
11	1	1	0.0149	0.0018	0.0110	0.0200
11	1	2	0.0075	0.0028	0.0020	0.0140
11	2	1	0.0056	0.0028	0.0000	0.0120
11	2	2	0.0080	0.0025	0.0020	0.0160
11	3	1	0.0053	0.0018	0.0000	0.0110
11	3	2	0.0019	0.0015	0.0070	0.0160
12	1	1	0.0104	0.0021	0.0050	0.0160
12	1	2	0.0039	0.0046	0.0000	0.0210
12	2	1	0.0063	0.0042	0.0000	0.0120
12	2	2	0.0046	0.0024	0.0000	0.0090
12	3	1	0.0010	0.0014	0.0000	0.0040
12	3	2	0.0102	0.0015	0.0070	0.0140
13	1	1	0.0039	0.0031	0.0000	0.0140
13	1	2	0.0134	0.0051	0.0020	0.0210
13	2	1	0.0058	0.0057	0.0000	0.0200
13	2	2	0.0045	0.0029	0.0000	0.0110
13	3	1	0.0037	0.0051	0.0000	0.0200
13	3	2	0.0060	0.0070	0.0000	0.0200
14	1	1	0.0063	0.0016	0.0040	0.0110
14	1	2	0.0083	0.0017	0.0050	0.0120
14	2	1	0.0029	0.0022	0.0000	0.0090
14	2	2	0.0045	0.0029	0.0000	0.0110

14	3	1	0.0105	0.0024	0.0050	0.0160
14	3	2	0.0025	0.0032	0.0000	0.0140
15	1	1	0.0057	0.0016	0.0020	0.0110
15	1	2	0.0049	0.0014	0.0020	0.0090
15	2	1	0.0041	0.0026	0.0000	0.0120
15	2	2	0.0122	0.0033	0.0040	0.0200
15	3	1	0.0102	0.0063	0.0000	0.0210
15	3	2	0.0045	0.0027	0.0000	0.0120

APPENDIX W

STEERING RMS RESPONSE DATA

Participant	Modality	Center or Right	MEAN	STD	MIN	MAX
1	1	1	505.340	680.800	0.090	2180.890
1	1	2	584.457	838.070	0.010	3249.000
1	2	1	645.022	905.562	0.010	3058.000
1	2	2	9.782	21.900	0.000	134.560
1	3	1	362.220	423.531	0.160	1421.290
1	3	2	283.080	423.940	0.010	1656.490
2	1	1	48.334	38.312	0.010	118.810
2	1	2	62.800	63.300	0.040	184.960
2	2	1	79.986	80.424	0.040	246.490
2	2	2	267.511	424.116	0.040	1857.600
2	3	1	245.235	342.916	0.250	1339.500
2	3	2	82.200	92.050	0.040	392.040
3	1	1	173.340	245.840	0.000	841.000
3	1	2	87.539	225.060	0.010	1142.440
3	2	1	583.564	565.345	0.000	1608.010
3	2	2	218.902	308.064	0.160	1062.760
3	3	1	356.917	529.557	0.000	1806.250
3	3	2	372.620	452.920	0.000	1451.610
4	1	1	365.580	596.840	0.000	2323.240
4	1	2	269.967	556.490	0.000	2756.250
4	2	1	152.312	287.255	0.040	1376.400
4	2	2	408.600	468.046	0.000	1436.400
4	3	1	134.236	196.650	0.000	870.250
4	3	2	260.127	375.060	0.000	1505.440
5	1	1	678.180	1195.130	0.000	4121.640
5	1	2	138.350	270.013	0.000	1036.840
5	2	1	71.603	163.100	0.000	756.250
5	2	2	76.487	147.494	0.040	635.040
5	3	1	47.871	51.742	0.010	184.960
5	3	2	62.016	107.580	0.000	484.000
6	1	1	25.865	37.409	0.000	118.810
6	1	2	64.330	73.350	0.000	231.040
6	2	1	3.610	0.000	3.610	3.610
6	2	2	28.595	29.614	0.040	68.890
6	3	1	3.093	4.134	0.000	19.360
6	3	2	32.115	37.359	0.000	118.810
7	1	1	55.126	62.304	0.000	222.010
7	1	2	189.212	241.277	0.000	739.840
7	2	1	65.002	82.061	0.000	309.760
7	2	2	180.875	238.661	0.000	894.010

