Effects of Haptic and Auditory Warnings on Driver Intersection Behavior and Perception

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ABSTRACT

Intersection crashes account for over one-third of all crashes in the U.S., and 39% of these result in injury or death. As part of a larger effort to develop and evaluate in-vehicle countermeasures to reduce the number of intersection-related crashes, haptic warnings and a combined haptic/auditory warning were explored and compared to combined visual/auditory warnings.

The first phase of this study determined which haptic brake pulse warning candidate most often resulted in the driver successfully stopping for an intersection. Five brake pulse warnings were tested (varied with respect to jerk, duration, and the number of pulses). Participants receiving the haptic warnings were 38 times more likely to stop at the intersection than those receiving no warning and 7.6 times more likely to stop than those receiving a combined visual/auditory tone warning. The 600ms-3 pulses condition was advanced to the second phase because it provided the longest warning and had a more favorable subjective rating; it was then combined with an auditory verbal warning (urgent "STOP"). This phase determined whether the added verbal warning resulted in differences from the haptic warning alone. Although the warning was activated 7.62 m (25 ft) closer to the intersection in the second phase than in the first phase, there were no significant differences for the reaction times and distance to stop bar. Participants receiving the haptic plus auditory verbal warning were also 1.5 times more likely to stop than those who received the haptic warning alone. Overall, this study shows that haptic warnings show promise for warning drivers of impending intersection violations. Guidelines for haptic intersection warnings were developed, including a recommendation that haptic warnings be combined with auditory verbal warnings for increased warning effectiveness.

DEDICATION

This thesis is dedicated to the memory of my brother, Dustin Brown, whose life was taken in a car accident. It is with hope that the research conducted here at the Virginia Tech Transportation Institute will save the lives of many brothers, sisters, sons, daughters, fathers, and mothers.

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CHAPTER 1 INTRODUCTION

Problem Statement

An intersection is the point at which traffic coming from different roads and directions crosses paths. Intersection traffic can be controlled by either traffic signals or traffic signs such as stop signs. As the number of roads increase, the number of intersections also increases, causing crossing traffic to be a growing problem. The problem of crossing traffic also rises as traffic density increases.

Every year intersection crashes account for nearly a quarter of police-reported crashes in the United States. While most intersection crashes result in only property damage, 39% result in injury or death (Lee et al., 2004). In 2003, it was reported that intersections were responsible for over 8,000 deaths yearly (NHTSA, 2005). Over one-third of all intersection crossing-path crashes (37%) have been attributed to driver distraction or inattention (Lee et al., 2004).

This study was part of a larger research project, *Intersection Collision Avoidance-Violation (ICAV)*, conducted by the Virginia Tech Transportation Institute (VTTI) for the National Highway Traffic Safety Administration.

The motivation for this study was to reduce the number of intersection violations, defined as crossing the intersection stop bar during the red phase. In reducing the number of violations, the number of crossing-path crashes would also be reduced. This research explored the effects of haptic warnings on driving behavior and perception. Other factors such as algorithm development and warning timing were concurrently studied by other parts of the ICAV project.

Driver Vehicle Interface

The overall purpose of the ICAV system is to reduce the number of intersection violations. The driver vehicle interface (DVI) system (Figure 1) is responsible for successfully transmitting a warning signal that results in the driver stopping, hence reducing the number of violations and crashes associated with these violations. DVI warnings can either remain in a steady state or can exhibit changing characteristics as the severity of the situation increases; this latter possibility is known as a graded warning. The warnings may also change through driver inputs as they adjust the system sensitivity to their preference. This DVI system can become more complex as various algorithm-specific issues, such as graded warnings or system sensitivity adjustments, are introduced.

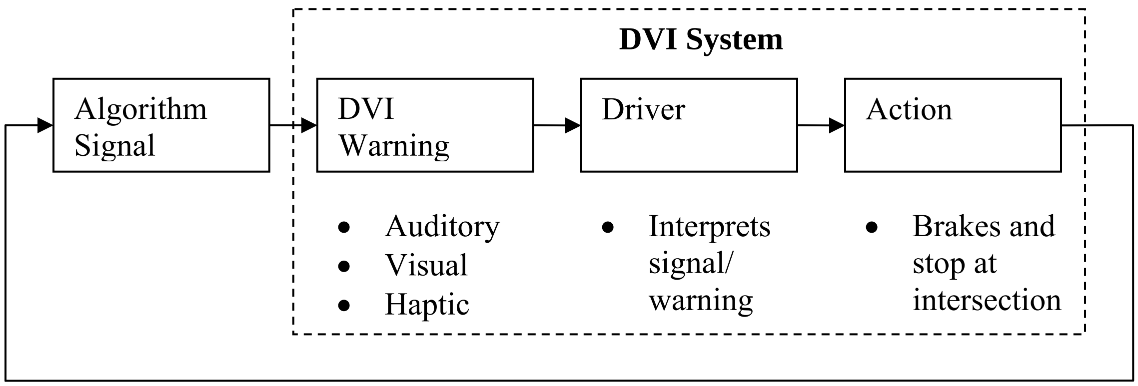


Figure 1: *DVI system*

The DVI system is able to receive a signal from the algorithm telling the DVI warning to activate in response to the driver's action (or lack of action) while approaching the intersection. Ideally, the driver is then able to process the warning signal and react to the warning. To account for the time it takes the driver to process the warning, a reaction time is added to the algorithm. A link can also exist between the driver's action and the algorithm. For example, if the algorithm detects the driver is not braking hard enough in response to the warning, a different auditory frequency or visual warning color may be displayed to further capture the driver's attention; this would be considered a graded warning. There may also be intentional inputs by the driver into the system that could account for driver preferences, such as increasing or decreasing warning volume.

In-vehicle warnings are designed to elicit certain reactions from the driver. An auditory and haptic warning may be used to direct the driver's attention back to the forward view, whereas a visual warning may be used to provide more specific information to the driver.

Studies have examined various warning attributes and their effects on drivers. For example, an auditory warning that is not loud enough may not alert the driver, but one that is too loud may startle the driver. Determining effective attributes for appropriate driver responses is paramount in warning development. Previous studies that have examined warning attributes and driver reactions are discussed in the following literature review, which are organized by modality (auditory, visual, and haptic).

The three warning modalities studied for the overall ICAV project were auditory, visual, and haptic. This thesis examined the haptic warning alone, and also determined the appropriate haptic feedback to be used with a verbal auditory warning. An iterative process was used, whereby auditory, visual, and haptic warnings were first being evaluated separately, and then combined into multi-modal combinations for further evaluation. This thesis evaluated several haptic displays and combined a haptic display with a verbal auditory warning.

Study Rationale

The rationale for this study is to reduce the number of crashes associated with intersection violations. Since driver distraction or inattention has been found to cause 37% of intersection crashes, in-vehicle warnings could prove to be advantageous. In order to reduce the number of violations, a viable warning must be developed that will elicit the appropriate response from the driver. The goal of this study is to evaluate different brake pulse candidates alone and in combination with auditory warnings, as well as developing human factors guidelines for haptic warnings for intersection violation warnings. The haptic warning should be effective at reducing the number of intersection violations and collisions.

Research Questions

1. Which brake pulse candidate results in the fastest reaction time and largest deceleration values?
2. What are the response differences between age groups?

3. Will having both a brake pulse and auditory warning result in a shorter response time than a brake pulse alone?

Research Goals:

1. Determine the correlation between objective and subjective responses to haptic brake pulses.
2. Determine driver perception of haptic warnings.
3. Determine guidelines haptic brake pulse warnings.

CHAPTER 2 LITERATURE REVIEW

In-vehicle Warning Modalities

Auditory

Auditory warnings use sound as a way to capture the driver's attention regardless of where the driver is looking. There are several different types of auditory cues that can be used; three general types of warnings are tone (conventional), auditory icon (earcon), and speech. Tone is the use of a frequency or a range of frequencies in either a continuous or intermittent signal. Auditory icons use a familiar sound to cue the driver, such as a tire screech or car horn. Speech is spoken language that is either synthesized or digitized voice.

When compared with voice feedback, tone feedback has generally resulted in better driving performance in critical situations (Lloyd, Bittner, & Pierowicz, 1996). It is suggested that non-speech auditory messages be used for alerting the driver, whereas human speech is preferred when the choice of message is relatively limited and is known ahead of time (Green, Levison, Paelke, & Serafin, 1993). Graham (1995) found that auditory icons produce significantly faster response times, but with more inappropriate responses of drivers braking during non-collision situations.

It is important that the auditory warning be detectable above other noises outside and inside the vehicle. Since older drivers require a higher dB level than younger drivers, a sound level control should be considered but should not allow going below a certain dB level (Baldwin, 2002). The auditory tone should be about 15dB above the masked threshold. A primary concern with using tone (conventional) auditory warnings lies in their integration with other warnings. When many assistance systems are used in the vehicle, the driver might be confused when multiple warnings occur simultaneously (Landau, 1996; Olney, Wragg, Schumacher, & Landau, 1996). The auditory warning system should also be compatible and integrated with stereo systems to allow for attenuation at the onset of warning (Sanders & McCormick, 1993).

Though auditory feedback is easily detectable (that is, it can be detected no matter where the driver is looking or what the driver is thinking about), problems may still exist when using it as a warning. There are drivers who have auditory impairments or shifted thresholds, leaving them unable to benefit from the warning. There are also concerns with the stereo system and conversation that can occur in the vehicle which could mask the auditory display. When speech is the chosen auditory warning, problems can exist with language barriers.

Visual

Visual warnings may provide the driver with information that cannot be expressed through an auditory or a haptic warning. Though visual warnings may have qualities that capture attention, they are only successful at capturing attention when located near the driver's line of sight, which might not be true for those accidents caused by driver inattention.

The general types of visual warnings are icon and text. Visual icon warnings use familiar symbols, such as a stop sign, to send information to the driver. Text warnings use words, such as STOP, that inform the driver of the required action. Each type of visual warning can be animated to further convey information to the driver. For example, icons can move to depict a crash scene between two vehicles; text can be scrolled or made to flash on a screen. Some parameters associated with visual warnings are choice of color, luminance levels, size, and location.

Icons are one visual method for advising drivers of certain conditions. Icons should be used in place of words only when the icon's meaning is as easily recognizable (Pierowicz, 2000). Situation specific icons should be used due to their higher driver recognition and acceptance levels when conveying safety-related messages (Nakata, Campbell, &

Richman, 2002). Because icons should be understood by all users, international symbols should be used when possible (Green, Levison, Paelke, & Serafin, 1995).

Animations were found to be advantageous when designing graded warnings (General Motors Corp. & Delphi-Delco Electronic Systems, 2002). Icon preference has been found to be age dependent— younger drivers prefer single-stage displays, whereas older drivers prefer multiple-stage displays.

Driver inattention has been found to be a leading cause of intersection violation crashes. While visual displays are good at presenting situation specific information, they may not be good when trying to capture the driver's attention, as the driver's line of site has to include the visual display. Also, since drivers may experience visual overload, the use of visual warnings may become overwhelming.

Haptic

Haptic warnings may combine the best attributes of both visual and auditory warnings. Haptic warnings are easily detectable and are not likely to be masked by other haptic stimuli. They do not rely on line of sight. However, additional research needs to be conducted to make haptic warnings a viable option for in-vehicle use. Haptic feedback uses the sense of touch and pressure on muscles and organs to cue the body. It is also known as tactile, kinesthetic, and proprioceptive feedback. Some forms of haptic warning used for in-vehicle application are steering wheel torque/pulsing, accelerator-push-back, shift stick feedback, seat vibrators/shakers, and brake pulsing. Haptic warnings have the advantage of being easily detected; it is difficult to block out the display. The haptic modality is also a way to capture the driver's attention regardless of where the driver is looking. The studies discussed below have shown promising results for both driver subjective assessments and objective performance in using haptic warnings.

Steering Wheel Feedback

It has been shown that steering wheel feedback is an effective method for transferring information to the driver. Steering wheel haptic feedback can use pulses, torque, or vibration to transmit information to the driver's hand. Steele and Gillespie (2001) conducted a study in a driving simulator in which 22 participants followed a path. Their ability to avoid obstacles and follow the path, as well as their visual demand, was measured. There was a 42% lower visual demand when the drivers were given haptic steering wheel feedback than with no haptic feedback. The error (path deviation) was reduced by 50% when using the haptic feedback. Steele and Gillespie also found no significant difference between the non-haptic trials and haptic trials when participants were asked to perform mathematic calculations verbally. Though there was a reduction in visual load, there was not a reduction in cognitive load.

Other simulator studies have looked into using steering wheel vibration and pulse-like steering torque. Suzuki and Jansson (2003) used auditory and haptic feedback for lane departure warnings. Twenty-four participants were recruited and most had experience with the simulator prior to the study. The study involved presenting the participants with an unexpected warning, either a monaural beep sound, stereo beep sound, steering vibration, or pulse-like steering torque for the first unpredicted trial. Participants were given a secondary task of reading numbers aloud as they were displayed. Suzuki and Jansson reported results for the steering reaction time, maximum lateral deviation, and steering strategies. For the unpredicted trials, they found that the steering wheel vibration and pulse-like steering torque produced less steering reaction time than the auditory warnings, although the auditory warnings were an effective means for reducing steering reaction time during the predicted trials. An interesting finding from the study was the occurrence of inappropriate responses to the steering torque. When the car would deviate, the steering wheel would torque in the direction needed to correct the car position. Instead of steering the wheel in the direction of the torque, participants would steer in the opposite direction tocompensate for the torque, causing the vehicle to deviate more. They found this inappropriate reaction in 50% of participants for the unpredicted trials, and found repeat behavior even after test-trials. No inappropriate reactions were caused by the steering vibration and auditory signals.

Several studies have recommended that steering wheel haptic warnings should only be transmitted when a steering input is desired (Steele & Gillespie, 2001; Suzuki, 2003). Because a pedal input rather than a steering input is required for a driver to stop at an intersection, a steering wheel haptic display was not considered to be applicable for this project.

Accelerator Push-Back

Accelerator push-backs, the use of torque or pulses on the accelerator pedal, have been examined for warning effectiveness. In a simulator study, Janssen and Nilsson (1993) used visual, auditory, and haptic feedback to support their collision avoidance system (CAS). The systems included a red warning light, a warning buzzer, and a smart gas pedal. Each system was coupled with the conditions of a time to collision (TTC) of 4 seconds and worst case criterion, which was when a collision would have occurred if the lead vehicle suddenly braked at 7 m/s (15 mph). They also tested a display that continuously indicated the braking distance required by the driver. The participants were given the task of driving at a speed of 60, 70, 80 or 90 km/h (37, 43, 50, 56 mph), when a lead vehicle would enter the road with 7s between the vehicles. This task was given once without the CAS, and then with the CAS for the second task. The headway, average driving speed, variability speed, and amount of time spent in the left lane were measured. In the TTC<4 criterion, the accelerator push-back gave the largest decrease in headway, while it "did not suffer from counter-productive effects in overall speed, speed irregularity, or driving in the left lane" (Janssen, 1993, p153).

Vibrating Seat

A simulator study conducted by Hoffman, Lee, and Hayes (2003) found that drivers may find haptic warnings more desirable than auditory warnings. The study involved pairing either an auditory warning or a haptic warning, in the form of a vibrating seat, with a visual warning being presented on a high head down display (HHD). The visual warning was presented as either an imminent collision icon or a graded warning in three severity levels represented as bars: negligible, moderate, and severe. Twenty participants were asked to rate the warning presented in each of the four 10 minute driving sessions, after which they ranked the warnings for various criteria. The results indicated significant differences between graded haptic warnings and graded auditory warnings; drivers assessed the haptic warnings as having a larger benefit and as being more trustworthy than auditory warnings. Drivers also found the imminent auditory warnings to be more annoying than both the imminent haptic warning and graded haptic warning.

Brake Pulsing

Brake pulsing is a method of activating and deactivating the brakes in a pattern intended to capture the driver's attention. Some studies have examined the effect of a single brake pulse, while others have explored the effect of multiple pulses on driver performance and acceptance. The development of a brake pulsing haptic warning was part of the intersection collision avoidance (ICA) study performed by Lloyd et al. (1996). Preliminary tests with brake pulsing found a 100ms pulse separated by 100ms or 200ms, with each pulse resulting in a -0.6 m/s (-2.2 kph) velocity change, provided the best driver response. This warning was presented until necessary actions were taken by the driver.

Other studies have emphasized design principles that should be followed when developing brake pulse haptic warnings. The FORWARN Collision Warning System (Landau, 1996; Olney et al., 1996) used the following guidelines:

- Brake pulse should be felt at the same time or after the audio warning is heard
- Brake pulse should not startle the driver because of onset or intensity of deceleration
- Brake pulse should not interfere with the driver's ability to control the vehicle
- Duration of the brake pulse should be approximately 300 msec

Some general guidelines developed by COMSIS (1996) for haptic displays include:

- Warning should be compatible with driver response
- Haptic characteristics should be:
  - Frequency of 100 to 300 Hz
  - Display intensity of 20 to 30 dB above masked vibratory threshold
  - Duration of the display should be as long as needed until the situation no longer exists, or is manually terminated
  - Pulse rate had yet to be determined and was thought to be location and application specific.

Collision avoidance warning systems are being developed as part of the Crash Avoidance Metrics Partnership (CAMP) between General Motors and Ford (Kiefer, 1999). One tested warning was a brake pulse lasting for 600 ms, with a peak deceleration of 0.24g. Based on the six warning combinations tested in a lead vehicle collision avoidance scenario, those receiving brake pulse + high head down visual display + non-speech auditory warning had the second slowest brake reaction time. Kiefer et al. (1999) did not recommend the brake pulse warning due to unresolved implementation and driver behavior issues (e.g., activation on slippery surfaces, driver braking onset delays, and observed foot / body movements).

On-road studies conducted by Tijerina, Johnston, Parmer, Pham, Winterbottom, and Barickman (2000) for rear-end collision avoidance and adaptive cruise control examined two haptic warnings. The first study used mono-pulse braking warnings, which tested three levels of both jerk (0.08g/s, 0.20g/s, and 0.32g/s) and duration (0.25s, 0.65s, and 1.00s). Though the six participants were aware of the true purpose of the study, they were given distraction tasks to be performed while on the test skid track. The participants were instructed to respond to the haptic warning by braking as soon as they felt the pulsing. Several driver responses were recorded, including detection accuracy, accelerator release time, stopping distance (beginning at the onset of the warning), brake stopping distance (beginning with a brake input), and maximum brake pedal force, as well as subjective ratings.

While most missed detections of the haptic system occurred at the lowest jerk and duration, it was found that these missed detections were not because of driver distraction. There was also a trend of greater jerk and longer durations resulting in shorter braking distances and greater brake pedal force. When participants were asked to rate the warnings, the greatest jerk and middle duration received the highest ratings. This study also found a large amount of variability due to participant differences. The values suggested by this study are a jerk of 0.32g/s and duration of 650 ms.

In the same study, Tijerina et al. (2000) also used a haptic steering wheel as a rear-end collision avoidance warning device. The participants were informed to begin braking once they felt the steering wheel vibrate. The authors suggested that steering wheel feedback be used when driver maneuvers, such as a lane departure, are required by the driver. Therefore, only brake pulsing haptic warnings were examined further when introducing a lead vehicle to the study.

A test track study conducted by Pierowicz et al. (2000) developed warnings for intersection collision avoidance (ICA). The project involved developing auditory, visual, and haptic warnings. The system used graphical information system (GIS) and global positioning service (GPS) to determine the intersection location, and then used radar to scan the intersection for other vehicles. Six employees were recruited to participate in the haptic evaluation, which tested two pulse durations (50ms and 100ms) and two pulse separations (50 ms and 100ms) for two intensity values (250 psi and 400 psi). Since the experimenters were more interested in the drivers' subjective evaluations of the warning, they were asked not to brake in response to the haptic warning. The participants were told when to stop and rate the warning. The haptic evaluation was conducted on the Veridian test track where interference with other vehicles would not occur. For both the

250 and 400 psi intensity levels, the more favorable pulse duration- separation was 50ms-100ms (50ms pulse followed by 100 ms off period).

A study conducted by Shutko (2001) examined the effects of three warning conditions on collision avoidance. The three warnings conditions were no warning, auditory icon-tire skid, and one second brake pulsing. There were 49 participants, each of whom received only one warning condition (14 participants received no warning, 15 received the auditory, and 20 received the brake pulse warning). The study was conducted using a commercial motor vehicle with drivers who held a Class A or B license. The participants were told they would be part of a navigational study, as well as a study to evaluate collision avoidance systems (CAS) for another project. After driving practice laps around the track, the driver was instructed to continue around Loop A so they could receive the CAS warnings to rate. Upon completion of the CAS evaluation, the driver was then told the navigational study was about to begin. The participants were given navigational tasks to complete while driving around Loop B of the test track. The navigational tasks were used as a distraction mechanism while the driver approached a trailer where soft barrels were released into their driving path. As the barrels were released, the participants were presented with either an auditory, haptic, or no warning. Videos and sensors were installed in the vehicle to record the drivers' responses.

Shutko (2001) found that the brake-pulse warning resulted in significantly fewer collisions than the no warning condition. Both the auditory and haptic warning resulted in a significantly slower speed than the no warning conditions for those participants who had a collision with the barrels. The brake pulse also resulted in significantly slower collision speed than the auditory warning.

In the study conducted by Shutko (2001), some participants said that they interpreted the haptic warning as indicating a problem with the vehicle, which then resulted in an inappropriate driver response. For example, one driver reacted by pressing the accelerator to free the fuel lines that he perceived to be jammed. Therefore, training must be an important part of any haptic warning system.

The haptic warning can cause some concerns because of its connection to the braking system of the vehicle and the need to train and educate people with such a system (Kiefer, 1999; Shutko, 2001). It is important to eliminate potential problems with the haptic warning, while maximizing driver safety. The driver also needs to be given the ability to override the system when needed.

There are still several concerns that need to be resolved to design a successful and safe haptic braking system. Though previous studies have shown promising results, research still needs to be conducted to refine and optimize the parameters chosen for each type of haptic warning. Some of these parameters include: number of pulses, pulse duration, duration of pulse separation, and velocity change. This thesis explored varying the number of pulses, pulse duration, and velocity change of haptic brake pulse(s). Once a haptic brake pulse candidate was chosen, it wase further examined by combining the brake pulse with a verbal auditory warning.

Multi-modal Warnings

Several warning systems have been designed using multiple modalities to warn the driver. These studies have found multi-modal warning systems to be more advantageous than single mode systems. An auditory or haptic warning can be used to alert the driver, whereas the visual display can transmit specific information to the driver. When using both a visual and auditory display, Belz, Robinson, and Casali (1998; 1999) found the performance of the participants to be better when multiple modalities were used. Lloyd et al. (1996; 1999; 1999) suggest using multiple modalities in attempting to warn all drivers. A person with a hearing disability may benefit by having a visual and haptic display, whereas a person who experiences visual impairments may benefit by having an auditory and haptic display. At least two modalities should be used when warning the driver of an imminent crash (COMSIS, 1996).

When combining warning modalities, each of the modalities should signal the driver at the same time (e.g., the auditory signal and visual signal should be heard and seen at the same time). The urgency of the warning can be expressed through a graded warning for all modalities or increasing the number of modalities used as the urgency increases.

Human Information Processing

When developing in-vehicle warnings, it is important to understand how people process the information they are given. The Communication Human Information Processing (C-HIP) model developed by Wogalter, Dejoy, and Laughery (1999) can be applied to a warning system used in a vehicle (Figure 2).

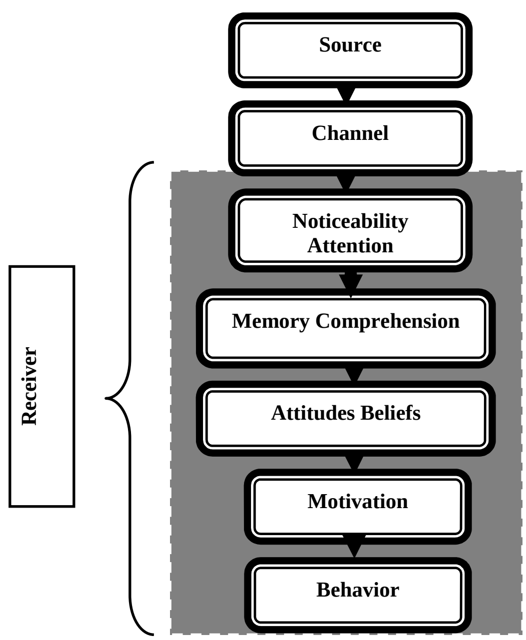


Figure 2: *C-HIP Model*

Note: From Warnings and Risk Communication (pg 17) by M.S. Wogalter, D.M. Dejoy, K.R. Laughery, London, UK: Taylor & Francis, Ltd. Reprinted by permission.