7	3	1	90.020	84.040	0.010	316.840
7	3	2	325.188	417.830	0.090	1369.000
8	1	1	171.919	202.962	0.000	625.000
8	1	2	141.220	196.595	0.000	739.840
8	2	1	199.208	232.331	0.000	676.000
8	2	2	129.888	255.863	0.040	1017.600
8	3	1	56.019	63.281	0.010	213.160
8	3	2	80.197	95.755	0.010	364.810
9	1	1	45.440	53.580	0.000	243.360
9	1	2	161.680	245.190	0.000	1024.000
9	2	1	87.253	100.459	0.010	412.090
9	2	2	133.144	231.520	0.000	967.210
9	3	1	119.599	199.834	0.010	750.760
9	3	2	71.320	97.703	0.040	376.360
10	1	1	38.247	44.460	0.000	187.690
10	1	2	77.420	83.850	0.000	265.690
10	2	1	48.922	63.329	0.000	222.010
10	2	2	57.415	66.419	0.000	272.250
10	3	1	47.734	83.480	0.010	342.250
10	3	2	92.140	114.170	0.000	388.090
11	1	1	139.766	137.120	0.090	392.040
11	1	2	56.440	79.388	0.010	353.440
11	2	1	34.972	30.510	0.010	102.010
11	2	2	23.613	25.138	0.010	102.010
11	3	1	41.863	37.520	0.010	121.000
11	3	2	20.920	19.050	0.010	79.210
12	1	1	188.630	216.540	0.000	707.560
12	1	2	91.540	150.019	0.000	645.160
12	2	1	99.493	89.589	0.010	306.250
12	2	2	78.761	139.324	0.000	571.210
12	3	1	80.707	87.916	0.040	327.610
12	3	2	82.550	150.270	0.000	691.690
13	1	1	451.488	684.080	0.000	2683.240
13	1	2	37.507	42.353	0.000	161.290
13	2	1	40.538	36.249	0.000	108.160
13	2	2	44.851	52.594	0.010	201.640
13	3	1	100.441	84.244	0.000	338.560
13	3	2	48.730	70.129	0.010	259.210
14	1	1	73.320	56.470	0.010	182.250
14	1	2	131.320	143.098	0.000	492.840
14	2	1	112.828	84.982	0.010	313.290
14	2	2	44.851	52.594	0.010	201.640

14	3	1	64.698	69.141	0.000	201.640
14	3	2	41.770	42.550	0.000	141.610
15	1	1	204.250	197.820	0.040	645.160
15	1	2	127.481	173.169	0.000	600.250
15	2	1	0.344	0.503	0.000	1.440
15	2	2	1.560	1.524	0.010	5.760
15	3	1	56.236	90.115	0.000	388.090
15	3	2	104.770	145.420	0.010	470.890

APPENDIX X

DRIVER ATTITUDE RESPONSE RANKINGS

Question	Participant	1=Vibration	2=Auditory	3=Combination
Benefit to Driving	1	3	2	1
Most Likely to Purchase	1	3	2	1
Level of Trust	1	2	3	1
Level of Annoyance	1	3	1	2
Level of Interference	1	1	2	3
Level of Appropriateness	1	2	3	1
Level of Urgency	1	3	2	1
Overall Preference	1	3	2	1
Benefit to Driving	2	3	1	2
Most Likely to Purchase	2	3	1	2
Level of Trust	2	3	1	2
Level of Annoyance	2	3	1	2
Level of Interference	2	3	1	2
Level of Appropriateness	2	3	2	1
Level of Urgency	2	3	2	1
Overall Preference	2	3	1	2
Benefit to Driving	3	2	3	1
Most Likely to Purchase	3	1	3	2
Level of Trust	3	2	3	1
Level of Annoyance	3	1	3	2
Level of Interference	3	2	1	3
Level of Appropriateness	3	1	3	2
Level of Urgency	3	2	3	1
Overall Preference	3	1	3	2
Benefit to Driving	4	3	2	1
Most Likely to Purchase	4	1	3	2
Level of Trust	4	2	3	1
Level of Annoyance	4	1	3	2
Level of Interference	4	1	3	2
Level of Appropriateness	4	1	3	2

Level of Urgency	4	2	3	1
Overall Preference	4	1	3	2
Benefit to Driving	5	1	3	2
Most Likely to Purchase	5	1	3	2
Level of Trust	5	1	3	2
Level of Annoyance	5	3	1	2
Level of Interference	5	3	1	2
Level of Appropriateness	5	1	3	2
Level of Urgency	5	1	3	2
Overall Preference	5	1	3	2
Benefit to Driving	6	1	3	2
Most Likely to Purchase	6	1	3	2
Level of Trust	6	1	3	2
Level of Annoyance	6	1	3	2
Level of Interference	6	1	3	2
Level of Appropriateness	6	2	3	1
Level of Urgency	6	1	3	2
Overall Preference	6	1	3	2
Benefit to Driving	7	2	3	1
Most Likely to Purchase	7	2	3	1
Level of Trust	7	2	3	1
Level of Annoyance	7	1	3	2
Level of Interference	7	1	3	2
Level of Appropriateness	7	3	2	1
Level of Urgency	7	2	3	1
Overall Preference	7	2	3	1
Benefit to Driving	8	3	2	1
Most Likely to Purchase	8	3	1	2
Level of Trust	8	3	3	1
Level of Annoyance	8	3	1	2
Level of Interference	8	2	3	1
Level of Appropriateness	8	2	3	1
Level of Urgency	8	3	2	1
Overall Preference	8	3	1	2
Benefit to Driving	9	3	2	1