The source is the device on which the warning would be presented to the driver when they are about to violate an intersection. The source (haptic feedback) uses a channel (tactile sensory) to transmit the message to the receiver. The noticeability of and attention to the warning is dependent on each driver. Once they notice the warning, drivers are then able to process the information received by the warning using comprehension, belief and attitudes, motivation, and a final behavior. Each of these factors can provide insight as to why a warning is either successful or unsuccessful.

Signal detection theory (TSD) examines the relationship between the physical stimuli and psychological sensations which are made through absolute, difference, and choice judgments. Using signal detection theory, there are two states and two responses that result in four outcomes when a driver approaches an intersection. The warning state can either be on or off, and the driver can either respond or not respond. A hit occurs when the warning is activated and the driver responds; conversely, a correct rejection occurs when the warning is not activated and the driver does not respond. Each outcome is represented in Figure 3.

		Warning State	
		(Signal) On	(Noise) Off
Driver Response	Yes	Hit	False Alarm
	No	Miss	Correct Rejection

Figure 3: *Signal detection theory: warning state versus driver response*

In the case of a haptic warning, the evidence variable, X (Figure 4), would be the tendency for the driver to stop. The y axis is the probability of a stop occurring. A hit would be when the driver stops in response to a signal or stimuli and a false alarm would be when the driver stops in response to noise. When the signal (or noise) is less than the criterion beta, a miss (or correction rejection) would occur, causing the driver to not stop.

This model (Figure 4) can vary with changing distributions, criterion beta, etc.; for example as the sensitivity (the difference between the means) changes, the distribution of each event would change. With the criterion beta placed at the intersection of two curves of noise and signal, a higher sensitivity would result in fewer misses and false alarms, while a lower sensitivity would result in more misses and false alarms. The ideal warning design would have only hits and correct rejections. An optimal warning design would minimize misses and false alarms.

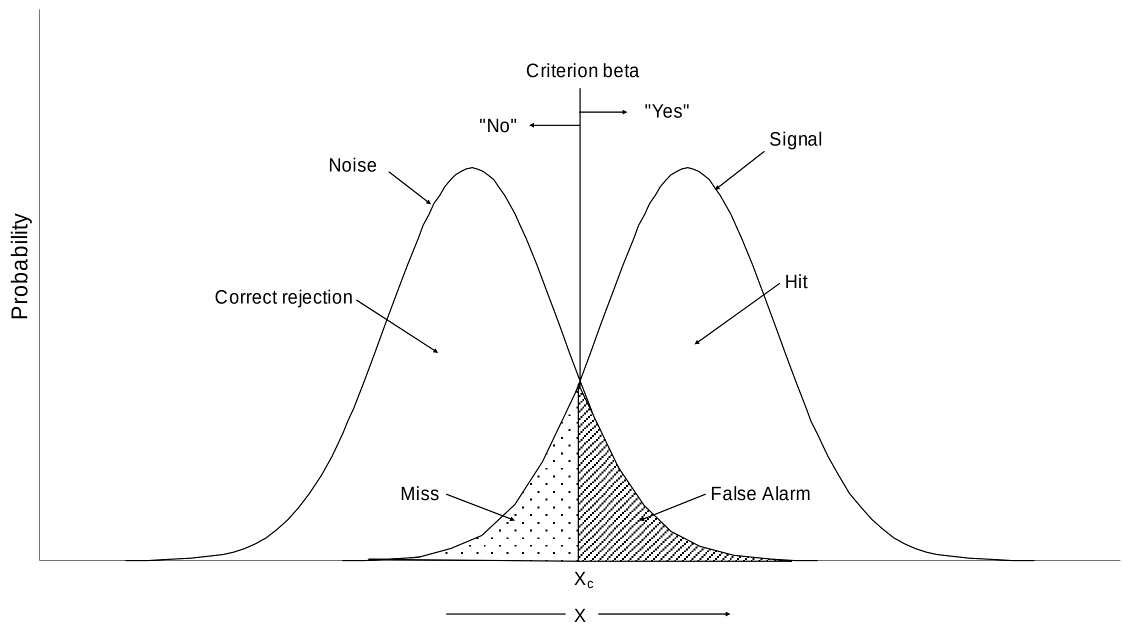


Figure 4: *Signal detection theory: hypothetical distributions*

The response outcome to a stimulus or stimuli can be measured in simple response time, which is the time interval between the stimulus onset and the response. Several factors can influence simple response time, including sensory mode, stimulus intensity, and temporal uncertainty. The auditory sensory mode provides a faster response than the visual mode as does a usually the larger intensity the better and a constant warning interval. In the context of driving a vehicle, there are most always several stimuli requiring different responses such as an intersection to brake for, a lead vehicle braking suddenly, tuning the stereo.

Warning Effectiveness

The DVI has to successfully capture the attention of the driver without startling the driver. Once the driver's attention has been captured, it is important that the correct information be transmitted to the driver. This information might include the location and type of intersection about to be violated, as well as the urgency of the warning. Based on the complexity of the algorithm, the system may also be required to provide an additional warning, depending on the driver's response or lack thereof at the onset of the warning.

The system should not annoy the driver; a key aspect of warning effectiveness is minimizing the number of false alarms. Furthermore, misses should also be minimized to develop driver trust in the system and to improve the safety of the system.

Age

Studies have found age related differences in reaction times to warnings. In an on-road study, Hanowski, Dingus, Gallagher, Kieliszewski, and Neale (1999) examined the effects of in-vehicle information systems on system use, driver behavior, and performance of younger and older drivers. Reaction time was the time elapsed from when the driver noticed the event to when the driver took action, such as braking. The two age groups were 18-25 years old and 65-75 years old. The authors found that older drivers had significantly slower mean reaction times than younger drivers. One explanation is that all of the older drivers wore glasses and bifocals that could have interfered with their ability to notice the display. The older drivers also went off route significantly more often than the younger drivers (older drivers were three times more likely than younger drivers to go off route). When presented with warning information, 90% of the older drivers versus 70% of the younger drivers found nothing about the system to be distracting. When presented with sign or navigation information, 30% of older drivers versus 100% of younger drivers found the system to be distracting. This suggests that older drivers may be less annoyed and more accepting of in-vehicle displays than younger drivers.

It has also been shown that age has an effect on crash risk. Crash statistics have shown that younger (18-25 years old) and older (65+) drivers are more likely than other age groups to be involved in fatal crashes. Preusser et al. (1998) evaluated the relative risk of older age groups using a comparison group of 40-49 year olds. They determined that 65-69 year olds were at a relative risk of 2.16 for intersection crashes. As age increased, so did the relative risk with respect to the 40-49 age group. Older drivers are also more likely to be involved in an intersection crash versus other crash situations. This risk value also increases with age.

Warning effectiveness may be explained by changes that occur with sensory degradation and information processing with age. Verrillo et al. (2002) found age to have an effect on subjective magnitude of vibration. This study confirms the results found previously by Verrillo (1982; 1993), that older participants rated vibration to be significantly less than the younger participants. Verrillo et al (2002) cite Botwinick (1978) as reporting that older participants could not discriminate vibration pulses with separations less than 150ms, while younger participants could resolve pulses at 25ms.

Based on research findings, Sanders and McCormick (1993) summarized the following guidelines when designing for the older population:

1. Strengthen signals displayed to the elderly. Make them louder, brighter, etc.
2. Design controls and displays to reduce irrelevant details that would act as noise.
3. Maintain a high level of conceptual, spatial, and movement compatibility
4. Reduce time-sharing demands.
5. Provide time between the execution of a response and the signal for the next response. Where possible, let the person set the pace of the task.
6. Allow more time and practice to initially learn material.

These guidelines will be considered when designing a haptic warning system for all ages of drivers. The signal strength in the form of velocity change will be varied for the brake pulsing. It would be difficult to reduce the vibration created by the road that could act as noise. The brake pulsing will hopefully act as a movement compatibility for the drivers.

Training and practice may be an important component of using haptic feedback as an intersection collision warning.

Driver Response Measures

Brake reaction time, measured as the time from stimuli onset to point of braking, includes both perception time and movement time. Because perception time is impossible to determine, the brake reaction time includes both the perception and movement time. It is important to optimize warnings to elicit the shortest brake reaction time, especially for those situations that require braking or stopping in order to avoid a crash or traffic. Green (2000) found a range of brake reaction times from 0.605 to 1.4 s for studies that involved *unexpected* trials. While defined as unexpected, Green lists many factors that can heighten the participants' expectations, including the expectation of a light to change. Results were mixed when examining the effects of age on reaction times. Green suggests it is difficult to attribute a brake response time difference to age alone, and proposes that many other factors can effect the brake response time.

A study conducted by Laundau (1996) for the FOREWARN Collision Warning System had drivers brake for both non-emergency and emergency scenarios for speeds of 15, 25, 35, and 45 mph. Drivers were willing to brake with larger decelerations as the vehicle approach speed increased. For the 35mph non-emergency and emergency trials, the average deceleration was -0.20g's and -0.24g's respectively. A second study determined an average brake response time of 0.875 s.

Warshawsky-Livne and Shinar (2002) conducted a simulator study that determined the effects of uncertainty, transmission type, driver age, and gender on brake reaction and movement time. The participants were instructed to respond to brake lights presented at different uncertainty levels: 2 s intervals, varying intervals of 2s-10s, and varying intervals with blanks. Reaction time was defined as the time from the onset of the light to the point of accelerator release and movement time was defined as the time from the accelerator to the brake pedal. They found that reaction time increased with age; the 25 and younger group had a mean reaction time of 0.35s, the 26-49 age group had a mean reaction time of 0.39 s, and the 50 and greater group had a mean reaction time of 0.43 s. The difference between the youngest and oldest age groups was significant. There was also significant difference between genders for movement times; females on average had a movement time of 0.16 s while males had an average movement time of 0.19 s.

Warning Timing

False Positives

False positives involve the warning activating at inappropriate or incorrect times. Lerner et al. (1996) examined the effects of inappropriate alarm rates on driver annoyance. They looked at four different inappropriate alarm rates; four inappropriate alarms per hour of driving, one inappropriate alarm per hour, one inappropriate alarm per four hours, and one inappropriate alarm per eight hours. Participants rated the warnings to have a 6.7 and 6.6 noticeability on a scale of 1 to 9 (with 1 being barely noticeable and 9 being very noticeable) for their daily and weekly responses, respectively. While driver annoyance did increase as the frequency of inappropriate alarms increased, there was a negative correlation between the driver annoyance and driver acceptance of a vehicle equipped with such a warning system.

The rear-end collision study conducted by Tijerina et al. (2000) also examined the effects of false-positive warnings on the driver. The false-positive trials occured when the warning system was activated even though the lead vehicle was not slowing down. When receiving a false positive, drivers perceived their braking to be harder than in the true positive cases. The subjective responses suggested that drivers perceived the haptic warning to be more intrusive when the false positives were introduced.

Bliss and Acton (2003) studied the effects of alarm reliability on driver responses. They tested 50%, 75%, and 100% reliability (false positive rates of 50%, 25%, and 0%, respectively). While driving in a simulator, participants were given an auditory warning indicating an approaching vehicle and were instructed to swerve to avoid the vehicle.

While the alarm reliability had no effect on the reaction time, it did affect whether or not the participants swerved correctly. There was a significant difference between the 100% reliability and each of the other reliability levels. Interestingly, participants had significantly fewer crashes with the 50% reliability than with the 100% reliability. Bliss and Acton suspected that participants were more aware in the 50% reliability trials. They implied that while alarms may provoke *quick* responses, more focus should be given to provoking the *correct* response from drivers.

Alarm Annoyance

An important component of designing in-vehicle warnings is minimizing alarm annoyance which can affect driver acceptance. Because alarm annoyance is highly dependent on the individual, it is a difficult human factors concept to include in a design. Alarm annoyance becomes greater as the number of false alarms increase. Lerner at al. (1996) found the drivers perceived the warnings to be more annoying as the frequency of false alarms increased.

Behavioral Adaptation

Researchers are aware of behavioral adaptation that occurs when drivers become over-reliant on a warning system. Behavioral effects for a CAS were examined by Janssen and Nilsson (1993). They found that as overall driving speed increased, acceleration and deceleration levels increased. It was hypothesized that the driver's increase in speed could indicate trust in the warning system. There was also an increase in the time spent in the left lane, which was explained by the driver wanting to reduce the likelihood of the CAS being activated by following another driver. They found the fewest behavioral effects (counter-productive effects in overall speed, speed irregularity, and driving in left lane) with the time to collision display + accelerator push-back pedal warning condition.

Trimpop (1996) introduced risk homeostasis theory, which is the compensation between the perceived risk and the desired risk for a specific situation. It is believed that people can begin to rely on systems to provide the warning needed in risky situations. In the case of the intersection warning system, drivers may become over-reliant and wait for a system to warn them before they begin braking. This could be dangerous when these over-reliant drivers in a situation where the system fails to warn them, causing them to violate the intersection, or brake hard at the last second, possibly causing a crash.

Human Factors Guidelines

Table 1 is a summary of the guidelines for haptic warnings and haptic warning characteristics discussed in the literature review.

Table 1: *Recommended guidelines for haptic warnings and warning characteristics.*

System	*Guidelines*
Haptic Warnings	Steering wheel feedback should be used when a steering maneuver is required from the driver
FORWARN CWS	Brake pulse should not startle driver because of onset or intensity of deceleration
	Brake pulse should not interfere with the driver's ability to control the vehicle
COMSIS	Duration of the display should be as long as needed, until the situation no longer exists, or is manually terminated
Warning Characteristics	***Parameters***
Lloyd (1996)	100ms pulse, 100ms or 200ms pulse separation, -0.6m/s
FORWARN (1996)	300ms pulse separation
COMSIS (1996)	100-300Hz frequency, 20-30dB above masked vibratory threshold
Kiefer et al. (1999)	600ms pulse duration, 1 pulse, -0.24 g peak deceleration
Tijerina (2000)	0.32g/s jerk, 0.65 pulse duration-separation

Conclusions

Studies have found in-vehicle warnings to be advantageous, though concerns have been introduced for each modality (visual, auditory, and haptic). Auditory warnings present problems with those people with hearing abilities or language barriers. Visual warnings do not possess the attention-capturing qualities of auditory and haptic warnings. They also present the problem of visually overwhelming the driver. Haptic warnings have been shown to be a viable in-vehicle option to warn drivers of impending situations. As with auditory and visual warnings, the warning effectiveness of haptic warnings should also be examined to determine the optimal settings.

Research Approach

These studies were conducted in two phases to most effectively and efficiently determine the optimal parameters. Phase 1 consisted of 41 participants who evaluated various brake pulse parameters. The results from phase 1 were used in phase 2 to reevaluate the haptic warnings combined with an auditory warning. Research questions 1 and 2 and research goals 1 and 2 were addressed by the first phase of this study, while question 3 was further explored in phase 2. The results of both phases were then used to address research goal 3. Both phases are further explained in the following methods section.

Hypotheses

1. Which brake pulse candidate results in the fastest reaction time and largest deceleration values?

   The 600ms duration, 3 pulses condition will result in the fastest reaction time and largest deceleration. The larger deceleration will be in part because of the deceleration caused by the brake pulse warning.

2. What are the response differences between age groups?

   Older drivers will have a longer reaction time than younger drivers, due to sensory degradation. Warshawsky-Livne and Shinar (2002) and Hanowski et al. (1999) found that reaction time increased with age; older drivers had significantly larger reaction times than younger drivers.

3. Will having both a brake pulse and auditory warning result in a shorter response time than a brake pulse alone?

   Drivers will have a shorter reaction time when both the haptic and auditory warning is activated than with just the haptic warning. Belz et al. (1998, 1999) found that performance measures improved when auditory and visual warnings were combined.

CHAPTER 3 PHASE I: BRAKE PULSE WARNING CANDIDATE

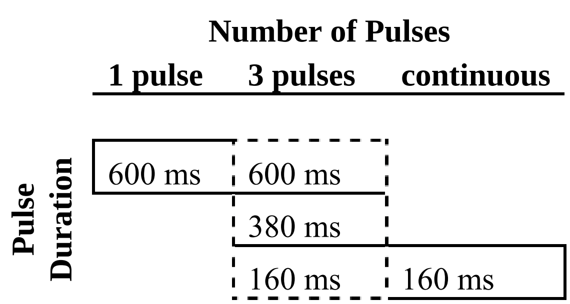
Method

Experimental Design

A partial-factorial design was used for Phase I (Table 2). Five different brake pulse conditions were used; these varied in the number of pulses and in the pulse duration. Conditions included: a single 600 ms pulse, three 600 ms pulses, three 380 ms pulses, three 160 ms pulses, and continuous 160 ms pulses. Each pulse was separated by a 100 ms off period. These pulse patterns were selected based on a combination of previous research, system constraints, and engineering judgment. The single 600 ms pulse group experienced a jerk of 12 g/s, while the remaining four groups experienced a jerk of 3 g/s. All haptic brake pulses reached an average deceleration of 0.3 g. Several objective measures were recorded for each haptic condition, including response time (measured from the onset of warning), deceleration values, and distance to stop bar. Subjective measures were also collected regarding the likeability, annoyance, trustworthiness, and perceived reliability of the warnings. The purpose of Phase I was to evaluate the effectiveness of each brake pulse warning condition and to determine a candidate to be combined with an auditory warning for Phase II.

Table 2: *Phase I experimental design*

Haptic Brake Pulse Conditions				Age	
Condition Number	**Jerk**	**Pulse Duration**	**Number of Pulses**	**Young**	**Old**
1	12 g/s	600 ms	1 pulse	S1-4	S5-8
2	3 g/s	600 ms	3 pulses	S9-12	S13-16
3		380 ms	3 pulses	S17-20	S21-24
4		160 ms	3 pulses	S25-28	S29-32
5		160 ms	continuous	S33-36	S37-40



Independent Variables

The independent variables were the jerk, pulse duration, and number of pulses. There was also an age factor that examined response differences between older and younger participants.

Controlled Variables

A speed of 56.3 kph (35 mph) was used for all participants. The warning algorithm used to determine warning location is discussed in the Warning Algorithm section of this chapter. Previous phases of the overall research project used a speed of 56.3 kph (35mph). The same speed was used for this phase so that the results could be compared to baseline data from the previous phases of the Intersection Collision Avoidance Violation Warning project (ICAV). There were an equal number of males and females for most conditions, with an extra younger male in Condition 4.

Dependent Variables

This study examined both the objective driving performance of the drivers and their subjective responses based on questionnaires administered during the study. The driving performance measures were recorded by the ICAV laptop inside the vehicle. Braking performance was recorded by the Data Acquisition System 2 (DAS2) connected to a gyroscope accelerometer.

Objective Measures

Several response variables were recorded during the test. These measures were recorded by in-vehicle sensors designed to capture driver inputs. The following measures were captured in the data stream:

- Braking intensity, measured from the time when the participant received the warning until the time they stopped, or 100 feet past the stop bar if they did not stop.
    - *Peak deceleration* (acceleration, g): the largest G-force recorded during the intersection approach.
    - *Time weighted deceleration* (acceleration, g): the average deceleration measured over the time from the onset of the warning until the participant stopped.
- Did they stop? (Yes/No)
    - Yes
        - Before Stop Bar
        - After Stop Bar
    - No
- Reaction Time (seconds) (see Figure 5)
    - *Time to Accelerator Release (TAR)*: time from the onset of the warning until the accelerator was released
    - *Time to Brake (ReactionTime,TB)*: time from the onset of the warning until the brake pedal was depressed 5%
    - *Time to Peak Brake (TPB)*: time from the onset of the warning until the brake pedal was fully depressed

- *Time from Brake to Peak Brake (TBPB) = TPB-TB*: time to peak brake minus the time to brake
- *Time for transition of accelerator release to the time to brake (ABT) = TB-TAR*: time to accelerator release minus the time to brake; this was a possible indicator of hesitation on the part of the participant.

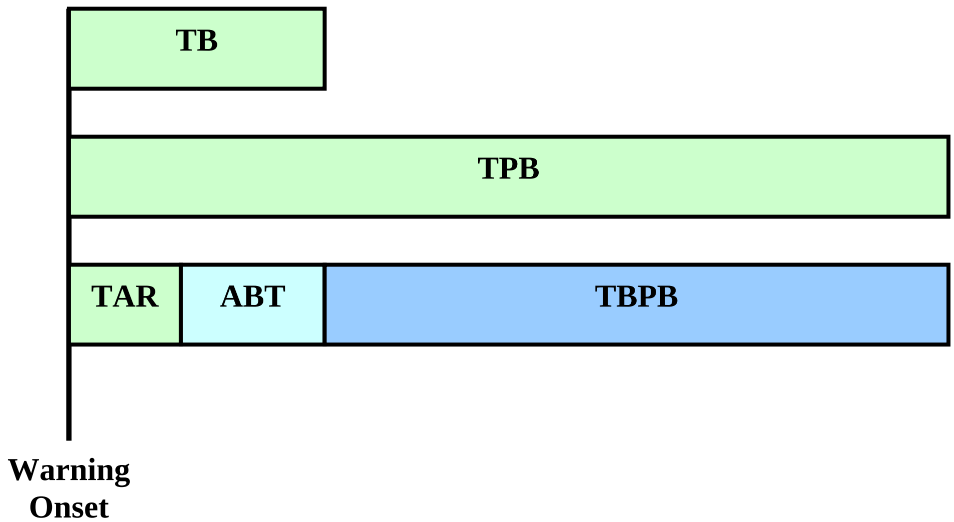


Figure 5: *Reaction time components*

- Calculated Variables
  - *Required Deceleration (RDP)*: the deceleration required to stop at the stop bar from the time to brake.

$$a = \frac{V^2}{2 \times g \times D_i}$$

where, a = constant deceleration as a proportion of g
V = vehicle speed at the point when driver initiated braking (m/s)
g = gravitational acceleration constant (9.81 m/s^2)
D_i = Distance to intersection when driver initiated braking (m)

  - *Speed Differential*: the speed difference over the duration of the warning; speed at warning onset minus speed at time to brake.

Subjective Measures

After receiving the initial warning, a retrospective interview was conducted with the participants. The purpose of the interview was to elicit any information from the participant about what they had experienced during the surprise trial. Participants then completed a post-event questionnaire. The participants also completed four additional evaluative trials and answered a short questionnaire after each additional trial.

Participant Population

There were a total of 69 participants in the first phase, 45 of whom produced usable data and four of whom were pilot participants. The participants' mean ages for the age and age by gender factor are given in Table 3.

Table 3: *Phase I mean ages*

	Mean Age (yrs)	St. Dev	N
Older	61.3	7.4	21
Younger	22.2	3.7	20
Older Females	58.2	7.6	10
Older Males	64.4	6.0	10
Younger Females	23.6	4.0	10
Younger Males	20.9	3.1	11

Those participants whose data were not useable can be categorized into three groups: system errors (problems with software/hardware), experimenter errors (not advancing to correct trial number, brake pump not activated), and inappropriate driver response (foot off accelerator at time of warning or foot on brake, thus no warning activated).

Each participant received one surprise trial and then four informed trials (each of four conditions), resulting in five exposures. Each haptic warning condition had at least eight participants. The age criterion for the younger population was 18 to 30 years old, while 50+ years old was used for the older population. These age groups were chosen because they exhibit the highest risk for crashes and intersection violations (Preusser et al., (1998) and because baseline data were available for the same age groups. Participants were recruited using flyers and from the Virginia Tech Transportation Institute database of potential research volunteers.

Equipment

The vehicle used for this study was a 2000 Chevrolet Impala (Figure 6) which was modified to fit the specifications for this project.

Figure 6: *2000 Chevrolet Impala*

The research vehicle was equipped with sensors to measure driver inputs (e.g., acceleration and braking) and car performance (e.g., acceleration and velocity). The research vehicle also had a differential global positioning system (DGPS) to identify the location of the research vehicle on the Smart Road. A data acquisition system was installed to record driver performance values. The data acquisition system included four video cameras to provide a quad split display of the front view, driver's face, driver's feet, and driver from his/her right side (Figure 7).

Figure 7: *Video capture*

Top left: face view, top right: front view, bottom left: driver's feet, bottom right: driver's side

Three computer systems were installed in the vehicle; the first one is referred to as the 100Car system, the second is referred to as the ICAV system, and the third one as the DAQ system. Two of the three systems are shown in Figure 8. The 100Car system was responsible for gathering information from vehicle sensors, while the ICAV system was responsible for receiving DGPS data and wirelessly communicating with the intersection; it also served as the human interface with the software (Figure 9) required for specification inputs. The DAQ system, located in the back seat area, consisted of data acquisition hardware with sensor inputs from the haptic pump system and a gyroscope. The data acquisition hardware transmitted data at 100Hz to a laptop that collected information about the driver's stopping performance.

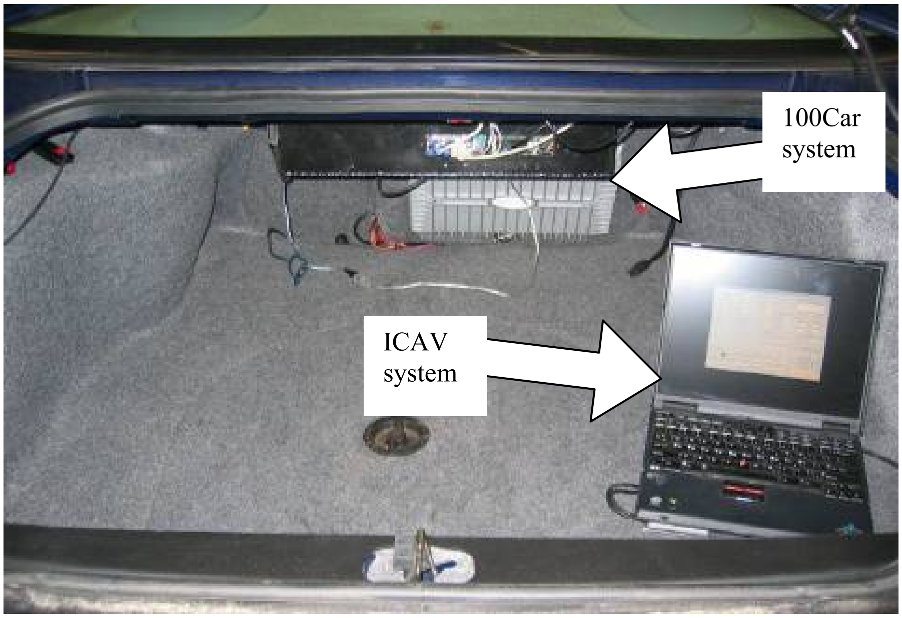


Figure 8: *Data Acquisition System*

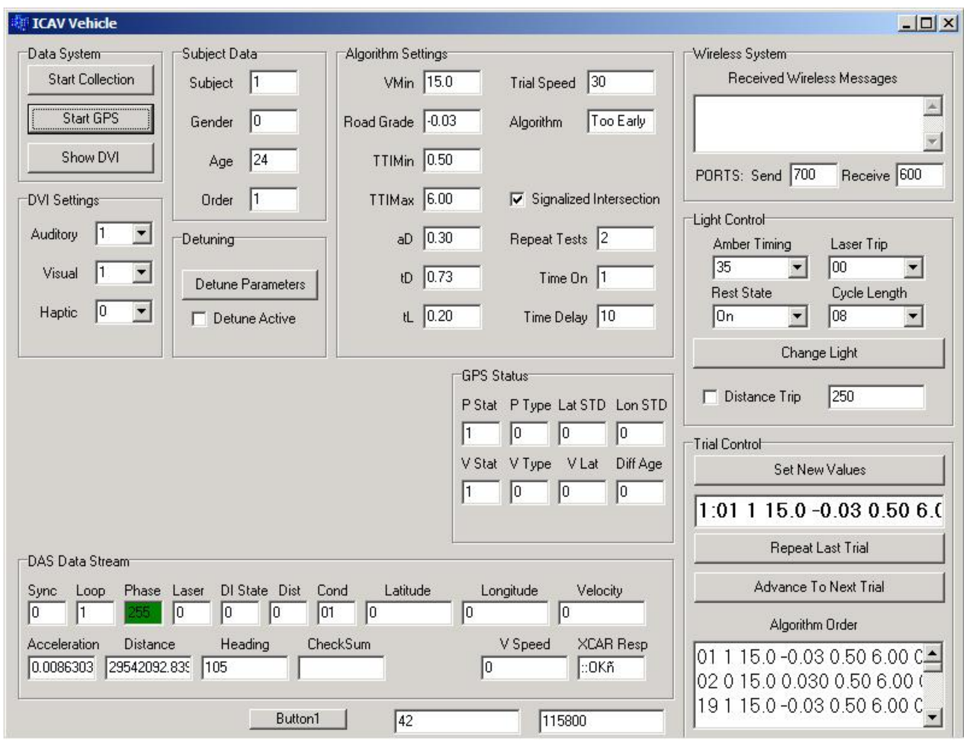


Figure 9: *ICAV software*

Haptic Technologies

A new braking system was developed in-house by the Hardware Engineering Laboratory (HEL) group at VTTI. The system was designed to work independently of the current brakes in the vehicle. The DAQ controlled the brake pulsing technology. It communicated with the ICAV laptop (which served as the user interface) and received information on the acceleration, speed pulse, pump pressure, and brake pressure. The DAQ then sent a signal to the valve controller, which was responsible for converting the signal from digital to analog. The analog signal then continued to the valve that controlled the amount of hydraulic fluid sent to the brake, ultimately controlling the braking intensity. There was also a relay signal sent to the pump controlling when and for how long the brakes activated. The brake system could be deactivated at any time by an emergency kill switch next to the front seat experimenter. The system was also deactivated if the signal from the DAQ to the braking system was lost or if the participant braked. The system was activated and deactivated by the ICAV laptop.

Warning Algorithm

The warning was activated at the point requiring a 0.37g deceleration to stop at the stop bar, which at a speed of 56 kph (35mph) was 41.1 meters (135 feet). Previous parts of the ICAV project had presented both auditory/visual warnings and baseline conditions at this distance, which had been shown to be an optimal warning distance for a verbal auditory and visual DVI.

Experimental Procedures

The experimental procedure was the same for each participant, except for the between subjects surprise haptic condition and the order of the additional informed trials. On initial contact (most often over the phone), participants were screened to ensure they were eligible for the study (Appendix B). They were then scheduled for an available time to meet the experimenter at VTTI.

In order to gain information on how people initially react to warnings, a mild form of deception was used in this study. Participants were first given an informed consent that explained that they would be involved in a study to evaluate occlusion goggles as a method for simulating driver distraction. After agreeing to the study and signing the informed consent (Appendix A), a health screening (Appendix C) was conducted to ensure that participants did not have any conditions that would impair their ability to safely operate the test vehicle. A Snellen vision test was conducted to make sure their visual abilities were within legal limits for Virginia of 20/40 or better. Their color vision was also tested and recorded, but not used to exclude participants from the study. If it was found that the participant was not in good health or their vision results fell outside the tolerable limits, they were excused from the study and paid for their time.

After administering the informed consent and vision tests, the participant was led to the vehicle and given time to make the necessary adjustments to the seat, mirrors, and climate control. They were then instructed to drive towards the Smart Road, where the study was conducted. Once on the Smart Road, participants were asked to stop, at which point they were given further instructions on the purpose of the study. At this time, the occlusion goggles were demonstrated to the participant while the car was still parked. They were told that the goggles would occlude their vision for 2 s at random intervals, during which time information would be recorded on their speed maintenance and lane position accuracy. They were asked to place the car in 3rd gear and maintain 35 mph through the entire study. Participants then began driving when they felt comfortable.

On the first drive down the Smart Road, there was a confederate vehicle (Primary Other Vehicle- POV) parked on a road parallel to the Smart Road. The driver of the POV, who was really an on-road experimenter, appeared to be working on a rain making tower. After the subject vehicle (SV) circled through the lower turn-around and approached the intersection for the second time, the POV drove to the adjacent stop bar where it appeared that the light signal was triggered by the vehicle, though the signal was really being controlled by the Back Seat Experimenter (BSE). The participant then received a red light while the POV crossed and exited the road. The participant then continued to drive up and down the road, while being occluded at random intervals. On the SV's 6th

intersection approach, the POV reentered the road from the opposite direction of the first crossing. When the SV continued to the lower turn-around, the POV inconspicuously exited the road. On the SV's 10^{th} intersection approach, a second confederate vehicle (Following Vehicle- FV) followed the SV up the road after a brief radio conversation asking permission to do so. As the participant neared the intersection, their vision was occluded while the light was still green. During the occlusion, the light changed to the amber phase; their vision was then unoccluded as they simultaneously received the haptic warning for the first time.

It was important to the have the POV and the FV in the experimental scenario to simulate real-world traffic. The purpose of the POV was to heighten the participants' awareness of the possibility of a vehicle crossing the intersection, while in fact there was no crossing traffic during the surprise trial. The adjacent traffic was blocked by a large van so the participant could not see whether or not crossing traffic was approaching. The FV was required to create a real-world situation in which a driver's decision to brake hard could be tempered by the presence of a following vehicle (and thus the possibility of a rear-end crash). It was hoped that this scenario would provoke a more realistic braking response from the driver.

After the surprise trial, the participant was given a retrospective interview (Appendix D) to determine what they experienced during their intersection approach. They were then given an additional questionnaire with an explanation of the true purpose of the study and asked to rate the warning (Appendix D). A debriefing form and new informed consent (Appendix A) was then given to the participants to read and sign. They then continued for four additional trials which were counterbalanced across conditions (Table 4), during which they evaluated the other haptic warnings. The experiment then concluded and the participant was asked to drive back to the building to finish the paperwork. The task numbers and warning conditions are presented in Table 5.

Table 4: *Additional trials counterbalance*

		Order			
		1	2	3	4
Downhill	**T11**	A_1	A_2	A_3	A_4
Uphill	**T12**	A_2	A_3	A_4	A_1
Downhill	**T13**	A_4	A_1	A_2	A_3
Uphill	**T14**	A_3	A_4	A_1	A_2

Table 5: *Participant surprise and order numbering*

Participant Number	Age	Gender	Surprise Condition	Order	Order Number
1, 2	Younger	Male	1	1, 2	21, 22
3, 4	Younger	Female		3, 4	23, 24
5, 6	Older	Female		1, 2	21, 22
7, 8	Older	Male		3, 4	23, 24
9, 10	Younger	Male	2	1, 2	25, 26
11, 12	Younger	Female		3, 4	27, 28
13, 14	Older	Female		1, 2	25, 26
15, 16	Older	Male		3, 4	27, 28
17, 18	Younger	Male	3	1, 2	29, 30
19, 20	Younger	Female		3, 4	31, 32
21, 22	Older	Female		1, 2	29, 30
23, 24	Older	Male		3, 4	31, 32
25, 26	Younger	Male	4	1, 2	33, 34
27, 28	Younger	Female		3, 4	35, 36
29, 30	Older	Female		1, 2	33, 34
31, 32	Older	Male		3, 4	35, 36
33, 34	Younger	Male	5	1, 2	37, 38
35, 36	Younger	Female		3, 4	39, 40
37, 38	Older	Female		1, 2	37, 38
39, 40	Older	Male		3, 4	39, 40

Pilot Testing

Extensive testing was required to determine the values needed to achieve a jerk of 3g/s, with a peak deceleration of 0.3gs. Testing was conducted with Human Factors Experts to tune the system to predetermined specifications. After the system was set to specifications, five pilot participants were used to determine if further testing would be needed. The five pilot participants were given the first brake pulse condition of 600ms, 1 pulse. Four out of the five pilots did stop when receiving the haptic warning at the intersection.

Data Analysis

The data output from the vehicle was in the form of a text file providing information about each trial. The only extensive data reduction required was categorically organizing the data based on the dependent variables of the participant stop. A MATLAB program was used to reduce the data to determine reaction times and distances with respect to the warning location, and also to calculate the deceleration values. Once the output files were cleaned up, descriptive statistics were performed in Excel, and then further analyzed using Statistical Analysis Software (SAS). Participant demographic information was associated with each output text file and included in the analysis.

The objective data consisted of both nominal data and response variable data. The nominal data were split into those who stopped and those who did not stop. Those participants who stopped were placed into one of two categories: before the stop bar and after the stop bar. The response variables included several types of reaction time, deceleration values, and a distance to stop bar, along with calculated variables. The subjective data included a retrospective interview and a post-event questionnaire for each of the times a warning was given, both for the surprise and additional evaluative trials.

Analysis of variance was used to test for significant differences between all haptic conditions. A Tukey-Kramer post hoc test was used to define these significant differences. Additional analyses tested for differences between the combined haptic warning conditions, the baseline (no warning) condition, and an auditory plus visual warning condition. Odds ratios were used to analyze the nominal data of stopped versus did not stop trials. ANOVAs and Tukey-Kramer post hoc tests were also run with the subjective data to determine differences between the haptic conditions. A content analysis was performed with the open ended responses from the participants.

Results

Phase I results are organized as follows: (1) comparison of the haptic brake pulse conditions, (2) comparison of the haptic warnings to the baseline condition (no warning), (3) comparison of the haptic warnings to the auditory + visual warning and (4) did not stop group, and (5) subjective analyses. The following research questions (RQ) and research goals (RG) are addressed.

RQ1. Which brake pulse candidate results in the fastest reaction time and largest deceleration values?

This research question is addressed in section 1 of the results comparing the differences in the haptic brake pulse conditions. Sections 2 and 3 of the results are supporting analyses, which compared the effectiveness of haptic warnings versus no warnings and auditory and visual warnings.

RQ2. What are the response differences between age groups?

This research question is addressed in section 1 of the results; for those variables with no significant differences between haptic brake pulse conditions, ANOVAs were conducted to test for differences attributed to age, gender, and age by gender interactions.

RG1. Determine the correlation between objective and subjective responses to haptic brake pulses.

This research goal is addressed in section 5 of the results. Pearson correlations were conducted between the subjective and objective measures.

RG2. Determine driver perception of haptic warnings.

This is addressed in the content analysis. The content analysis is split into the retrospective interview and the open-ended written responses. Codes were created to summarize all responses.

The dependent variables (Table 6) recorded for each participant were separated into components of reaction time, including time to accelerator release, time to brake, and time to peak brake; movement times, including time from brake to peak brake and time from accelerator release to brake press; deceleration values, which included peak deceleration and time-weighted average deceleration; distance to stop bar; and two calculated variables (deceleration required to stop by stop bar and speed differential over warning duration). The subjective responses are discussed at the end of the results.

Table 6: *Dependent measure identification and definitions*

	Dependent Measure	*Variable Name*
	Reaction Times- Measured from the onset of warning (time, s)	
1	Time to Accelerator Release	TAR
2	Time to Brake	ReactionTime, TB
3	Time to Peak Brake	TPB
	Movement Times (time, s)	
4	Time from Brake to Peak Brake	TBPB
5	Time from Accelerator to Brake Pedal	ABT
	Deceleration Values- Measured over duration of stop (acceleration, g)	
6	Peak Deceleration	MaxDecel
7	Time Weighted Deceleration	AvgDecel
	Distance to Stop Bar- Measured where participant stops (distance, feet)	
8	Distance to Stop Bar- Negative Number- beyond stop bar, Positive Number- before stop bar	DistanceBSB
	Calculated Variables	
9	Required Deceleration- Deceleration required to stop at stop bar based on time to brake (acceleration, g)	RDP
10	Speed Differential- Measured speed change over duration of warning (speed, mph)	SpeedDifferential

An important measure of warning effectiveness was the number of people who complied with the warning and stopped for the red light. The distribution of those who did not stop and those who did stop are reported in Table 7 for each haptic brake pulse, baseline, and auditory + visual warning condition.

Table 7: *Frequency table of stop versus did not stop for each condition*

		Did Not Stop	Stopped	Total
Haptic Brake Pulse Conditions	**600ms, 1 pulse**	1	7	**8**
	600ms, 3 pulses	0	9	**9**
	380ms, 3 pulses	2	6	**8**
	160ms, 3 pulse	0	8	**8**
	160ms, continuous pulses	0	8	**8**
	All Haptic	**3**	**38**	**41**
	Baseline	12	4	**16**
	Auditory ("Stop") + Visual	0	16	**16**
	Auditory (CAMP) + Visual	10	6	**16**

The odds ratios in Table 8 illustrate that those participants who received the haptic brake pulse warnings were 38 times more likely to stop than those participants who received no warning and 7.6 times more likely to stop than those receiving the auditory (CAMP) + visual warning. Those receiving the "Stop" auditory + visual warning are 3 times more likely to stop than those receiving the haptic warning.

Table 8: *Odds ratios of haptic condition in comparison to other conditions*

	Did Not Stop	Stopped	Did Not Stop : Stop		Odds Ratio
Baseline	12	4	3.00	**Haptic: Baseline**	38.0
All Haptic	3	38	0.08	**Haptic : CAMP**	7.6
Aud ("Stop") + Visual	0	16		**"Stop" : Haptic**	3*
Aud (CAMP) + Visual	6	10	1.67		

*correctional value of 0.5 used in cells containing zero.

1) Haptic Brake Pulse Conditions

An analysis of variance (ANOVA) was conducted to detect differences between haptic brake pulse conditions; where no significant differences were found between the conditions, ANOVAs were conducted to test the effects of age, gender, and the age X gender interaction on the dependent variables. The criterion for significance between haptic brake pulse conditions was p-value<0.10, while all other analysis used a criteria of p<0.05. An alpha level of 0.10 was chosen to test for significance between haptic brake pulse conditions due to the exploratory nature of the first phase of this research.

Reaction and Movement Times

No significant differences were found between the haptic brake pulse conditions for the reaction and movement times. ANOVAs were then used to determine differences due to age, gender, and the age X gender interaction for the reaction and movement times. Older participants had a slightly higher time to accelerator release than the younger drivers ($F[1, 34]= 3.65$, $p=0.065$) (Older: $M = 0.35$ s, $SD = 0.15$; Younger: $M = 0.28$ s, $SD = 0.07$). Older drivers also had a significantly higher time to brake ($F[1, 34]=6.60$, $p=0.015$) than younger drivers (Older: $M = 0.88$ s, $SD = 0.31$; Younger: $M = 0.69$ s, $SD = 0.12$).

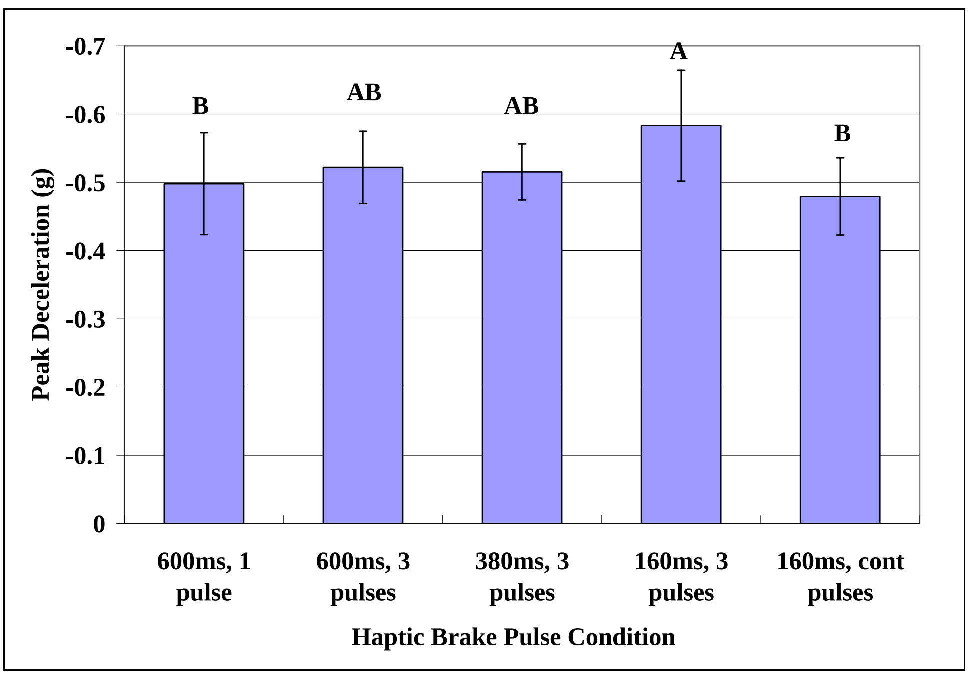
Deceleration Values

Significant differences between haptic brake pulse conditions for deceleration values are reported in Table 9. There were significant differences between haptic conditions with respect to peak deceleration ($F[4, 33]= 3.03$, $p=0.031$). The *post hoc* test found that those receiving the 160ms-three pulses condition had a significantly higher peak deceleration than those receiving the 160ms-continuous pulses and the 600ms-1 pulse conditions (Figure 10).

Table 9: *Deceleration measures between haptic conditions*

	Source (p-value)
Dependent Variable	**Haptic Condition**
MaxDecel	0.031*
AvgDecel	0.039*

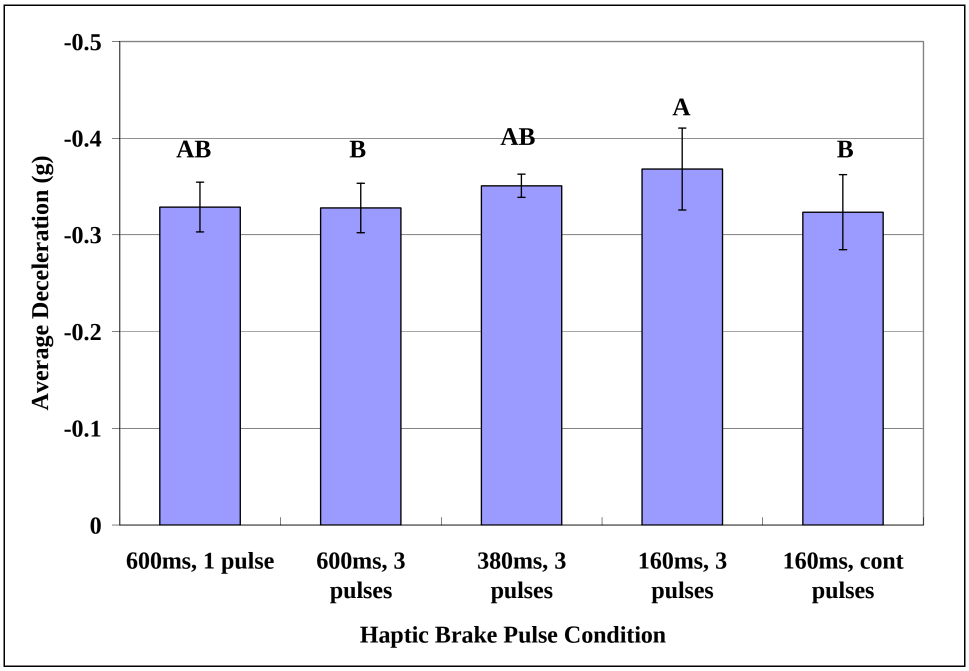
**post hoc* test conducted



Note: Conditions with no letters in common are significantly different from one another.

Figure 10: *Peak deceleration per condition mean and SD*

There were also significant differences between the haptic conditions with respect to average deceleration ($F[4, 33]=2.80$, $p=0.039$). The post hoc test found the 160ms-three pulses condition to have a significantly higher average deceleration than the 600ms-3 pulses and the 160ms-continuous pulses conditions (Figure 11).



Note: Conditions with no letters in common are significantly different from one another.

Figure 11: *Average deceleration per condition mean and SD*

The data were collapsed across haptic conditions to check for significant differences due to age, gender, and age by gender. Older drivers had a significantly higher peak deceleration than younger drivers ($F[1,34]=4.82$, $p=0.035$) (Older: M = -0.55 g, SD = 0.07; Younger: M = -0.50 g, SD = 0.07). It is important to note that any significant differences could have been influenced by the haptic condition, though there was not enough power to test for this.