Most Likely to Purchase	9	3	2	1
Level of Trust	9	3	1	2
Level of Annoyance	9	1	3	2
Level of Interference	9	1	2	3
Level of Appropriateness	9	3	1	2
Level of Urgency	9	3	1	2
Overall Preference	9	3	1	2
Benefit to Driving	10	3	2	1
Most Likely to Purchase	10	3	2	1
Level of Trust	10	3	2	1
Level of Annoyance	10	3	2	1
Level of Interference	10	2	3	1
Level of Appropriateness	10	2	3	1
Level of Urgency	10	3	2	1
Overall Preference	10	3	2	1
Benefit to Driving	11	3	2	1
Most Likely to Purchase	11	3	2	1
Level of Trust	11	2	3	1
Level of Annoyance	11	1	2	3
Level of Interference	11	1	2	3
Level of Appropriateness	11	3	2	1
Level of Urgency	11	3	2	1
Overall Preference	11	3	2	1
Benefit to Driving	12	2	3	1
Most Likely to Purchase	12	2	3	1
Level of Trust	12	2	3	1
Level of Annoyance	12	1	3	2
Level of Interference	12	1	2	3
Level of Appropriateness	12	2	3	1
Level of Urgency	12	2	3	1
Overall Preference	12	2	3	1
Benefit to Driving	13	2	3	1
Most Likely to Purchase	13	2	3	1
Level of Trust	13	2	3	1

Level of Annoyance	13	2	3	1
Level of Interference	13	1	3	2
Level of Appropriateness	13	1	3	2
Level of Urgency	13	2	3	1
Overall Preference	13	2	3	1
Benefit to Driving	14	2	3	1
Most Likely to Purchase	14	2	3	1
Level of Trust	14	2	3	1
Level of Annoyance	14	3	1	2
Level of Interference	14	2	1	3
Level of Appropriateness	14	2	3	1
Level of Urgency	14	2	3	1
Overall Preference	14	2	3	1
Benefit to Driving	15	2	3	1
Most Likely to Purchase	15	2	3	1
Level of Trust	15	1	3	2
Level of Annoyance	15	1	3	2
Level of Interference	15	3	2	1
Level of Appropriateness	15	1	2	3
Level of Urgency	15	3	2	1
Overall Preference	15	1	2	3
TOTAL		246	290	185

APPENDIX Y

PARTICIPANT HISTORY QUESTIONNAIRE RESULTS

Subject #	Age	Gender	Annual Miles Driven	Years Driving	# Trips/Year	# of Accidents
1	29	F	9,000	13	2	0
2	20	M	10,000	6	4	1
3	21	F	12,00	5	5	0
4	35	F	5,000	20	2	0
5	48	F	15,000	32	2	0
6	44	M	12,000	29	6	0
7	31	F	15,000	16	7	2
8	27	M	25,000	12	10	0
9	36	F	12,000	21	5	1
10	36	F	12,000	21	2	1
11	25	F	25,000	9	3	0
12	29	F	15,000	13	3	2
13	43	F	12,000	28	1	0
14	29	F	7,500	15	1	0
15	28	M	5,000	12	0	2

Participant #	Occupation	Revoked License, O=No	Education Program, 1=Yes	Medication	Medical
1	Transportation Planner	0	1	Advair	Asthma
2	Student	0	1	0	0
3	Student	0	1	Antibiotics	0
4	Biologist	0	1	Wellbutrin	0
5	CAD Trainer	0	1	Zoloft	0
6	Education	0	1	0	0
7	Grad Student	0	1	0	0
8	Grad Student	0	1	0	0
9	Administration	0	1	Spiranocactone, Meridia, Nephridipine, Enacapril, Metformin, Baby Asprin	Kerataconus - Eye Disease, Polycistic Ovarian Syndrome
10	Education	0	1	0	0
11	Student	0	1	0	0
12	Grad Student	0	1	0	0
13	Admin. Assoc.	0	1	0	0
14	Accountant	0	1	0	0
15	Researcher	0	1	0	0