Distance Beyond Stop Bar

There were no significant differences between the haptic conditions with respect to distance to stop bar. The data were collapsed to check for significant differences due to age, gender, and the age by gender interaction. There was an age by gender interaction for distance beyond stop bar (F[1,34]=5.28, $p=0.028$). The older males stopped significantly further into the intersection than older females (Older males: M = -2.74 m, *SD* = 2.84; Older females: *M* = -0.20 m, *SD* = 2.43). A scatter plot of stopping location for age by gender is illustrated in Figure 12 and the age by gender interaction is shown in Figure 13.

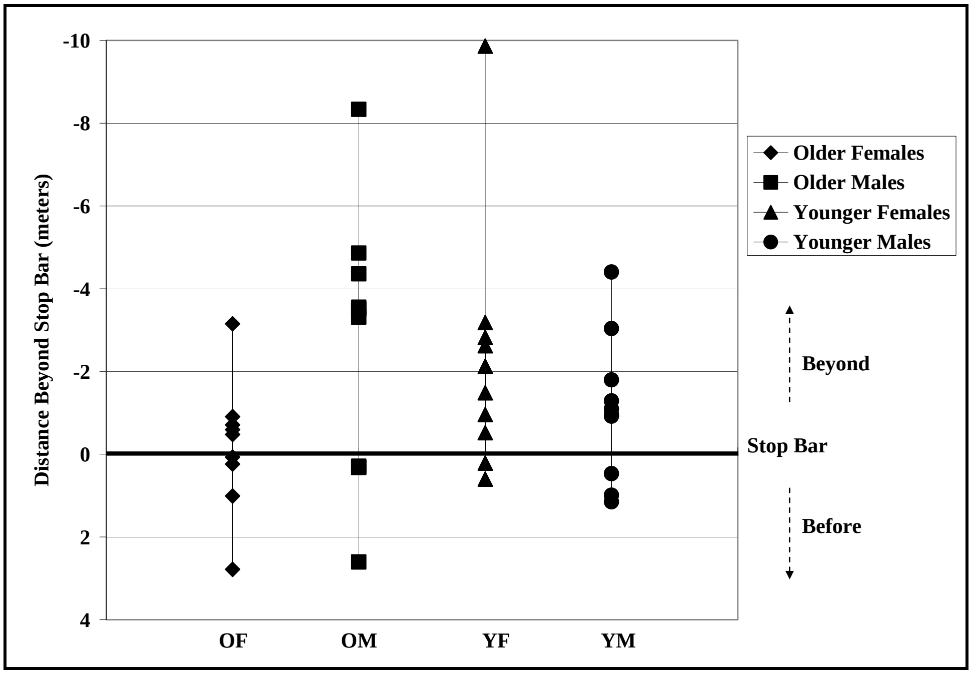


Figure 12: *Age X Gender stopping location scatter plot*

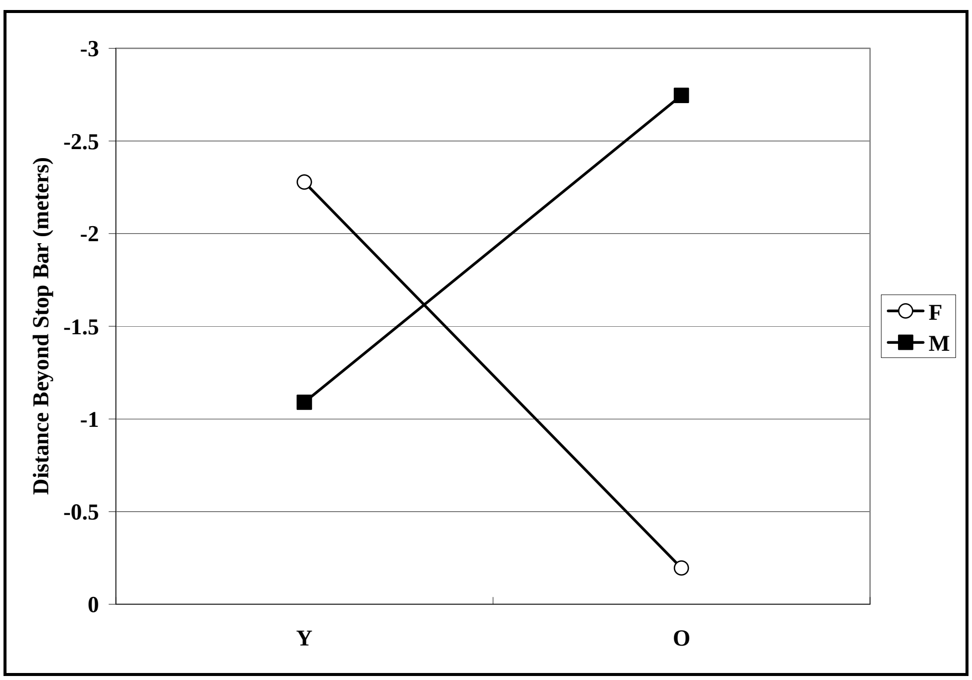


Figure 13: *Age X Gender distance beyond stop bar interaction*

Calculated Variables

No significant differences were found between haptic conditions with respect to required deceleration and speed differential variables. ANOVAs were conducted to determine significant differences due to age, gender, and the age X gender interaction (Table 10). Significant differences between the age groups were found with respect to required deceleration ($F[1, 34]= 4.88$, $p=0.034$). Older drivers required a significantly higher deceleration than younger drivers in order to stop at the stop bar (Older: $M = -0.37$ g, $SD = 0.04$; Younger: $M = -0.34$ g, $SD = 0.02$).

Table 10: *Calculated measure between age, gender, and age by gender*

	Source (p-value)		
Dependent Variable	**Age**	**Gender**	**Age*Gender**
RDP	0.034*	NS	NS
SpeedDifferential	NS	NS	NS

**post hoc* test conducted, NS = Not significant

2) Haptic Warnings Compared with Baseline

Given that there were only four data points for those who stopped in the baseline condition, there was not enough power to conduct ANOVA's for this comparison. Descriptive statistics for those who stopped in both conditions are summarized in Table 11. Those receiving no warning had nearly double the time to accelerator release than those receiving the haptic warnings. The time to brake was also faster for those receiving the haptic warnings than those receiving no warning.

Table 11: *Descriptive statistics for those who stopped in the baseline condition*

	Baseline (N = 4)		Haptic Collapsed (N = 38)	
Variable	**Mean**	**Std Dev**	**Mean**	**Std Dev**
TAR (s)	0.62	0.19	0.32	0.12
ReactionTime, TB (s)	0.94	0.21	0.78	0.25
TPB (s)	3.68	0.32	3.31	0.77
TBPB (s)	2.78	0.35	2.59	0.69
ABT (s)	0.32	0.05	0.46	0.25
MaxDecel (g)	-0.64	0.05	-0.52	0.07
AvgDecel (g)	-0.42	0.04	-0.34	0.03
DistanceBSB (m)	-1.92	0.94	-1.58	2.60
RDP (g)	-0.53	0.03	-0.35	0.03

The warning type failed to influence stopping location for those receiving the haptic warning and those receiving no warning (p = 0.3082, two-sided Fisher's exact test). The frequency of stopping location for each condition is reported in Table 12.

Table 12: *Contingency table for warning type (Baseline & Haptic) X stop location*

	Stop Location	
	Before Stop Bar	**Beyond Stop Bar**
Baseline	0	4
Haptic	26	12

3) Haptic Warnings Compared with Auditory plus Visual Warnings

The warning type did influence the stopping location for the haptic warning as compared to the auditory (CAMP) plus visual warning (p=0.048, two-sided Fisher's exact test). The warning type failed to influence stopping location for the haptic warning compared with the auditory ("Stop") plus visual warning. The frequency of stopping location for each condition is reported in Table 13. Descriptive statistics for those who stopped are summarized in Table 14.

Table 13: *Contingency table for warning type (CAMP, "Stop", and Haptic) X stop location*

	Stop Location	
	Before Stop Bar	After Stop Bar
CAMP	0	10
"STOP"	6	10
Haptic	26	12

Table 14: *Descriptive statistics for auditory (CAMP & "Stop") and visual warnings and haptic warnings*

	CAMP (N = 10)		"STOP" (N = 16)		Haptic Collapsed (N = 38)	
Variable	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
TAR (s)	0.53	0.18	0.41	0.13	0.32	0.12
ReactionTime, TB (s)	0.93	0.15	0.67	0.10	0.78	0.25
TPB (s)	3.51	0.31	3.08	0.48	3.31	0.77
TBPB (s)	2.64	0.30	2.48	0.48	2.59	0.69
ABT (s)	0.39	0.13	0.26	0.07	0.46	0.25
MaxDecel (g)	-0.68	0.10	-0.70	0.07	-0.52	0.07
AvgDecel (g)	-0.46	0.07	-0.45	0.05	-0.34	0.03
DistanceBSB (m)	-4.67	4.67	-0.97	2.72	-1.58	2.60
RDP (g)	-0.53	0.04	-0.47	0.04	-0.35	0.03

Analysis of variance (ANOVA) was conducted to detect differences between the warning type, including haptic brake pulse warnings, tone auditory (CAMP) plus visual warning, and verbal warning ("STOP") plus visual warning. The criterion for a significance difference was $p < 0.05$. In cases where there was no significant difference between individual haptic brake pulse warnings and the other two warning types, the haptic warnings were collapsed across all conditions. The power of the analyses was increased by collapsing across conditions, by increasing the number of data points and decreasing the number of comparisons made. For those analyses showing significant differences between individual haptic brake pulse warnings and the other warning types, the haptic brake pulse conditions remained separate, and significant difference were further explained by the post hoc tests.

Reaction and Movement Times

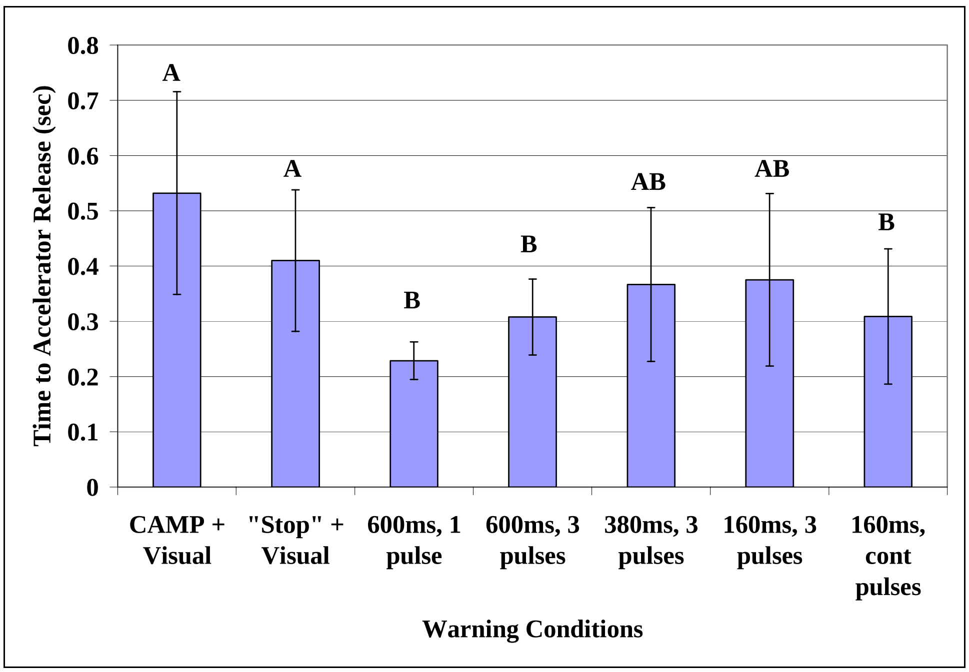
Significant differences between warning type for reaction and movement times are reported in Table 15. Significant differences between the individual haptic warning conditions and auditory and visual warning conditions were found with respect to time to accelerator release ($F[6, 57]= 487$, $p<0.001$). Significant differences between the collapsed haptic warning conditions and the auditory and visual warning conditions were found with respect to time to brake ($F[2,61] = 4.57$, $p=0.014$). Significant differences between the individual haptic warning conditions and the auditory and visual warning conditions were found with respect to time from accelerator to brake ($F[6,57] = 2.70$, $p=0.022$).

Table 15: *Reaction and movement time measures between haptic conditions*

	Source (p-value)
Dependent Variable	**Warning Types**
TAR	<0.001
ReactionTime, (TB)	0.014
TPB	NS
TBPB	NS
ABT	0.022

**post hoc* test conducted, NS = Not significant

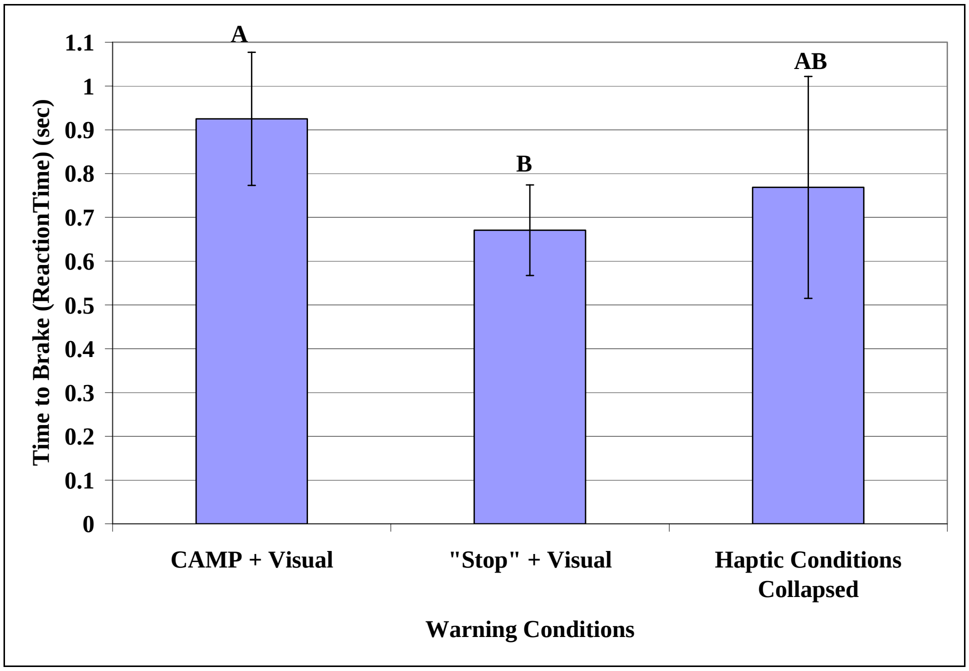
The *post hoc* test for time to accelerator release (TAR) showed significant differences between the warning conditions (Figure 14). Those who received the CAMP auditory plus visual warning (*M* = 0.53 s, *SD* = 0.18) had a significantly higher time to accelerator release than those in the 600ms-1 pulse (*M* = 0.23 s, *SD* = 0.03), 600ms-3 pulses (*M*= 0.31 s, *SD* = 0.07), and 160ms- continuous pulses (*M* = 0.31 s, *SD* = 0.12) conditions. The "STOP" auditory plus visual warning conditions resulted in a significantly lower TAR than the 600ms- 1 pulse condition ("STOP": M = 0.42 s, *SD* = 0.13).



Note: Conditions with no letters in common are significantly different from one another.

Figure 14: *TAR per warning condition, mean and SD*

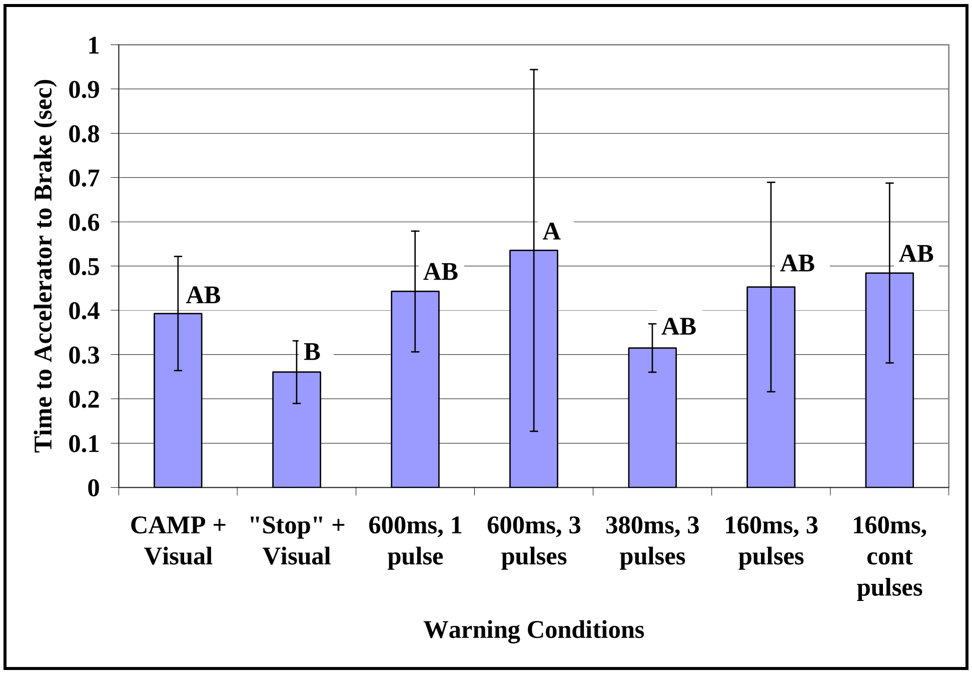
The *post hoc* test for time to time to brake (ReactionTime, TB) showed significant differences between the warning conditions (Figure 15). Those who received the CAMP auditory plus visual warning (M = 0.93 s, SD = 0.15) had a significantly higher time to brake than the "Stop" auditory plus visual warning (M =0.67 s, SD = 0.10).



Note: Conditions with no letters in common are significantly different from one another; there were no differences between individual haptic conditions and other warnings, so collapsed all haptic conditions

Figure 15: *Time to brake per warning condition, mean and SD*

The *post hoc* test for time from accelerator release to brake (ABT) for warning conditions showed significant differences between the warning conditions (Figure 16).   Those who received the "Stop" auditory plus visual warning (*M* = 0.26 s, *SD* = 0.07) had a significantly lower ABT than the 600ms-3 pulses (*M* = 0.54 s, *SD* = 0.41).



Note: Conditions with no letters in common are significantly different from one another

Figure 16: *Time from accelerator to brake per warning condition, mean and SD*

Deceleration Values

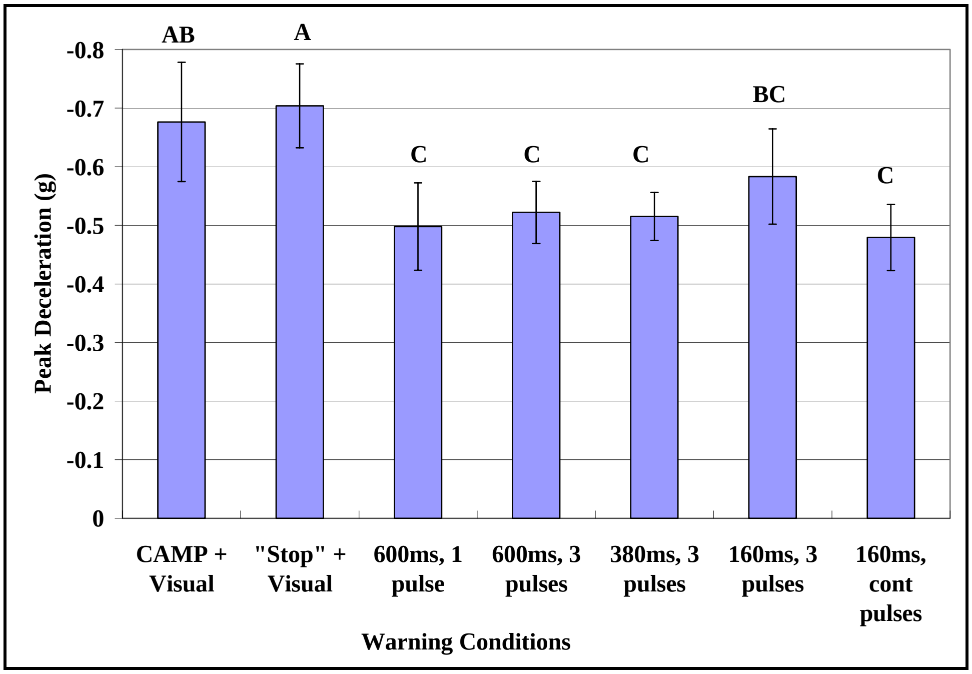
Significant differences between warning types for deceleration values are reported in Table 16. Significant differences between haptic warning conditions and auditory and visual warnings were found with respect to peak deceleration ($F[6, 57]= 16.15$, $p<0.0001$) and average deceleration ($F[2, 63]= 53.28$, $p<0.0001$).

Table 16: *Deceleration measures between haptic conditions*

	Source (p-value)
Dependent Variable	**Warning Types**
MaxDecel	<0.0001*
AvgDecel	<0.0001*

**post hoc* test conducted

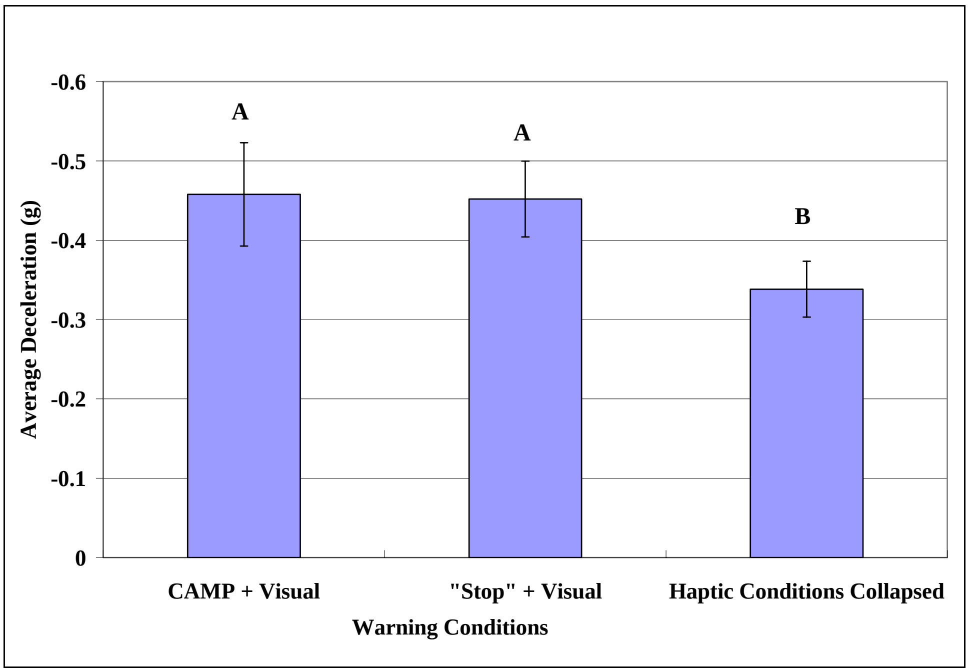
The *post hoc* test for peak deceleration for warning condition showed a significant difference between the warning conditions (Figure 17). Those who received the "STOP" auditory plus visual warning had a significantly higher peak deceleration than those receiving the haptic brake pulse warning conditions ("STOP": *M* = -0.704 g, *SD* = 0.07). The CAMP auditory plus visual warning group had a significantly higher peak deceleration than all haptic groups, excluding the 160ms-3 pulses condition (CAMP: *M* = -0.68 g, *SD* = 0.10).



Note: Conditions with no letters in common are significantly different from one another

Figure 17: *Peak deceleration per warning condition, mean and SD*

The *post hoc* test for average deceleration for warning condition showed a significant difference between the warning conditions (Figure 18). The haptic brake pulse warning groups had significantly lower peak deceleration than both the CAMP auditory plus visual warning group (M = -0.46 g, SD = 0.07) and the “STOP” auditory plus visual display group (M = -0.45 g, SD = 0.05).

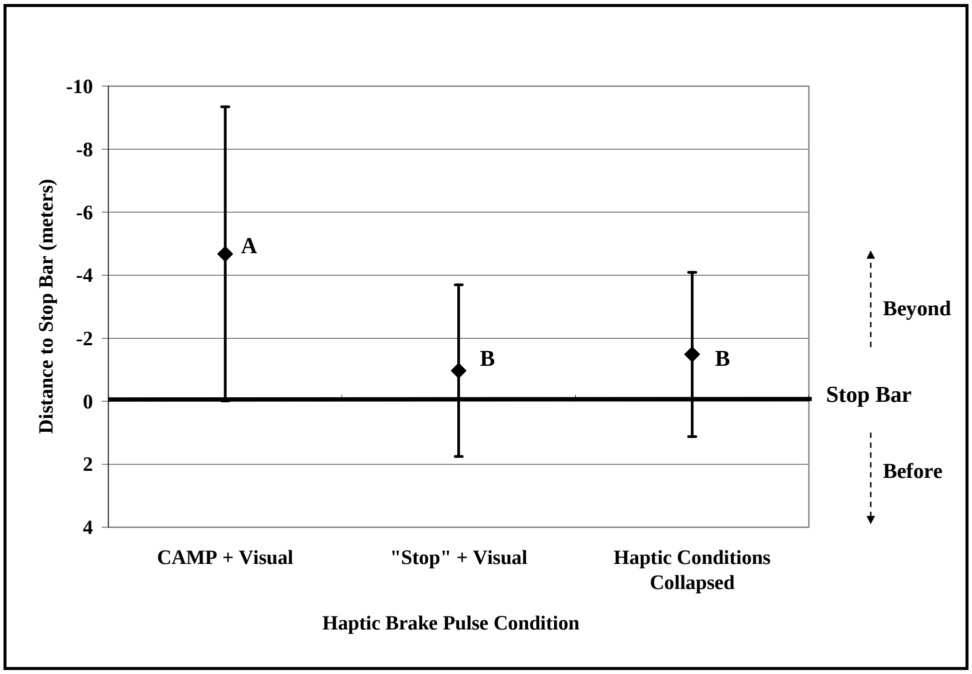


Note: Conditions with no letters in common are significantly different from one another; there were no differences between individual haptic conditions and other warnings, so collapsed all haptic conditions

Figure 18: *Average deceleration per warning condition, mean and SD*

Distance Beyond Stop Bar

Significant differences between the warning conditions were found with respect to distance beyond stop bar ($F[6, 57]= 2.52$, $p=0.031$). The *post hoc* test for distance beyond stop bar for warning condition showed a significant difference between the warning conditions (Figure 19). The CAMP auditory plus visual group stopped significantly farther into the intersection than both the “STOP” auditory plus visual and the haptic warning conditions (CAMP: M = -4.7 m, SD = 4.67; “STOP: M = -0.97 m, SD = 2.72; Haptic: M = -1.5 m, SD = 2.61).

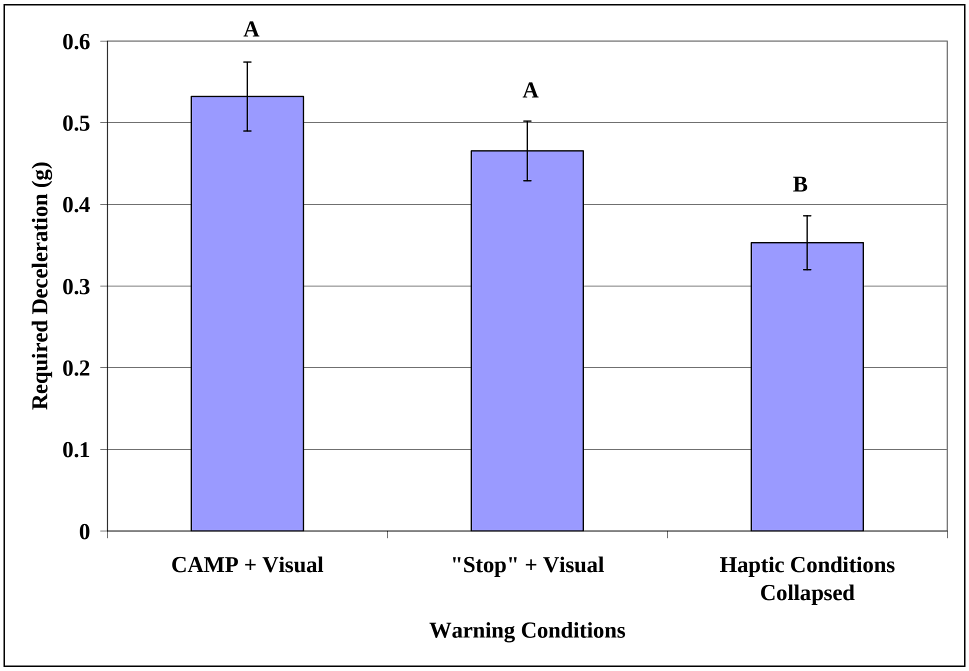


Note: Conditions with no letters in common are significantly different from one another

Figure 19: *Distance to stop bar per warning condition means and SD*

Calculated Variables

Significant differences between the warning conditions were found with respect to required deceleration ($F[2, 54]= 124.35$, $p<0.0001$). The speed differential variable was not testable with the auditory plus visual warning conditions, there for it was not included in the analyses. The *post hoc* test for required deceleration for warning condition showed a significant difference between the warning conditions (Figure 20). The haptic brake pulse warning conditions (*M* = -0.353 g, *SD* = 0.03) required a significantly lower deceleration than both the CAMP auditory plus visual warning group (*M* = -0.532 g, *SD* = 0.04) and the “STOP” auditory plus visual display group (*M* = -0.465 g, *SD* = 0.04).



Note: Conditions with no letters in common are significantly different from one another; there were no differences between individual haptic conditions and other warnings, so collapsed all haptic conditions

Figure 20: *Required deceleration per warning condition, mean and SD*

4) Did Not Stop Group

Upon reviewing the data for the three participants who did not stop in the haptic conditions, it was found that all participants did begin to brake upon receiving the warning, but then proceeded to violate the red light. Although their initial response to the warning was appropriate, the drivers noted several reasons for not stopping, including the presence of the following vehicle, that they were continuing to follow the original instruction of maintaining 35 mph, and the assumption that it was part of the experiment and a signal that the test was over.

5) Subjective Analysis

The analysis of the subjective data is separated into the retrospective interview responses, post-event questionnaire, additional trials questionnaire, and content analysis. ANOVAs were conducted to test for differences between haptic conditions on the post-event questionnaire ratings and additional trials questionnaire ratings. A correlation was performed between the objective and subjective measures. These correlations are reported in Table 17.

Table 17: *Correlation between subjective and objective measures*

		Subjective										
		Effect	Urgent	Like.	Annoy.	Expect.	Time	Comfort.	Control	Safety	Trusty	Reliable
Objective	TAR	0.143	0.037	0.288	-0.078	0.143	-0.209	-0.151	0.195	-0.093	-0.186	-0.069
	p-value	0.39328	0.82355	0.07931	0.64246	0.39008	0.20714	0.3646	0.24076	0.57854	0.31775	0.71079
	N	38	38	38	38	38	38	38	38	38	31	31
	ReactionTime	-0.153	-0.082	-0.041	0.151	-0.046	0.035	-0.158	-0.061	-0.200	-0.119	-0.188
	p-value	0.35835	0.62399	0.80816	0.36704	0.78477	0.834	0.34479	0.71594	0.22875	0.52264	0.31205
	N	38	38	38	38	38	38	38	38	38	31	31
	TPB	-0.113	0.063	-0.003	0.109	-0.138	-0.452	-0.274	0.001	-0.294	0.091	0.047
	p-value	0.49865	0.70853	0.98569	0.51356	0.40705	0.00437	0.0961	0.99621	0.07322	0.62578	0.80031
	N	38	38	38	38	38	38	38	38	38	31	31
	TBPB	-0.076	0.096	0.017	0.058	-0.147	-0.513	-0.248	0.029	-0.257	0.148	0.122
	p-value	0.64916	0.56714	0.92144	0.72991	0.3797	0.00098	0.1325	0.86202	0.11955	0.42749	0.51156
	N	38	38	38	38	38	38	38	38	38	31	31
	ABT	-0.220	-0.099	-0.176	0.186	-0.113	0.133	-0.086	-0.152	-0.156	-0.034	-0.154
	p-value	0.1854	0.55273	0.29143	0.26229	0.4997	0.42543	0.60716	0.36167	0.35068	0.85706	0.40934
	N	38	38	38	38	38	38	38	38	38	31	31
	MaxDecel	0.061	0.263	0.157	-0.116	-0.323	-0.111	0.238	-0.342	-0.333	0.205	0.340
	p-value	0.71452	0.11059	0.34553	0.48913	0.04828	0.50762	0.1502	0.03572	0.04129	0.26933	0.0615
	N	38	38	38	38	38	38	38	38	38	31	31
	AvgDecel	-0.141	0.034	0.020	-0.029	-0.440	-0.236	0.053	-0.280	-0.250	0.111	0.092
	p-value	0.39879	0.83765	0.903	0.86347	0.00572	0.15302	0.75229	0.08828	0.1294	0.55371	0.62366
	N	38	38	38	38	38	38	38	38	38	31	31
	DistanceBSB	0.117	-0.123	-0.167	-0.146	0.228	0.239	0.072	-0.002	0.296	-0.161	-0.111
	p-value	0.48274	0.46081	0.31606	0.3828	0.16843	0.14794	0.6656	0.98888	0.07082	0.38817	0.55253
	N	38	38	38	38	38	38	38	38	38	31	31
	RDP	-0.058	0.012	0.051	0.177	0.241	-0.003	-0.123	0.244	-0.079	-0.027	-0.080
	p-value	0.72931	0.94216	0.76233	0.28653	0.14457	0.98802	0.46195	0.1394	0.63606	0.88442	0.66849
	N	38	38	38	38	38	38	38	38	38	31	31
	SpeedDifferential	-0.136	-0.149	-0.121	0.102	-0.295	0.024	-0.047	-0.342	-0.208	-0.186	-0.236
	p-value	0.41626	0.37091	0.47016	0.54098	0.07226	0.88562	0.77781	0.03586	0.20975	0.31757	0.20121
	N	38	38	38	38	38	38	38	38	38	31	31

*p<0.05 significant, significant correlations highlighted

There was a correlation between expecting the light to change and the peak and average deceleration; as the driver's expectation for the light to change increased,the peak and average deceleration increased (harder braking). As time to peak brake and time from brake to peak brake decreased, the participants rated the warning as being increasingly late. As peak deceleration increased, participants tended to rate their vehicle control as being out of control; as the speed differential decreased (the speed difference over the duration of warning), participants' rating for being out of control increased. Lastly, as the peak deceleration increased, the feeling of safety decreased.

Retrospective Interview

When the participant came to a stop after their surprise trial, they were asked if they noticed anything unusual before they stopped. Many participants mentioned the car "stopping itself," or the car jerking, or someone else applying the brake for them. They were then asked to describe the braking sensation and whether they felt constant braking or pulses. If they felt pulses, the number of pulses they felt was recorded. These interview responses are explored further in the content analysis.

Post-event Questionnaire

There was a significant difference ($F[4, 36]=5.42$, $p= 0.002$) between conditions with respect to annoyance (Figure 21). The *post hoc* test found that those participants receiving the 600ms-1 pulse and the 160ms-3 pulses conditions found the warning to be significantly more annoying than the groups receiving the 600ms-3 pulses and 380ms-3 pulses conditions. There were no significant differences between the groups for any of the remaining measures (illustrated in Figure 22 and Figure 23). There were no significant differences in ratings between those participants who stopped and those who did not stop.

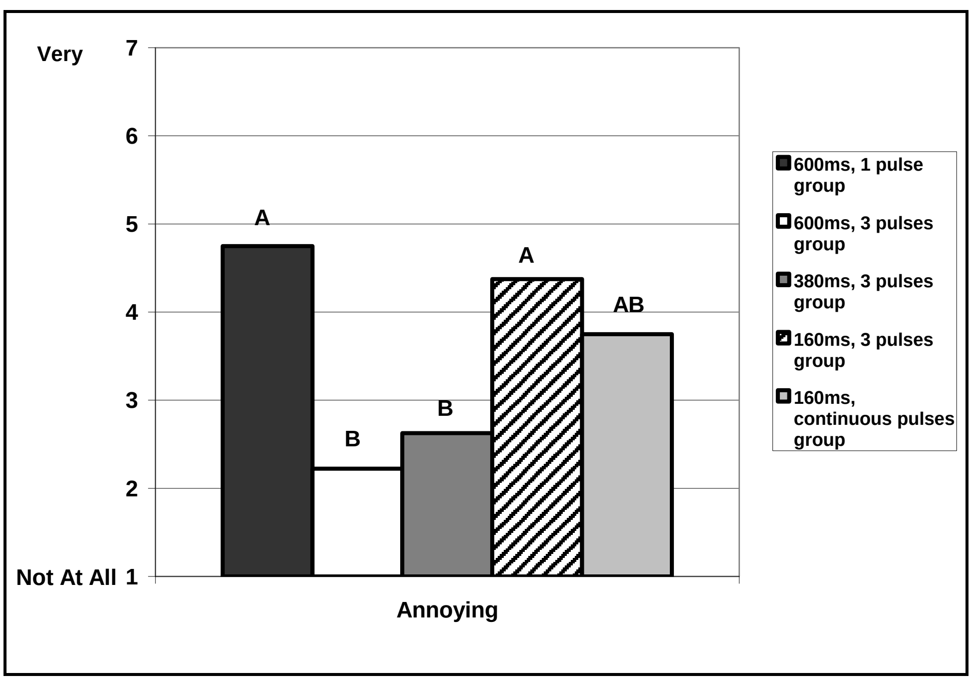


Figure 21: *Surprise trial annoyance rating mean for conditions*

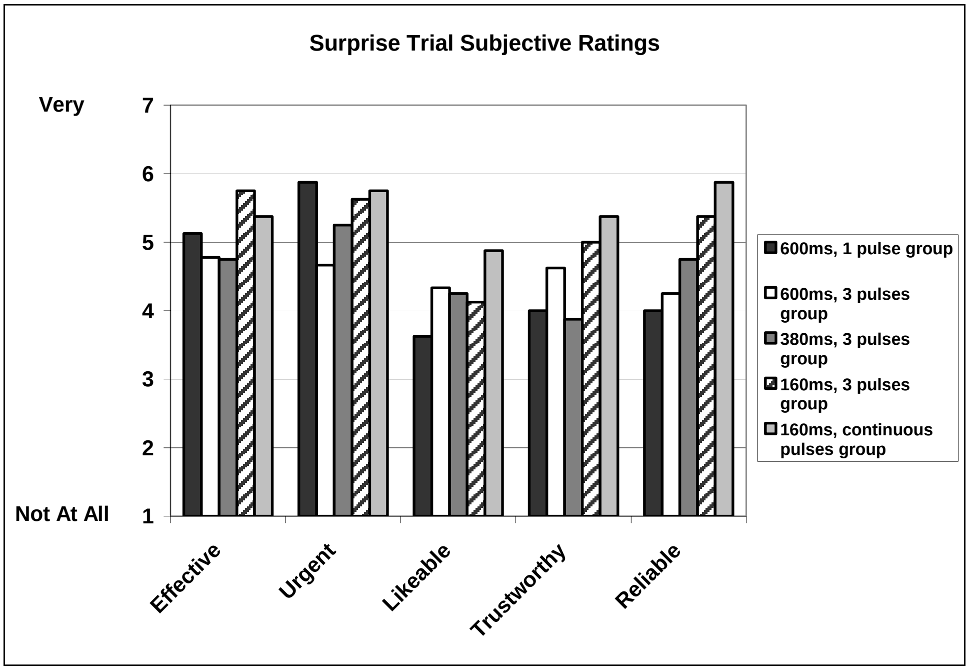


Figure 22: *Surprise trial subjective mean ratings for first five measures*

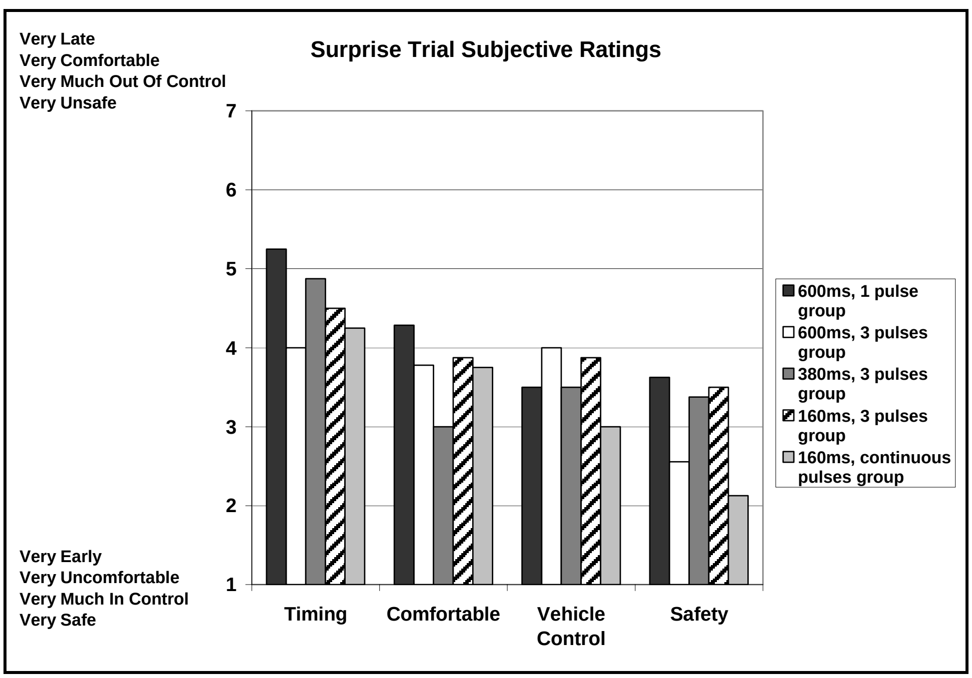


Figure 23: *Surprise trial subjective mean ratings for remaining four measures*

There was a significant difference between younger and older drivers when asked how comfortable the stop was ($F[1,34]) = 5.21$, p=0.029). On a seven point scale (1- Very Uncomfortable, 7-Very Comfortable), younger drivers rated their comfort level at 3.30 (SD = 1.3), whereas older drivers rated it as 4.28 (SD = 1.4). There was a significant difference between males and females when asked to rate their feeling of safety during the stop ($F[1,37] = 7.38$, p=0.01). Females rated their safety level at 3.7 (SD = 1.7), whereas males rated their safety level at 2.2 (SD = 1.2) (1- Very Safe, 7- Very Unsafe). Age and gender failed to influence any other subjective variables.

A pearson correlation was performed between all subjective factors (Table 18). The warning effectiveness rating was positively correlated with the warning urgency, likeability, trustworthiness, and reliability. Warning urgency was correlated with trustworthiness and reliability. Likeability was negatively correlated with annoyance and warning timing; as people considered the warning to be too early they were more likely to rate the warning as being very likeable and vice versa. Also, they were likely to rate the warning as more likeable if they felt more safe. Likeability was also positively correlated with reliability.

Warning annoyance was correlated with driver's perceived safety. Warning timing and vehicle control were also correlated with safety, so as the warning timing moved toward too early and the vehicle control moved towards very much in control, the perceived safety moved closer to very safe. Warning timing was negatively correlated with trustworthiness (as they moved toward the warning being too late, participants tended to rate it as being less trustworthy). And lastly, warning trustworthiness was highly correlated with reliability.

Table 18: *Pearson correlation between ratings for surprise trial*

	Effect	Urgent	Like.	Annoy.	Expect.	Time	Comfort.	Control	Safety	Trusty	Reliable
Effectiveness	1.000										
p-value	0.0000										
N	38										
Urgency	0.553	1.000									
p-value	0.0003	0.0000									
N	38	38									
Likeable	0.494	0.171	1.000								
p-value	0.0016	0.3042	0.0000								
N	38	38	38								
Annoying	-0.080	0.176	-0.450	1.000							
p-value	0.6335	0.2908	0.0046	0.0000							
N	38	38	38	38							
Expected	0.057	-0.199	0.083	-0.263	1.000						
p-value	0.7342	0.2320	0.6224	0.1107	0.0000						
N	38	38	38	38	38						
Timing	-0.172	-0.089	-0.360	0.202	-0.021	1.000					
p-value	0.3029	0.5938	0.0265	0.2249	0.9026	0.0000					
N	38	38	38	38	38	38					
Comfortable	0.302	-0.052	0.273	-0.064	0.095	-0.112	1.000				
p-value	0.0653	0.7579	0.0978	0.7044	0.5697	0.5040	0.0000				
N	38	38	38	38	38	38	38				
VehicleControl	0.035	-0.055	0.091	0.069	-0.078	0.013	-0.196	1.000			
p-value	0.8348	0.7435	0.5882	0.6805	0.6411	0.9396	0.2391	0.0000			
N	38	38	38	38	38	38	38	38			
Safety	-0.169	-0.106	-0.334	0.358	0.035	0.474	-0.283	0.546	1.000		
p-value	0.3119	0.5248	0.0405	0.0275	0.8342	0.0027	0.0847	0.0004	0.0000		
N	38	38	38	38	38	38	38	38	38		
Trustworthy	0.469	0.599	0.284	0.003	-0.157	-0.423	0.198	0.099	-0.220	1.000	
p-value	0.0077	0.0004	0.1222	0.9866	0.3998	0.0178	0.2845	0.5944	0.2350	0.0000	
N	31	31	31	31	31	31	31	31	31	31	
Reliable	0.480	0.589	0.376	0.126	-0.242	-0.335	0.147	0.064	-0.234	0.741	1.000
p-value	0.0063	0.0005	0.0370	0.4995	0.1889	0.0652	0.4310	0.7328	0.2053	0.0000	0.0000
N	31	31	31	31	31	31	31	31	31	31	31

*p<0.05 significant, significant correlations highlighted

Additional Trials Questionnaire

For the additional trials, the haptic condition had no effect on the subjective measures. The subjective measures for each haptic condition are illustrated in Figure 24.

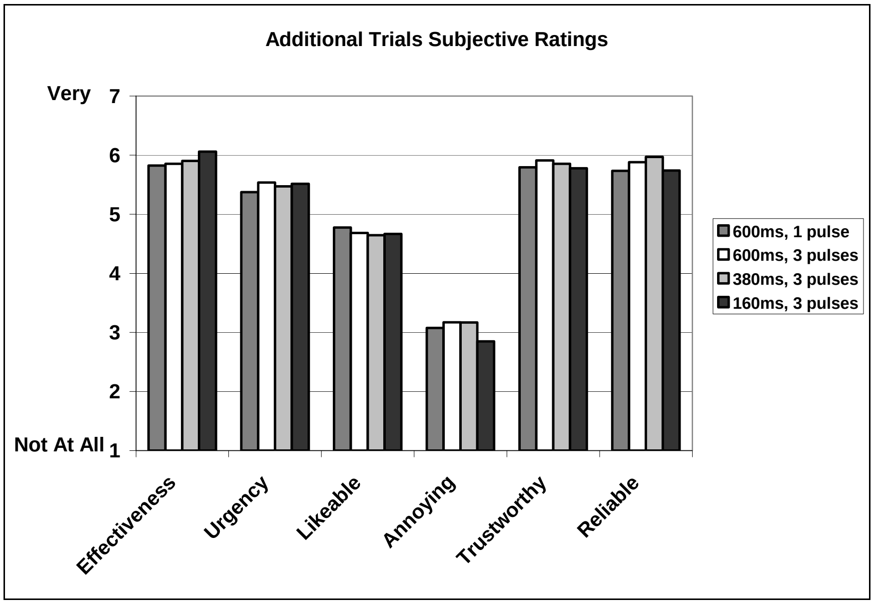


Figure 24: *Additional trials subjective mean ratings*

Content Analysis

The retrospective interview was categorized into: 1) those who mentioned the braking initially when asked if they noticed anything unusual during their last stop; 2) those who mentioned the braking after being asked if they felt the car beginning to slow down; and 3) those who felt no braking. Next, six codes were created to summarize the participants' experiences; the six codes were as follows: car stopped, brakes applied, someone/something else braked, outside control, something wrong, and scared. Table 19 shows the frequency of codes for those participants who mentioned the braking initially and for those who mentioned the braking after being asked by the experimenter. There was one participant who, after being asked, said he did not feel the car beginning to slow down; therefore no column was created for that participant.

Table 19: *Content analysis on retrospective interview: frequency of codes*

Codes	Mentioned braking initially	Mentioned braking after asked	Total
Someone/something else braking	13	3	**16**
Brakes applied	11	4	**15**
Car stopping	8	0	**8**
Outside control	2	1	**3**
Something wrong	3	0	**3**
Scared	1	0	**1**

A second content analysis was performed on the post-event questionnaire responses to the open-ended questions. The two questions were to describe what they first thought when they felt the braking, and what they thought was happening when they felt the braking. The codes and the frequency of occurrence are summarized in Table 20.

Table 20: *Content analysis on post-event questionnaire: frequency of codes*

Codes	Frequency
Something wrong with car	14
Light changing	11
Someone/something else braking	9
Did not know what was going on	5
They (participant) did something wrong	4
Scared	4
Surprised	3

Discussion

Similar to the results, the discussion is separated by research questions and research goals.

RQ1. Which brake pulse candidate results in the fastest reaction time and largest deceleration values?

There were no significant differences between the haptic brake pulse conditions for reaction and movement times. When the haptic warnings were compared against the auditory + visual warnings, several of the haptic brake pulse conditions resulted in significantly lower time to accelerator release times than both auditory + visual warnings. Although there was a significantly lower time to accelerator release for several haptic conditions versus auditory and visual warnings, this reduction in time did not translate to a faster brake reaction time. This may support the theory that people perceive haptic warnings sooner than other modalities, but may then require more time to make a decision. Ultimately, the total time to brake for the haptic brake pulse conditions was not significantly different from the two auditory + visual warnings.

Those receiving the 160ms- 3 pulses condition had a significantly higher peak deceleration than those receiving the 600ms-1 pulse condition and 160ms-continuous pulses conditions. The 160ms-3 pulses group also had a significantly higher average deceleration than the 600ms-3 pulses condition and 160ms- continuous pulses condition. This significant difference could have been due to the group traveling at a higher speed when they received the warning. The speed at brake for the 160ms-3 pulse condition did approach being significantly faster than the 600ms-3 pulses and 160ms- continuous pulses conditions. Also, the higher average deceleration for the 160ms- 3 pulse condition could have been influenced by the higher peak deceleration.

When haptic warnings were compared to auditory + visual warnings, the haptic brake pulse conditions had a significantly lower average deceleration. Most of the haptic brake pulse condition groups had a significantly lower peak deceleration as well. Similarly, the required deceleration for the haptic warnings was significantly lower than the auditory + visual warning groups. These results may be explained by the additional system braking such that the drivers may not have felt the need to brake as hard or did not have to brake as hard. Also, these findings may suggest that use of haptic warnings could mitigate rear-end collisions at intersections. With the lead vehicle responding sooner and at a lower deceleration rate, the following vehicle, with an attentive driver, would have more time to react and decelerate in response to the intersection and lead vehicle.

There was one participant in the 600ms- 3 pulses condition who had a time to brake of 1.9 seconds. Based on his distance to stop bar and speed at time of braking, he would have required a deceleration of 0.34 g to stop at the stop bar, which is comparable and even less than some of the other participants. This would indicate that the system braking was successful at slowing the vehicle down so that a hard deceleration was not required (possibly even reducing the number of rear-end collisions). It also supports having the three pulse condition instead of the single pulse, as the same participant's decision may have been to violate the intersection had he not been warned for the additional two pulses.

There were no differences between the haptic brake pulse conditions for distance to stop bar, meaning that all groups stopped in relatively the same location. The relative lack of significant differences between the haptic groups could be partially due to low power (because of the low number of participants used) and partially due to there being only small differences between the haptic brake pulse stimuli.

RQ2. What are the response differences between age groups?

For those variables not influenced by the haptic brake pulse condition, additional analyses were conducted to test the effects of age, gender, and the age by gender interaction. Older drivers had a significantly higher time to accelerator release and time to brake than their younger counterparts. These findings are consistent with Warshawsky-Livne and Shinar (2002), who found that older drivers react 0.08 seconds later than younger drivers. The reaction time difference due to age could be attributed to a decrease in perceptual ability by older drivers.

Although there were differences between haptic conditions for the deceleration values, a secondary analysis was conducted to test for differences due to age, gender, and age by gender. Older drivers had a significantly higher peak deceleration than younger drivers. This difference may have been due to their significantly higher reaction times, and they may have been compensating during their braking to stop at a similar location as younger drivers. It is important to note that the significant difference between age groups for required deceleration was due to higher reaction times. The required deceleration was calculated using the distance at which braking was initiated and the speed at braking initiation. Because older drivers began their braking closer to the intersection (for a set experiment speed), a larger deceleration was required to stop at the stop bar.

RG1. Determine the correlation between objective and subjective responses to haptic brake pulses.

Several correlations were found between the objective measures and the subjective responses. While such correlations are easy to conduct, it is more difficult to determine the cause and effect. Those who expected the light to change had a higher average and peak deceleration. This expectation did not influence the distance to stop bar once they stopped. It is interesting that those who rated the warning as increasingly late had a shorter time to peak brake and time from brake to peak brake, although their perception of warning timing did not vary with time from accelerator release and time to brake. This may be a reflection of how quickly they felt the car could respond to their own braking after the vehicle released control of the system braking. Several participants mentioned that it did not seem like the brakes responded quickly to their own braking actions.

As peak deceleration increased and speed differential decreased (the speed difference over the duration of the warning), drivers tended to rate their feeling of vehicle control towards being out of control. The methods used for this study took a certain amount of control away from the driver by occluding their vision at random intervals; this feeling of being out of control could have influenced the driver to *retake control* by braking harder. However, the less the warning reduced the speed, the more out of control they felt. Those drivers who felt more out of control may have tried to accelerate through the system braking, thereby reducing the potential capability of the system braking.

Those who had a higher peak deceleration also felt more unsafe. There was also a correlation between the feeling of safety and control; those who felt more out of control felt unsafe. Those drivers who came to a hard stop tended to feel both out of control and unsafe. Conversely, those who were not braking hard tended to feel in control and safe.

RG2. Determine driver perception of haptic warnings.

There was a significant difference with respect to annoyance between the haptic brake pulse conditions. Those receiving the 600ms-1 pulse and 160ms-3 pulses conditions found the warning to be significantly more annoying than the 600ms- 3 pulses and 380ms- 3 pulses groups. Those in the 600ms- 1 pulse group received a jerk of 12g/s which may have attributed to the higher annoyance. The higher annoyance for the 160ms- 3 pulses group may be due to having a few number of short duration pulses; people may be more forgiving if the system continues to warn them to an imminent hazard. While these two conditions resulted in a higher annoyance level, they did not cause the driver to stop any quicker than the other conditions. An important aspect of warning design is to minimize driver annoyance while increasing warning effectiveness, with more weight given to warning effectiveness.

For the additional trials, the participants did not rate the various haptic warning conditions differently for any of the subjective factors. This provides support for the use of the surprise trial method and argues against using additional trials when evaluating haptic warnings.

The retrospective interview and the open-ended questions were an effective means for gathering participants' opinions about the system. While the reviews of the brake pulse system were mixed, there was a general positive response after the drivers better understood the meaning of the warning. Several participants expressed interest in possibly having such a warning system in their future vehicles.

When speaking with the participants during the retrospective interview, four people said they thought something was wrong, while in the written responses 18 people said that something was wrong with the car or they had done something wrong. Similar to the concern of something being wrong, only one person expressed fear when completing the retrospective interview, while four people expressed fear in their written responses. This discrepancy could be due to the participants having time to process the event and form a more complete opinion, or because they felt uncomfortable speaking of their concerns and more comfortable writing them.

In order to determine which of the brake pulse conditions would be used in Phase II, the following filters were used:

- Eliminated those conditions for which some participants did not stop (600ms-1pulse and 380ms- 3pulses conditions).
- Eliminated those conditions considered to be more similar to automatic braking than a warning system (160ms- continuous pulses).

After the filters were used, the 600ms- 3 pulses and 160ms- 3 pulses candidates remained. The 600ms-3 pulses candidate was chosen for further evaluation because it theoretically results in the largest velocity change. It would also warn the driver for up to 2 seconds, whereas the alternate haptic brake pulse would warn the driver for 780ms. The following section discusses the methods, results, and findings from the second phase of this research.

CHAPTER 4 PHASE II: BRAKE PULSE PLUS AUDITORY WARNING

Methods

Experimental Design

The second phase of this study combined one of the brake pulse candidates from the first phase with an auditory warning. The brake pulse candidate chosen was the 600ms- 3 pulses condition. The pulses were separated by 100ms, and the jerk was 3 g/s, with an average deceleration of 0.3 g. The auditory warning was a female voice urgently saying "STOP." The auditory warning sound level was at 75dB, which was about 15dB above the masked threshold. The experimental design (Table 21) required an equal number of younger and older participants.

Table 21: *Phase II experimental design*

	Age	
Condition	**Younger**	**Older**
600ms-3 pulses brake pulse + Auditory Warning (Verbal "Stop")	S1 - 4	S5 - 8

Independent Variables

The independent variable was the haptic brake pulse warning combined with a verbal auditory warning. The age factor was separated into a younger group (18-30 years old) and an older group (50 years of age and older).

Controlled Variables

A speed of 56.3 kph (35 mph) was used for all participants. The warning algorithm used to determine warning location is discussed in the Warning Algorithm section of this chapter. Previous phases of ICAV used a speed of 56.3 kph (35 mph). The same speed was used for this phase so that the results could be compared to baseline data from the previous phases of ICAV. There were an equal number of males and females.

Dependent Variables

This study examined both the objective driving performance of the drivers and their subjective responses based on questionnaires administered during the study. The driving performance measures were recorded by the ICAV laptop inside the vehicle. The braking performance was recorded by the DAQ system connected to a gyroscope accelerometer.

Objective Measures

Several response variables were recorded during the test; these measurs are further defined in Phase 1, Objective Measure section.

- Stop (Before and After Stop Bar)/Did Not Stop
- Time to Accelerator Release (TAR)
- Time to Brake (ReactionTime, TB)
- Time to Peak Brake (TPB)
- Time from Brake to Peak Brake (TBPB)
- Time for transition of accelerator release to the time to brake (ABT) = T_B-T_{AR}
- Peak deceleration (acceleration, g)
- Time weighted deceleration (acceleration, g)
- Required declaration (acceleration, g)
- Speed Differential (mph)

Subjective Measures

After receiving the surprise warning, participants were given a retrospective interview. The purpose of the interview was to elicit any information from the participant about what they experienced during the surprise trial. They were then given a post-event questionnaire to complete. These questionnaires can be found in Appendix D.

Participant Population

A total of 13 drivers participated in this study. The first two participants were run with the warning activated at 38.1 meters (125 feet) feet; the remaining 11 participants were run with the warning activated at 33.5 meters (110 feet). A total of eight good data points were obtained during this phase. There were equal numbers of males and females as wekk as older and younger drivers. The participant mean ages for the age and age by gender factor are given in Table 22.

Table 22: *Phase II mean ages*

	Mean Age (yrs)	St. Dev	N
Older	57	3.4	4
Younger	20	2.3	4
Older Females	58.5	4.9	2
Older Males	55.5	0.7	2
Younger Females	20	2.8	2
Younger Males	20	2.8	2

Equipment

The equipment used for this second phase of the study was the same as the first phase. The only addition was the use of a speaker encased in a display mounted above the dashboard. The remaining apparatus was previously discussed in the equipment section of the Phase I methods.

Warning Algorithm

Initially the warning was activated at 38.1 meters (125 feet), for a speed of 56.3 kph (35 mph) and an average time to brake of 0.5 seconds. It was determined after the first two participants that the warning distance should be moved forward. Based on the required deceleration averages for other warning modalities, it was calculated that an average deceleration of 0.48 g should be used. For the remaining participants, the warning distance was moved to 33.5 meters (110 feet), for a speed of 56.3 kph (35 mph) and an average time to brake of 0.5 seconds.

Experimental Procedures

The experimental procedure was the same for each participant, and the same Phase I protocol was used for this phase, except that the surprise condition also had an auditory component. After the surprise trial, participants received the same retrospective interview and were then asked to complete a post-event questionnaire. The experiment concluded after the participant signed the new debriefing informed consent form. No additional trials were conducted in this phase.

Data Analysis

The data reduction process was the same as for Phase I. The text file from the data acquisition systems in the vehicle was processed by MATLAB to obtain discrete response variables. Those variables were then analyzed using SAS.

The objective data consisted of both nominal data and response variable data. The frequency data were split into those who stopped and those who did not stop. Those participants who stopped were placed into one of two categories: before the stop bar and after the stop bar. The response variables included several types of reaction time, including time to accelerator release (TAR) and time to brake (TB). The subjective data included a retrospective interview and a post-event questionnaire for the surprise trial.

Analysis of variance was used to test for significant differences between the haptic brake pulse and auditory group and the haptic brake pulse groups. Tukey-Kramer post hoc test was used to define these significant differences. Fisher's Exact tests were used on the stopping location for the different Phase I and Phase II groups. ANOVAs and Tukey-Kramer post hoc test were also run with the subjective data to determine differences between the haptic conditions.

Results

Phase II results are organized as follows: (1) Haptic and auditory warning compared with haptic warnings and (2) subjective analyses.

> *RQ3.* Will having both a brake pulse and auditory warning result in a shorter response time than a brake pulse alone?
>
> This research question is addressed in section 1 of the results; for those variables with no significant differences between haptic brake pulse conditions, ANOVAs were conducted to test for differences attributed to age, gender, and age by gender.

RG3. Determine guidelines haptic brake pulse warnings.

Guidelines were developed based on the results from both phases. The guidelines are expressed in the discussion and expanded on in the conclusion section of this thesis.

1) Haptic and Auditory Warning Compared with Haptic Warning

It is important to note that there was a warning distance difference between the haptic warnings alone (41.1 meters- 135 feet) and the multi-modal warning (33.5 meters- 110 feet). This distance difference may have had a confounding effect on significant differences found with the objective measures. Analyses were conducted to test for differences in reaction and movement times, and distance to stop bar between warning types.

The odds ratios illustrates that those participants who received the haptic brake pulse combined with the auditory warning were 1.5 times more likely to stop than those participants who received the haptic warning alone, even at the shorter warning distance. Table 23 summarizes how many stopped and did not stop for each condition.

Table 23: *Odds ratio of haptic condition compared to other haptic + auditory warning*

	Did Not Stop	**Stopped**	**DNS : Stop**		**Odds Ratio**
Haptic (Phase I)	3	38	0.08	**Haptic + Aud : Haptic**	1.546*
Haptic + Aud (Phase II)	0	8			

*correctional value of 0.5 used in cells containing zero.

The warning type failed to influence stopping location ($p = 0.421$, two-sided Fisher's exact test). The frequency of stopping location for each condition is reported in Table 24.

Table 24: *Contingency table for warning type (Haptic and Haptic + Auditory) X stop location*

	Stop Location	
	Before Stop Bar	**After Stop Bar**
Haptic (Phase I)	26	12
Haptic + Auditory	4	4

Reaction and Movement Times

No significant differences were found between the haptic brake pulse warning and the haptic + auditory warning for the reaction and movements times. ANOVAs were conducted to determine differences due to age, gender, and age by gender for the reaction and movement times (Table 25). Analyses included data points from both phases. Older participants had a significantly higher time to accelerator release than the younger drivers (F[1, 42]= 4.78, p=0.034) (Older: M = 0.35 s, SD = 0.13, Younger: M = 0.28 s, SD = 0.07). Older drivers also had a significantly higher time to brake (F[1, 42]=6.13, p=0.017) than younger drivers (Older: M = 0.84 s, SD = 0.30, Younger: M = 0.67 s, SD = 0.12).

Table 25: *Results of ANOVA for reaction and movement time measures between age, and gender, and age by gender*

	Source (p-value)		
Dependent Variable	**Age**	**Gender**	**Age*Gender**
TAR	0.034*	NS	NS
ReactionTime, (TB)	0.017*	NS	NS
TPB	NS	NS	NS
TBPB	NS	NS	NS
ABT	NS	NS	NS

**post hoc* test conducted, NS = Not significant

Distance Beyond Stop Bar

The warning type did not affect the distance to stop bar. ANOVAs were conducted to test for differences among age, gender, and the age by gender interaction. There was a significant difference for the age by gender interaction (F(1,42)=9.31, p=0.0039). Older females, on average, tended to stop before the stop bar (M = 0.5 m), which was significantly different from older males (M = -2.4 m) and younger females (M = -2.6 m), which both stopped on average over the stop bar. A scatter plot of stopping location for age by gender for both phases is illustrated in Figure 25 and the age by gender interaction is shown in Figure 26.

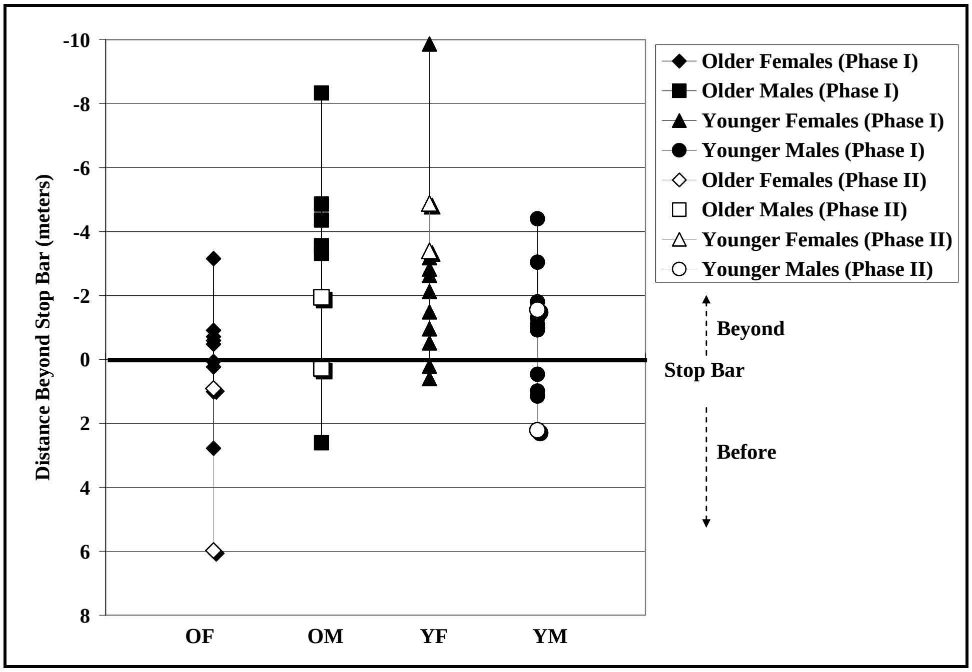


Figure 25: *Age X Gender stopping location scatter plot*

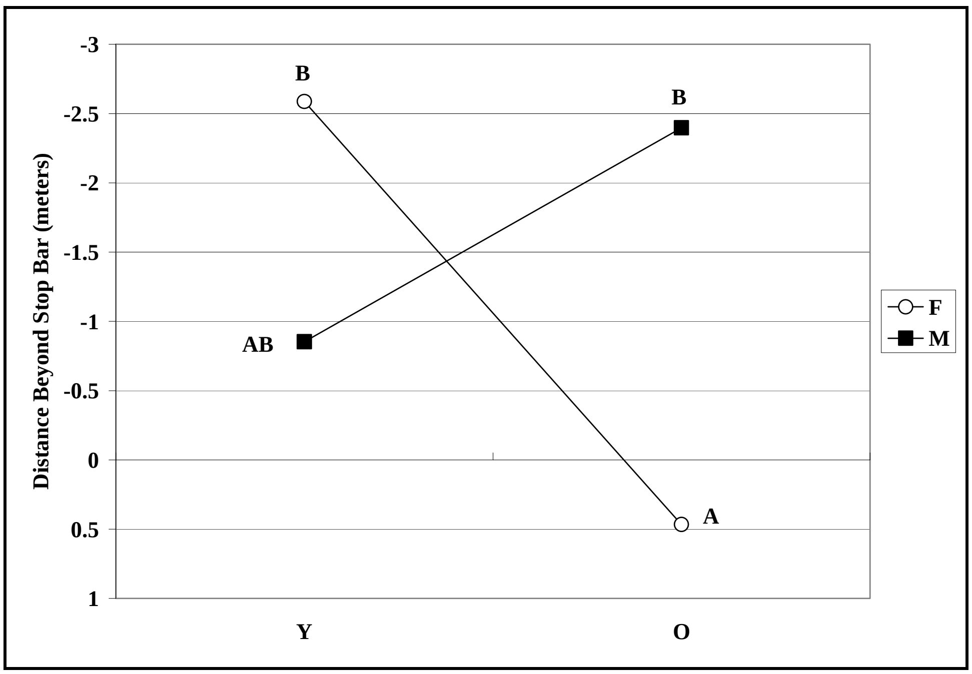


Figure 26: *Age X Gender distance beyond stop bar interaction*

2) Subjective Analysis

The subjective analysis includes the retrospective interview responses, post-event questionnaire, and content analysis. ANOVAs were used to analyze differences between Phase I and Phase II for the post-event questionnaire.

Retrospective Interview

Interestingly, those people who experienced the combined brake pulse and auditory warning mostly noted the auditory alarm when asked what they experienced during their intersection approach. Some participants mentioned the braking sensation, but others had to be prompted before talking about the car braking. A content analysis on the participant responses was conducted and is discussed in a later section.

Post-event Questionnaire

When comparing the responses from this phase to the 600ms- 3 pulses condition from the first phase, there were no significant differences between the two groups for any of the subjective factors (Figure 27).

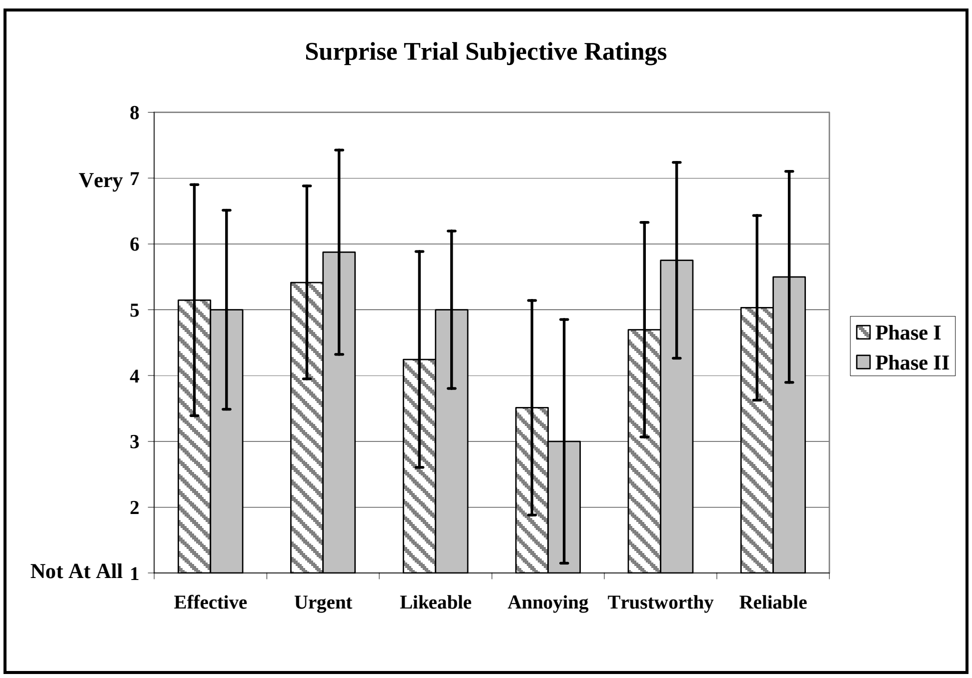


Figure 27: *Surprise trial subjective mean ratings and SD for Phase II*

Content Analysis

The retrospective interview was categorized into: 1) those who mentioned the braking initially when asked if they noticed anything unusual during their last stop; 2) those who mentioned the braking after being asked if they felt the car beginning to slow down; and 3) those who felt no braking. Codes were created to summarize the participants' experiences; the three codes were as follows: car stopped, brakes applied, and something wrong. Table 26 presents the codes that applied for those participants who mentioned the braking initially and for those who mentioned the braking after being asked by the experimenter.

Table 26: *Content analysis on retrospective interview: frequency of codes*

Codes	**Mentioned braking initially**	**Mentioned braking after asked**	**Total**
Brakes applied	3	2	**5**
Car stopping	3	0	**3**
Something wrong	1	0	**1**

A second content analysis was performed on the post-event questionnaire responses to the open-ended questions. The two questions were to describe what they first thought when they felt the braking, and what they thought was happening when they felt the braking. The codes and the frequency of occurrence are summarized in Table 27.

Table 27: *Content analysis on post-event questionnaire: frequency of codes*

Codes	**Frequency**
Car stopping	3
There was a need for participant to brake/stop	3
Did not know what was going on	2
Light Changing	2
Something wrong with car	1
They (participant) did something wrong	1
Surprise	1
Something/someone else braking	1

Discussion

RQ3. Will having both a brake pulse and auditory warning result in a shorter response time than a brake pulse alone?

There were no significant differences between the Phase I and Phase II groups for the reaction and movement times and distance to stop bar. The lack of difference in stopping location despite a closer warning distance points to a higher deceleration achieved by those receiving the haptic plus auditory warning in order to stop in a comparable location as those receiving just the haptic warning. However, because of these differences in warning location, analyses were not conducted to test for differences between groups for the deceleration values and calculated variables. Had an analysis been done for the deceleration, it would have been difficult to attribute the differences to either warning distance or to differences in the warnings.

While there were no significant differences that could be attributed to warning type, it is important to discuss the algorithm differences. There was a 92.3% compliance rate across all haptic conditions for the first phase (warning distance of 41.1 meters- 135 feet) and a 100% compliance rate for the second phase (warning distance of 33.5 meters- 110 feet). The odds ratio illustrated that those receiving the haptic plus auditory warning was 1.5 times more likely to stop than those receiving the haptic warning alone, even at the shorter warning distance. This finding supports including an auditory alarm with a haptic warning. There were no significant differences between reaction and movement times for those people who stopped in the two groups, which may suggest that the auditory warning does not aid in the decision making process for those people who would normally stop, but does help for those who otherwise might not have stopped.

CHAPTER 5 GENERAL DISCUSSION

The haptic brake pulse warning was an effective means for increasing drivers' compliance at intersections in this study. When just the haptic brake pulse warning was activated, drivers were 38 times more likely to stop than when receiving no warning and 7.6 times more likely to stop than when receiving an auditory tone plus visual warning. Those receiving the auditory verbal plus visual warning were only slightly more likely to stop than those receiving the haptic warning conditions. When the haptic warning was combined with an auditory warning, it increased the likelihood of stopping by 1.5 times (over the haptic warning alone).

Wickens (1992) proposed that optimal encoding into working memory occurs when the display modality and format matches the working memory encoding. Haptic brake pulse warnings may be advantageous because the stimulus uses a similar modality/display format code (haptic/spatial) to the working memory required (spatial), whereas an auditory verbal plus visual warning uses a verbal/auditory display for encoding into spatial working memory. When an auditory tone warning was used during the ICAV project, there was a reduction in effectiveness (measured in terms of reaction time and compliance), which may have been due to the low compatibility between display mode and working memory. When using a haptic brake pulse display, the modality/display format agreement could aid in the coding process for spatial working memory; the compatibility in display and working memory could also aid in reducing the choice reaction time. Although the Wickens model of compatibility of modality/display format to working memory code (Wickens, 1992) does not address haptic displays explicitly, the results found in this study agree with those modalities included in the Wickens' model. Wickens' model can be adapted to include the findings of this research by adding a haptic modality of a brake pulse to the spatial display format. This modality/display format combination would then be assigned to the spatial working memory.

The Hick-Hyman law for choice reaction time (Wickens, 1992) may explain why the auditory verbal plus visual warning was more effective at reducing reaction times than the haptic warning. The Hick-Hyman law can be expressed as an equation:

$$RT = a + b\,[\log_2(N)]$$, where

a = latency speed constant,
b = rate of information processing, and
N = number of stimulus-response alternatives

The rate of information can be affected by such things as practice, stimulus-response compatibility, stimulus modality, and arousal. Only a small percentage of the participants (25%) actually saw the visual display, making the warning appear to be a single-modal (auditory) display ($N = 1$). The verbal "STOP" is more command-like and may have increased the rate of information processing. The rate of information processing may decrease with haptic warnings as compared with verbal auditory warnings; also as verbal warnings are added to haptic warnings, the number of stimuli as increased which ultimately may increases the reaction time as compared to the verbal auditory warning alone.

Lastly, the CHIP model may explain why the haptic plus auditory verbal warnings were more effective than the tone auditory warning. The haptic brake pulse warnings may capture the attention sooner and motivate the driver to continue the motion of the vehicle by taking over the braking. The verbal warning is easier for the driver to comprehend. Each of these factors may increase the likelihood of the driver exhibiting the necessary behavior to comply with the warning.

In both phases of the study it was found that time to brake increased with age. Also, the the time to accelerator release was significantly higher for older participants when data from both phases were combined. This may be explained by the decline of perceptual speed with age. Even with a reduction in perceptual speed, older drivers were willing to brake harder and thus stopped at a comparable location as younger drivers. A study of the effects of age on typing (Salthouse, 1984) found that older participants compensated for their slower reaction times by looking ahead at the text to be written. The older participants were thus able to type at a comparable rate as the younger participants. The results of this thesis are consistent with these findings, in that older people compensated for reduced perceptual speed by maintaining or increasing their end performance above that of younger people. One potential advantage of a haptic braking pulse warning is that the vehicle would already be braking indicating to a following vehicle that a stop may be made. The system braking would not have to take into account whether the driver is younger or older.

The social implications of haptic brake pulse warnings are an important issue. Drivers may be less accepting of warning systems with a high degree of social invasiveness; any auditory or visual warnings heard or seen by passengers may embarrass the driver. In contrast, the driver may be the only person in the vehicle who is aware that the haptic brake pulse warning is coming from the system rather than the driver. While the haptic warning combined with the auditory warning may be more effective, it may also be perceived as more invasive and possibly less acceptable to the driver.

While annoyance was the only subjective factor to be influenced by the different brake pulse conditions, there were other factors that provide insight to drivers' perception of haptic brake pulse warnings. The less annoying the warning can be made, the more drivers are going to like the warning and the safer they will feel. Designers can increase perceived warning trustworthiness and reliability by increasing driver perception of warning effectiveness and urgency. As drivers feel the warnings are effective them and that there is a need to stop in compliance with the warning, they may be more willing to put their trust into such a system. This may indicate that people could lose trust with high false positive warnings (warnings activating at inappropriate times). Also, if drivers feel that the warning is too late, this may also reduce their trust. These subjective findings support including algorithm timing research into the design of the warning to ensure a warning is not too early or late.

RG3. Determine guidelines for haptic brake pulse warnings.

Guidelines were developed based on the results from both phases.

Guidelines for Haptic Warnings

Haptic Warning Guidelines

1. Haptic warnings should be included as more technology is introduced in vehicles.
   - Auditory warning systems cannot control for the exterior environment, such as cell phones and loud environments, which cannot be attenuated by the system. Haptic warning systems are not easily masked and can be detected even when the other senses are saturated.
2. Use the smallest jerk possible to obtain driver's attention, while maintaining warning effectiveness.
   - A high jerk may annoy the driver, while not improving warning effectiveness (whether measured objectively or subjectively).
3. To increase the effectiveness of haptic brake pulse warnings, verbal auditory warnings should be added.
4. Because each braking system developed by independent organizations vary in design, all braking parameters should be reported in repeatable measures.
   - Report values that are convertible to distance, time, speed, acceleration, and jerk. It is recommended to use units of m, s, kph, g, and g/s when reporting parameters.
5. Education and training programs should be used to increase public awareness of the existence of haptic feedback as an in-vehicle warning device.

General Intersection Collision Avoidance Warning Guidelines

1. Intersection collision warnings should be combined with forward collision warnings
   - This is to ensure that the driver responds to all hazardous situations, and that the algorithm takes into account where the driver should stop, rather than assuming the driver should stop at the stop bar.

2. If possible, advisory information should be given to drivers when approaching an unequipped intersection (one that is not capable of receiving algorithm timing information).
    - Obtain intersection information from GPS/GIS; would have to keep this information current as more intersection are added.

CHAPTER 6 CONCLUSIONS

The results of this research indicate that haptic countermeasures have the potential to increase the number of distracted drivers who would comply with a red-light during an intersection approach. Based on objective measures and subjective responses, this study supports future research in the area of brake pulses for intersection collision avoidance warnings, as well as other applications such as forward collision avoidance warnings, curve warnings, and emergency brake assist (aiding the driver's braking in emergency situations). It would be practical for the automobile industry to maximize utilization of this technology by also using it for other applications.

Although there were response differences between the two age groups, the overall results do not support using different algorithms based on driver age. Older drivers were willing to compensate for their increased reaction time by braking harder, therefore stopping at comparable locations as their younger counterparts.

As technology advances and more driver vehicle interfaces appear in the driver's environment, the human role is shifting away from the manual controller and more towards a partnership with the vehicle. The vehicle supplies the power and information (haptic warning), and then allows the human to control the vehicle. In the decision matrix by Price et al. (1982), as the ability for both the human and machine to perform functions equally well increases, a need for dynamic function allocation arises. In the context of the intersection, if the system determines that the driver is unsatisfactory in their response (not braking soon enough), the system can warn the driver and then allow the human to take over, creating a dynamic situation between the machine and the human.

One concern with haptic brake pulse warnings is the social implications of a movement towards a "supervisory control" role of the human driver. Sheridan (1997) has listed several concerns that can occur as automation is introduced, including remoteness from the product, mystification, and eventual abandonment of responsibility. While Sheridan lists these concerns in terms of the workplace, these ideas may also translate to human interactions with the automobile.

Based on the results of this study, a retrospective interview is recommended immediately following a surprise event or an unfamiliar stimulus. The retrospective interview should not contain any words to bias the participant, but should be structured such that more information can be given to the participant as needed to elicit responses. A written questionnaire should also be given to the participant with open-ended questions to elicit additional information. The participants have had more time to think about their responses by the time they complete the written questionnaire, and they may also be more likely to divulge negative feelings of the stimulus in their written responses. With both an interview and written questionnaire, the experimenter can gain insight into both the participant's initial impression and fully considered perception of the stimuli.

Research Limitations

Due to the exploratory nature of this research, several limitations prevented further exploration of differences due to possible effects such as age, weather, and social factors. It was possible to explore the effects of age for some variables, but there was not enough statistical power to determine any effects due to an age by haptic condition interaction.

As with any experiment, there are concerns with construct and face validity. While the Smart Road is an actual two-lane road and the intersection appears to be a normal, active light controlled intersection, participants were still aware of being on a test-track and in an experiment. The participants were exposed to experimenters and a vehicle different from their own; therefore, they may have exhibited altered or more cautious behavior compared to how they would normally respond in their own vehicle. Several participants cited not being on a "real road" or being "part of a study" as contributing to their decision to not stop or what they first thought when they felt the car braking. While the occlusion goggles were an effective means for "distracting" all participants at the same location with respect to the intersection, this is not the type of distraction that would occur with the normal driver.

This study also included a front-seat experimenter who was responsible for monitoring the driving and using the experimenter brake if needed; the participants may have believed that the front seat experimenter was braking rather than the haptic brake system. People may be more willing to put trust in another person than in an automatic system.

Another limitation with verbal warnings in general is the use of language. All participants included in this study understood and fluently spoke English, which is the language used for the verbal warning. The warning comprehension may drastically reduce if such a warning system were to be used with a driver who is not fluent in English.

Future Research

Future research should continue using the three haptic brake pulse warnings for which all participants stopped. The warning distance should be moved closer to the intersection to determine the optimal warning distance at which all drivers comply with the warning. The optimal haptic warning locations, both with and without the use of verbal warnings, should be determined.

Future research should continue to explore the effects of age and the age by haptic modality interactions. Due to a sensitive response (either high or low), only two jerk values were used in this study, although different jerk values should be evaluated as braking systems become easier to manipulate. Future research should also vary the duration between the pulses. Varying pulse-off-duration time could also be explored (e.g., 300ms after first pulse, then 200ms after second pulse). This graded warning idea could also be applied to the pulse-on-duration and the deceleration change, thus varying the duration of the pulse or the deceleration change as the situation becomes more urgent.

Haptic brake pulse warnings should also be explored across applications to determine if the same braking parameters are as effective for all warning situations (e.g., curve warnings, forward collision avoidance warnings, closer to the intersection for intersection collision avoidance warnings). The effectiveness of haptic brake pulse warnings should also be tested in different weather conditions to assure that there are no adverse effects.

Different audiences who are not fluent in English should also be included a similar study. The haptic brake pulse warnings may be advantageous to the group of driver who do not understand the verbal warning.

Finally, there are several applications and scenarios in which haptic brake pulse warnings can be used, such as intersection collision avoidance warnings, forward collision avoidance warnings, curve warnings, emergency brake assist, and adaptive cruise control. This research does show haptic brake pulse warnings to have some advantages, though it is recommended that research still be conducted on the various applications and scenarios before fully deploying this technology.

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APPENDIX A: Institutional Review Board Documentation

A.1 Expedited Review

REQUEST FOR APPROVAL OF RESEARCH INVOLVING HUMAN SUBJECTS:
Vehicle-Based Countermeasures for Signal and Stop Sign Violations: Intersection Collision Avoidance, Violation Warning (ICAV) Project DVI Experiment #2, Haptic Warnings, Phase I

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JUSTIFICATION OF RESEARCH PROJECT

Purpose of the Project

It is estimated that as many as 2.7 million crashes per year occur at intersections or are intersection related. These statistics have prompted government and corporate sponsored research to develop countermeasure systems that can enhance safety at intersections. One proposed system under development for this project monitors the road and intersection information, predicts the likelihood of the vehicle violating the intersection, and warns the driver in time to brake safely. It is believed that intersection accidents can be avoided if the driver is alerted to potential intersection violations. As part of developing such a system, the warning design must be effective and optimized. This experiment will present participants with intersection violation warnings with various attributes. In addition to driver performance variables (participants' ability to stop, deceleration level, etc.), subjective opinions regarding the warning will also be gathered.

Contribution of Research Findings

This experiment will present participants with haptic intersection violation warnings (either brake pulsing or seat vibration) that will vary in the number of pulses, pulse separation, and velocity change/vibration magnitude. The results from this research will be used to develop intersection violation warnings.

Findings of this research will directly contribute to the design of collision avoidance systems. The study will provide understanding of driver response timing and preferences for vehicle and system behavior. By understanding the capabilities of users, a system can be designed to complement and suit a user's needs. A violation warning system is expected to help prevent intersection crashes, since nearly all of these crashes occur when one or more drivers have violated the traffic control device. The findings should also be useful for algorithm developers for other types of collision avoidance systems. The outcome of this investigation may have a significant impact on driving safety, system usability, and design of future automated systems.

EXPERIMENTAL PROCEDURES

Participant Population

This study will use an on-road experiment with 32 participants, equally split by age and gender. Two age groups will be used: 18-30, and 50-65 years old. The participants will be recruited from the community via posted advertisements, the VTTI participant database, and word-of-mouth. Participants will be screened with a verbal questionnaire to determine if they are licensed drivers and if they have any health concerns that should exclude them from participating in the study. In compliance with the Virginia Tech Controller's Office, only drivers who report they are eligible for employment in the United States will be eligible to participate in this study. The attached Screening Questionnaire used for the study is provided in Appendix B and is the standard questionnaire used by the Virginia Tech Transportation Institute to screen participants. Drivers who have participated in similar intersection or surprise studies at VTTI will not be eligible. Selected participants will report to the Virginia Tech Transportation Institute for the experimental session which should consume approximately one and a half hours.

At the conclusion of the experiment, drivers will be asked to return to the Virginia Tech Transportation Institute where they will be compensated for their time at a rate of $20/hr. If the participant chooses to withdraw, he or she will be compensated for the portion of time of the study for which he or she participated.

Experimental Tasks

After arrival, participants will read an informed consent form and sign it if they agree to take part in the study (Appendix A). One of the experimental tasks requires an element of surprise. Therefore, it is not detailed on the initial informed consent form. Next, their license to operate a motor vehicle will be verified and they will be asked to fill out a Virginia Tech W-9 tax form. The Virginia Tech Controller's office has requested that these forms be submitted to them in the event that a participant receive a payment of $75.00 or greater. An eye exam will be administered at this time (must be better than 20/40 to operate a motor vehicle per Virginia law), followed by a color blindness test. Finally the participants will be asked to complete a medical questionnaire to verify they are not under the influence of any drugs or alcohol and do not have medical conditions that may impair their ability to drive (Appendix C).

After orientation, participants will enter the experimental vehicle and drive onto the Smart Road. The Smart Road provides a controlled access facility ensuring that only the experimental vehicles will be on the roadway during testing. There will be no interaction with atypical roadway obstacles or non-experimental vehicles. Tests will only be conducted during the daytime and with dry road conditions. Two in-vehicle experimenters will be present at all times. The front seat experimenter (FSE) will operate an auxiliary experimenter brake pedal should the need arise. The FSE will also provide instructions, answer questions as necessary, and administer any required questionnaires. The back seat experimenter (BSE) will be seated behind the FSE operating the computer system. Participants will drive loops on the Smart Road crossing a four-way signalized intersection where the data is collected.

Participants will initially be told that the experiment concerns the use of occlusion goggles to simulate distracted driving. Occlusion goggles allow experimenters to obstruct the driver's forward view for short periods of time (not to exceed two seconds in this case). These occlusion goggles were first used in a static experiment approved by the IRB in February of 2003 (Evaluation of Crosswalk Lighting Design, IRB #03-112). The occlusion goggles were also recently approved in an experiment using a very similar protocol evaluating the warning timing for intersection violations (IRB #04-322; June 18, 2004). Safeguards carried over from this previous IRB include:

- The original occlusion goggle wiring has been reversed so that the default state is now clear (before, the default state was opaque).
- The goggles have been rewired so that the vehicle power supply can be used instead of batteries. We feel this is a much safer and more reliable source of power for a dynamic experiment. As a back-up in case of vehicle power failure, a fresh battery will be installed in the power supply for the goggles every two weeks. The electrical connection will also be checked before each participant to make sure it is secure.
- The steering wheel will have a limited range of motion (±5º in the steering wheel, which equates to about ±1º at the front wheels) while the occlusion glasses are opaque so that the driver will not be able to deviate in the lane to a significant degree during those two seconds when the goggles are opaque. The bracket holding the steering wheel brake caliper travels with the turn of the steering wheel and thus centers the ±1° steering limits about the wheel position when the calipers are actuated. With this design, if the steering brake fails to unlock, the driver will be prevented from returning to a straight-ahead course if he is offset by more than 1-degree from 0° when the steering brake is actuated. For this reason, the onboard test monitor should avoid actuating the delimiter when the driver is not steering straight-ahead.
- The FSE will have an auxiliary brake pedal to use if necessary, and will also be able to reach the steering wheel if needed.
- The traveling speed for this experiment has been limited to 35 mph (in the original version of this experiment, without the occlusion goggles, we were going to use 45 mph as the top speed).
  - At 35 mph, if the vehicle is held within a ±1° heading on a straightaway section of the road, then the car could only travel laterally ≤ 0.9 ft during each second of occlusion. If the passenger seat monitor chooses to brake the car after it deviates across the shoulder line and he reacts in 0.4 seconds with an assumed-constant braking decel of 0.6g's, then the car should stop in 89 ft. If the car veers another

    - 4° upon braking, then traveling 89 ft at a 5° net incidence angle to the shoulder will place the front right corner of the car at 7.8 ft beyond the shoulder line.
    - Similarly, for 45 mph, the car could only wander laterally at 1.2 ft per sec occlusion. The monitor would need 139 ft to stop the car, placing it at 12.1 feet across the shoulder if the vehicle path takes a 5° heading relative to the shoulder.
    - The road curvature of 900m = 2953 ft radius would add: SQRT (89^2+2953^2) - 2953 = 1.35 ft. This added to the 7.8 ft displacement (for a 35mph & 5-deg veer off shoulder line) means the outer vehicle bumper corner could stop a little over 9 ft outside the shoulder line. Similarly, for the 45mph case requiring 139 ft to stop, a 900m radius would add about 3.3 ft more lateral displacement to the 5-deg offset, already at 12.1 ft.
- All debris will be cleared from the road shoulders in the areas where occlusions will occur, and no fixed obstacle will be located on the shoulder in the area where occlusions will occur. The road and shoulders will also be checked for and cleared of gravel or other debris that might impact braking or stopping distance.
- The occluded period has been limited to no more than 2 seconds, which represents the upper end of a look away from the forward view for a distracted driver.
- To enhance realism, there will be confederate vehicles on the road occasionally during the experiment, but the subject vehicle will never encounter the confederate vehicle when the goggles are occluded.
    - In order to make sure this does not happen, the BSE will secretly signal the confederate vehicle when it is safe to enter the roadway, and will not do so when the goggles are occluded. The confederate vehicle will not enter the roadway without this permission from the BSE that it is safe to do so.
- There will be a bail out signal if any unsafe conditions occur. This signal can be controlled by any experimenter and dispatch. The signal will alert all vehicles to immediately come to a stop and abort the experiment.

Participants will be told that they are to follow all the normal traffic rules. They will also be told that maintenance vehicles will occasionally be entering and leaving the road (this is really the confederate vehicle).

Participants will drive loops around the Smart Road at 35 mph, with occasional occlusion periods (of 2 seconds). They will make a “U” turn at the lower turnaround before reaching the Smart Road Bridge. As they approach the intersection, they will occasionally be presented with a changing light. The signal change will occur such that the decision to stop is obvious (signal turns red while car is still far from the intersection). The confederate vehicle will then cross the intersection from an adjacent approach and either leave or enter the roadway while the light is red and the subject vehicle is stopped.

As the participant begins the approach towards the intersection for the surprise presentation, a confederate vehicle will begin following the subject vehicle. The following vehicle will stay 3 seconds behind the subject vehicle as it nears the intersection. This vehicle is felt to be a necessary addition to the scenario to simulate real world conditions in which a signal violation warning might be presented and to obtain a driver's realistic reaction to such a warning (with following traffic and the possibility of cross traffic). In order to minimize any possibility of interaction between the subject vehicle and following vehicle, the following precautions will be taken:

- The following vehicle scenario will only be employed on the last trial. The driver of the following vehicle will be an alert, trained experimenter who will be expecting the lead vehicle to brake hard, and will have one foot over the brake to respond to the lead vehicle's braking as quickly as possible.
- In the event the occlusion goggles begin to malfunction, the participant may brake quickly and unexpectedly. The following vehicle driver will be alert and ready to brake the entire length of the road, not just at the intersection. The following vehicle driver will also steer off the road to further minimize the chance of an interaction with the lead vehicle.
- The following vehicle driver will stay 3.0 sec back (9 to 10-car lengths) as the vehicle near the intersection and react to the SV braking onset within 1.5 sec with a deceleration profile at least "comparable" to the SV driver.

For the surprise condition, the participants will be presented with an occlusion immediately prior to the signal changing to amber. When the occlusion has expired, they will see a red light, and might be expected to believe that the maintenance vehicle (really the confederate vehicle) is entering the road. However, the confederate vehicle will not be near the intersection at this time. This scenario is felt to be necessary to obtain a reaction closer to a driver's true reaction under real world conditions where traffic might be expected to enter an intersection. The participants will also be presented with a violation warning (haptic display) as the goggles clear.

Participants who stop in reaction to the warning will be asked to complete a short questionnaire, while those who do not stop will be asked to come to a stop and complete a different questionnaire. All questionnaires can be found in Appendix D. They will then be informed of the true purpose of the experiment and asked to read and sign a new informed consent form (Appendix A) detailing the true purpose of the experiment. They will then continue to evaluate the haptic warnings for 16 additional trials, after which the experiment will conclude.

The initial driver vehicle interface (DVI) presentation (haptic warning) must be unexpected to gather data as to how drivers of these systems might react the first time they encounter such a warning. The element of surprise is crucial to determine realistic reaction time in a time-critical situation. If all exposures are anticipated, the data will not be indicative of system efficacy. The informed consent form (Appendix A) indicates the nature of the research and its objectives. However, this experiment requires an element of concealment in that the subject will not know that an intersection violation warning will be presented to them. For this reason, a debriefing is considered desirable to explain the purpose and necessity of the surprise element and to obtain a second informed consent. The debriefing will also explain the project goals in terms of increasing driver safety. After signing the debriefing form and if they agree, the participants will continue to evaluate additional haptic warnings. They will be instructed to continue driving loops through the intersection, where they will receive additional warning presentations. After each presentation, they will answer a short questionnaire (Appendix D). The experiment will end after these additional evaluation trials.

RISKS AND BENEFITS

Participants may be exposed to the following risks or discomforts by volunteering for this research. They include the following:

1) The risk of an accident normally present while driving.
2) Any risk present when driving a new and unfamiliar vehicle.
3) The risk of driver stress due to the unexpected presentation of the intersection violation warning.
4) While participants are driving the vehicle, cameras will videotape them. Due to this fact, we will ask subjects not to wear sunglasses. If this at any time during the course of the experiment impairs their ability to drive the vehicle safely, they are instructed to notify the experimenter.
5) Participants who have had previous eye injuries are at an increased risk of further eye injury by participating in a study where risks, although minimal, include the possibility of collision and airbag deployment.

The following precautions will be taken to ensure minimal risk to the participants.

1) The surprise event will be conducted in a closed and controlled area (without interfering traffic).
2) The surprise event will be conducted away from potentially hazardous objects.
3) The back seat experimenter is able to prevent presentation of the surprise event if there is any reason to doubt the safety of those involved or risk to equipment.
4) Participants and in-vehicle experimenters will be required to wear the lap and shoulder belt restraint system while in the car. The vehicle is equipped with a driver's side airbag supplemental restraint system, fire extinguisher and first-aid kit.
5) All data collection equipment is mounted such that, to the greatest extent possible, it does not pose a hazard to the driver in any foreseeable case.
6) The experiment will not be run during hazardous road conditions, including foggy, wet or icy conditions.

In addition, the following safety precautions are in place to ensure a safe driving environment with the use of the occlusion goggles:

1. The original wiring has been reversed do that the default state is now clear (before, the default state was opaque).
2. The goggles have been rewired so that the vehicle power supply can be used instead of batteries. We feel this is a much safer source of power for a dynamic experiment.

3. The steering wheel will have a limited range of motion when the occlusion glasses are opaque so that the driver will not be able to deviate in the lane to a significant degree during the two seconds when the goggles are opaque.
4. The FSE will have an auxiliary brake pedal to use if necessary, and will also be able to reach the steering wheel if needed.
5. FSE also has a kill switch to terminate the steering limiter.
6. The traveling speed for this experiment has been limited to 35 mph (in the original version of this experiment, without the occlusion goggles, we were going to use 45 mph as the top speed).
7. The opaque period has been limited to no more than 2 seconds, which represents the upper end of a look away from the forward view for a distracted driver.
8. There will be confederate vehicles on the road occasionally during the experiment, but the subject vehicle will never encounter the confederate vehicle when the goggles are opaque.
9. The BSE will secretly signal the confederate vehicle when it is safe to enter the roadway, and will not do so when the goggles are opaque. The confederate vehicle will not enter the roadway without this permission form the BSE that it is safe to do so.

There are no direct benefits to the participant beyond potentially finding the experiment interesting. No promise or guarantee of benefits will be made to encourage subjects to participate. Subject participation may have significant impact on driving safety, system usability, and the design of future collision avoidance systems.

CONFIDENTIALITY / ANONYMITY

The data gathered in this experiment will be treated with confidentiality, and data collected will be used for research purposes only. Shortly after participants have participated, their name will be separated from their data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 3). Participants will be allowed to withdraw their data from the study if they so desire. Participants must inform the experimenter immediately of this decision, as the data will be difficult (if not impossible) to track once the session is over.

While the participant is driving the vehicle, cameras will videotape his or her eye and foot movements. Videotapes will be stored in a locked room at the Virginia Tech Transportation Institute. Video tapes will be converted to digital video and stored on a password protected server. Access to video will be under the supervision of Drs. Vicki Neale and Suzanne Lee, the Principal Investigator and Co-PI for the project. Participants will be asked for their permission to allow VTTI to turn over the videotape including their data and image to the client. Participants may refuse to allow the videotape of their image to be given to the client, and still be eligible to participate in the study. At no time will the researchers release the results of the study to anyone other than the client and individuals working on the project without participants' written consent.

INFORMED CONSENT

Please see attached sheets labeled *VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY: Informed Consent for Participants of Investigative Projects.*

A.2 Phase 1 and 2 Initial Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants of Investigative Projects

Title of Project: **INVESTIGATION OF THE USE OF OCCLUSION GOGGLES TO SIMULATE THE DISTRACTED DRIVER**

Investigators: Vicki Neale, Suzanne Lee, and Sarah Brown

I. The Purpose of this Research/Project

This experiment will look at whether future studies will be able to use a special type of goggles to examine driver distraction behavior. These goggles are called occlusion goggles, and they will blank out for up to 2 seconds while you are driving. We are interested in whether driver behavior during those 2 seconds is similar to the behavior of a driver who is looking away from the road for up to 2 seconds due to an in-vehicle distraction.

II. Procedures

1. Read and sign this Informed Consent Form (if you agree to participate).
2. Show a current valid driver's license.
3. Complete questionnaires.
4. Participate in the experimental session.

Your role during this session will be to drive a vehicle on the VTTI Smart Road facility. It is important that you understand that we are not evaluating you in any way. We are collecting information about drivers and the occlusion goggles.

III. Risks

Caution should be exercised when operating a vehicle with which you are not familiar. Be aware that accidents can happen at any time while driving.

Participants may be exposed to the following risks or discomforts by volunteering for this research. They include the following:

1) The risk of an accident normally present while driving.
2) Any risk present when driving a new and unfamiliar vehicle.
3) While you are driving the vehicle, cameras will videotape you. Due to this fact, we may ask you not to wear sunglasses. If this at any time during the course of the experiment this impairs your ability to drive the vehicle safely, please notify the experimenter.

4) If you have had previous eye injuries you are at an increased risk of further eye injury by participating in a study where risks, although minimal, include the possibility of collision and airbag deployment.

The following precautions will be taken to ensure minimal risk to you:

1) You may take breaks or decide not to participate at any time.
2) The vehicle is equipped with a driver's side and passenger's side airbag supplemental restraint system, fire extinguisher and first-aid kit.
3) You do not have a history of back or neck conditions.
4) You are not pregnant.
5) You do not have a history of heart conditions.
6) You have not had epileptic seizures within the last twelve months or diabetes for which insulin is required.
7) All data collection equipment is mounted such that, to the greatest extent possible, it does not pose a hazard to you in any foreseeable case.
8) The experiment will not be run during hazardous road conditions, including wet or icy conditions.
9) You are required to wear the lap and shoulder belt restraint system while in the car.
10) In the event of a medical emergency, or at your request, VTTI staff will arrange medical transportation to a nearby hospital emergency room.

In the event of an accident or injury in an automobile, the automobile liability coverage for property damage and personal injury is provided. The total policy amount per occurrence is $2,000,000. This coverage (unless the other party was at fault, which would mean all expense would go to the insurer of the other party’s vehicle) would apply in case of an accident for all volunteers and would cover medical expenses up to the policy limit.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation; under Commonwealth of Virginia law, workers compensation does not apply to volunteers; therefore, if not in an automobile, the participants are responsible for their own medical insurance for bodily injury. Appropriate health insurance is strongly recommended to cover these types of expenses.

IV. Benefits of this Project

While there are no direct benefits to you from this research, you may find the experiment interesting. No promise or guarantee of benefits is made to encourage you to participate. Participation in this study will contribute to the improvement of future studies concerning advanced vehicle systems.

V. Extent of Anonymity and Confidentiality

The data gathered in this experiment will be treated with confidentiality. Shortly after participation, your name will be separated from your data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 1). You will be allowed to see your data and withdraw the data from the study if you so desire, but you must inform the experimenters immediately of this decision so that the data may be promptly removed. At no time will the researchers release data identifiable to an individual to anyone other than individuals working on the project without your written consent. VTTI will not turn over the video of your image to the client without your permission.

VI. Compensation

You will be paid $20.00 per hour for participating. You will be paid at the end of this study in cash.

VII. Freedom to Withdraw

As a participant in this research, you are free to withdraw at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations without penalty.

VIII. Approval of Research

Before data can be collected, the research must be approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Virginia Tech Transportation Institute. You should know that this approval has been obtained.

IX. Participant Responsibilities

If you voluntarily agree to participate in this study, you will have the following responsibilities:

1. To follow the experimental procedures as well as you can.
2. To inform the experimenter if you have difficulties of any type.
3. To wear your seat and lap belt.
4. To abide by the posted speed limits and traffic laws.
5. To abstain from any substances that will impair your ability to drive.
6. To drive the test vehicle in a safe and responsible manner.

X. Participant's Permissions and acknowledgments

Check one of the following:

☐ I have **not** had an eye injury/eye surgery (including, but not limited to, LASIK, Radial Keratotomy, and cataract surgery.)

- ☐ I **have** had an eye injury/eye surgery and I've have been informed of the possible risks to participants who have had eye surgery. I choose to accept this possible risk to participate in this study.

Check one of the following:

- ☐ VTTI **has my permission** to give the videotape including my image to the client who has sponsored this research. I understand that the client will only use the videotape for research purposes.

- ☐ VTTI **does not have my permission** to give the videotape including my image to the client who has sponsored this research. I understand that VTTI will maintain possession of the videotape, and that it will only be used for research purposes.

Check all that apply:

- ☐ I am not under the influence of any substances which may impair my ability to safely operate a vehicle.
- ☐ I am not pregnant.
- ☐ I do not have lingering effects of a heart condition.
- ☐ I do not have a history of neck or back injury or pain that could place me at higher risk of injury if an accident were to occur.
- ☐ I have not had epileptic seizures within the past 12 months.
- ☐ I do not have diabetes for which insulin is required.

XI. Participant's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

____

Signature Date

Should I have any questions about this research or its conduct, I may contact:

Vicki Neale	231-1500
Suzanne Lee	231-1500
Sarah Brown	231-1500
David Moore (Institutional Review Board Chair)	231-4991

A.3 Phase 1 and 2 Debriefing and New Informed Consent

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants of Investigative Projects

Debriefing and Informed Consent for Participants of Investigative Projects

Title of Project: Vehicle-Based Countermeasures for Signal and Stop Sign Violations: Intersection Collision Avoidance, Violation Warning (ICAV) Project *DVI Experiment #2, Haptic Warnings, Phase 1*
Investigators: Vicki Neale, Suzanne Lee, and Sarah Brown

THE PURPOSE OF THIS RESEARCH
The true purpose of this research is to evaluate the timing of intersection violation warnings. One aspect of the research project deals with how people might respond to such a warning the first time they encounter it. To do this, we needed to create a situation where you were presented with the warning while looking away from the road in front of you. If you had been looking directly at the road, you might have seen the light turn red and the data would not have been as useful. There was no “correct” or “incorrect” information in the data that you provided. We needed to compare your response to others who were presented with the same situation. All known precautions were taken to ensure your complete safety throughout this session and during the presentation of the scenario. We would like to thank you for your participation in this study, as the results may contribute to future improvements of collision avoidance systems. We would also like to ask that you do not talk about the details of this study to others for at least 8 months after your participation as this may invalidate future data that may be collected.

We again assure you that all data will be treated with complete anonymity. Shortly after participating, your name will be separated from the data. A coding scheme will be employed to identify the data by subject number only (for example, Subject No. 3).

We will continue running the experiment, and you will be presented with additional intersection violation warnings. A short questionnaire for you to answer will be given after each warning presentation.

All other aspects of the earlier informed consent you signed, including risks, benefits, safety precautions, and your responsibilities, continue to apply to the remainder of this experiment.

I hereby acknowledge the above and give my voluntary consent for my data to be used in this project.

____
Participant's Signature Date

Should I have any questions about this research or its conduct, I may contact:

Vicki Neale	231-1500
Suzanne Lee	231-1500
Sarah Brown	231-1500
David Moore (Institutional Review Board Chair)	231-4991

A.4 IRB Expedited Approval

Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Institutional Review Board

Dr. David M. Moore
IRB (Human Subjects) Chair
Assistant Vice President for Research Compliance
CVM Phase II Duckpond Dr., Blacksburg, VA 24061-0442
Office: 540/231-4991, FAX: 540/231-6033
email: moored@vt.edu

DATE: September 21, 2004

MEMORANDUM

TO: Vicki Neale VTTI 0536
Suzanne E. Lee VTTI 0536
Sarah Brown ISE 0118

FROM: David Moore

SUBJECT: **IRB Expedited Approval:** "Vehicle-Based Countermeasures for Signal and Stop Sign Violations: Intersection Collision Avoidance, Violation Warning (ICAV) Project, *DVI Experiment #2, Haptic Warnings, Phase I*" IRB # 04-441

This memo is regarding the above-mentioned protocol. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective September 14, 2004.

cc: File
Department Reviewer Jon Hankey VTTI 0536

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An Equal Opportunity/Affirmative Action Institution

APPENDIX B: Driver Screening and Demographic Questionnaire

Note to Researcher:
Initial contact between participants and researchers may take place over the phone. If this is the case, read the following Introductory Statement, followed by the questionnaire. Regardless of how contact is made, this questionnaire must be administered verbally before a decision is made regarding suitability for this study.

Introductory Statement:
After prospective participant calls or you call them, use the following script as a guideline in the screening interview.

Hello. My name is _____ and I'm a researcher with the Virginia Tech Transportation Institute in Blacksburg, VA. We are currently recruiting people to participate in a research study.
This study involves participating in one driving session during daylight hours. The session lasts approximately one hour. Participants will be paid $20.00 per hour. Participants will drive a vehicle that will be equipped with data collection equipment on the Smart Road and grounds of VTTI. Does this sound interesting to you?

First, I would like to collect some information from you. A researcher will then review this information. You will be contacted at a later date to let you know if you are eligible.

1. **Do you have a valid driver's license?**
    - **Yes**
    - **No**

2. **How old are you? _______________**

3. **How often do you drive each week?**

    Every day ____ At least 2 times a week___ Less than 2 times a week_____

4. **Are you eligible for employment in the United States?**
    - **Yes**
    - **No**

5. **How long have you held your driver's license? _________________**

6. **Are you able to drive an automatic transmission without assistive devices or special equipment?**

- **Yes**
- **No**

7. Have you participated in any experiments at the Virginia Tech Transportation Institute? If "yes," please briefly describe the study.
- **Yes ____**
- **No**

8. Have you had any moving violations in the past 3 years? If so, please explain.
- **Yes ____**
- **No**

9. Have you been involved in any accidents within the past 3 years? If so, please explain.
- **Yes ____**
- **No**

10. Do you have a history of any of the following? If yes, please explain.

Heart Condition	**No____**	**Yes________________________________**
Stroke	**No____**	**Yes________________________________**
Brain tumor	**No____**	**Yes________________________________**
Head injury	**No____**	**Yes________________________________**
Neck or back pain or injury	**No____**	**Yes________________________________**
Epileptic seizures	**No____**	**Yes________________________________**
Respiratory disorders	**No____**	**Yes________________________________**
Motion sickness	**No____**	**Yes________________________________**
Inner ear problems	**No____**	**Yes________________________________**
Dizziness, vertigo, or other balance problems	**No____**	**Yes________________________________**
Diabetes	**No____**	**Yes________________________________**
Migraine, tension headaches	**No____**	**Yes________________________________**

11. **(Females only, of course) Are you currently pregnant?** ***If yes, explain that they can not participate because this is a research study where we are unable to give complete details of all the tasks prior to their participation. This makes them unable to discuss with their doctor all the risks involved.***
- **Yes _____**
- **No _____**

12. Are you currently taking any medications on a regular basis? If yes, please list them.
- **Yes ____**
- **No**

13. **Do you have normal or corrected to normal hearing and vision? If no, please explain.**
    - **Yes**
    - **No** ____

Criteria for Participation:

1. ***Must hold a valid driver's license.***
2. ***Must be 18-30 or 50-65 years of age.***
3. ***Must be eligible for employment in the U.S.***
4. ***Must drive at least 2 times a week.***
5. ***Must have normal (or corrected to normal) hearing and vision.***
6. ***Must be able to drive an automatic transmission without special equipment.***
7. ***Must not have more than two driving violations in the past three years.***
8. ***Must not have caused an injurious accident in the past two years.***
9. ***Must not have lingering effects of back or neck injury or pain.***
10. ***Cannot have lingering effects of heart condition, brain damage from stroke, tumor, head injury, recent concussion, or infection. Cannot have had epileptic seizures within 12 months, respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, chronic migraine or tension headaches.***
11. ***Cannot currently be taking any substances that may interfere with driving ability (cause drowsiness or impair motor abilities).***
12. ***Must not have been a participant in previous Rear Video I or II, ACC/A Day 3, Rear Lighting Task 3 (Smart Road study), or other surprise studies.***
13. ***Must not be pregnant.***

Name ____

Age ____________

Phone Number ________________________

Best Time/Day to Call ____

Date and Time Scheduled ____

APPENDIX C: Health Screening Questionnaire

Health Screening Questionnaire

1. Are you in good general health? Yes No

   If no, list any health-related conditions you are experiencing or have experienced in the recent past.

   ____
   ____
   ____

2. Have you, in the last 24 hours, experienced any of the following conditions?

Inadequate sleep	Yes	No
Hangover	Yes	No
Headache	Yes	No
Cold symptoms	Yes	No
Depression	Yes	No
Allergies	Yes	No
Emotional upset	Yes	No

3. Do you have a history of any of the following?

Visual Impairment	Yes	No

(If yes, please describe.)

____
____
____

Seizures or other lapses of consciousness	Yes	No

(If yes, please describe.)

____
____
____

Any disorders similar to the above or that would impair your driving ability	Yes	No

(If yes, please describe.)

____
____
____

4. List any prescription or non-prescription drugs you are currently taking or have taken in the last 24 hours.

____
____

5. List the approximate amount of alcohol (beer, wine, fortified wine, or liquor) you have consumed in the last 24 hours.

____
____

6. Are you taking any drugs of any kind other than those listed in 4 or 5 above?

Yes No

______________________________ ______________________________
Signature Date

Vision Test (Snellen) __________________

Color vision: ____________

____

____

____

____

____

APPENDIX D: Post-Event Questionnaires

D.1 Retrospective interview

Given verbally by the experimenter

Before giving questionnaire- ask the following questions

1) Did you notice anything unusual before you stopped? (If participant stopped)

1) Did you notice anything unusual while you were approaching the intersection? (If participant did not stop)

(Yes)

2) Describe what you noticed?

(No)

Did you feel the car begin to slow down? (if no, go on to other questionnaire)

(If a mention of feeling braking)

3) Describe what the brakes did?

4) Did you feel a constant brake or pulses?

(Pulses)

5) How many pulses did you feel?

D.2 Post-Event Questionnaire for Those Who Stopped

The true purpose of this research is to evaluate intersection violation warnings. One aspect of the research project deals with how people might respond to such a warning the first time they encounter it. To do this, we needed to create a situation where you were presented with the warning while not looking at the road in front of you. If you had been looking directly at the road, you might have seen the light turn red and the data would not have been as useful. There was no "correct" or "incorrect" information in the data that you provided. We needed to compare your response to others who were presented with the same situation. All known precautions were taken to ensure your complete safety throughout this session and during the presentation of the scenario. Let the experimenter know at this time if you would like further explanation before completing this questionnaire.

Questionnaire

There was no "correct," "incorrect," or expected way for you to respond.

Please **circle one number** that most closely corresponds to your experience during this stop.

1. What did you think about the effectiveness of the warning to alert you?

Very Ineffective	1	2	3	4	5	6	7	Very Effective

2. What did you perceive the warning urgency to be?

Not At All Urgent	1	2	3	4	5	6	7	Very Urgent

3. How likable was the warning?

Not At All Likeable	1	2	3	4	5	6	7	Very Likeable

4. How annoying was this warning?

Not At All Annoying	1	2	3	4	5	6	7	Very Annoying

5. I expected the light to change as I approached the intersection.

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

6. What do you think about the timing of the warning?

Very Early	1	2	3	4	5	6	7	Very Late

7. How comfortable was the stop you just made?

Very Uncomfortable	1	2	3	4	5	6	7	Very Comfortable

8. Please rate your level of vehicle control during the stop you just made.

Very Much In Control	1	2	3	4	5	6	7	Very Much Out of Control

9. Please rate your feeling of safety during the stop.

Very Safe	1	2	3	4	5	6	7	Very Unsafe

10. How trustworthy was this warning?

Not At All Trustworthy	1	2	3	4	5	6	7	Very Trustworthy

11. How reliable was this warning?

Not At All Reliable	1	2	3	4	5	6	7	Very Reliable

12. Please describe what you first thought when you felt the braking?

13. What did you think was happening when felt the braking?

D.3 Post Event Questionnaire for Those Who Did Not Stop

The true purpose of this research is to evaluate intersection violation warnings. An intersection violation warning would detect a vehicle that is likely to run the red and warn that driver such that a collision could be avoided. One aspect of the research project deals with how people might respond to such a warning the first time they encounter it. To do this, we needed to create a situation where you were presented with the warning while not looking at the road in front of you. If you had been looking directly at the road, you might have seen the light turn red and the data would not have been as useful. There was no "correct" or "incorrect" information in the data that you provided. We needed to compare your response to others who were presented with the same situation. All known precautions were taken to ensure your complete safety throughout this session and during the presentation of the scenario. Let the experimenter know at this time if you would like further explanation before completing this questionnaire.

Questionnaire

There was no "correct," "incorrect," or expected way for you to respond.

Please **circle one number** that most closely corresponds to your experience during this stop.

1. What did you think about the effectiveness of the warning to alert you?

Very Ineffective	1	2	3	4	5	6	7	Very Effective

2. What did you perceive the warning urgency to be?

Not Urgent At All	1	2	3	4	5	6	7	Very Urgent

3. How likable was the warning?

Not Likable At All	1	2	3	4	5	6	7	Very Likeable

4. How annoying was this warning?

Not At All Annoying	1	2	3	4	5	6	7	Very Annoying

5. I expected the light to change as I approached the intersection.

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

6. What do you think about the timing of the warning?

Very Early	1	2	3	4	5	6	7	Very Late

7. Why did you decide not to stop?

8. If I had decided to stop the car it would have been:

Not At All Difficult	1	2	3	4	5	6	7	Very Difficult

9. Please rate your feeling of safety as you crossed the intersection

Very Safe	1	2	3	4	5	6	7	Very Unsafe

10. How trustworthy was this warning?

Not At All Trustworthy	1	2	3	4	5	6	7	Very Trustworthy

11. How reliable was this warning?

Not At All Reliable	1	2	3	4	5	6	7	Very Reliable

12. Please describe what you first thought when you felt the braking?

13. What did you think was happening when felt the braking?

D.4 Questionnaire for Additional Trials

Please **say one number** that most closely corresponds to your opinion about the warning. The experimenter will record your answers.

1. How many pulses did you feel?

0 1 2 3 4 5 6 7 8 9 10 more

2. What did you think about the effectiveness of the warning to alert you?

Very Ineffective	1	2	3	4	5	6	7	Very Effective

3. What did you perceive the warning urgency to be?

Not Urgent At All	1	2	3	4	5	6	7	Very Urgent

4. How likable was the warning?

Not Likable At All	1	2	3	4	5	6	7	Very Likeable

5. How annoying was this warning?

Not At All Annoying	1	2	3	4	5	6	7	Very Annoying

6. How trustworthy was this warning?

Not At All Trustworthy	1	2	3	4	5	6	7	Very Trustworthy

7. How reliable was this warning?

Not At All Reliable	1	2	3	4	5	6	7	Very Reliable

8. Please describe what you thought about this warning

APPENDIX E: Protocols

E.1 In-Building Experimenter

Preparation and Participant Orientation

---

1. Set up the conference room
- Make sure to have pens
- Make sure to have a watch to know when the participant arrives
- Packets with all the necessary forms
- Close all the shades
- Turn on all overhead lights
- Turn off halogen lamps

2. Make sure the participant packets include the following:
- Time In/Out Debriefing Form
- Informed Consent (2 copies)
- Health Screening
- W-9 Form

3. Greet Participant

4. Record the time that the participant arrived on the debriefing form

5. Show driver's license
- Must be a valid Class A driver's license. Out of state is fine.
- Check to make sure it has not expired

6. Informed consent
- Give the participant the form- Encourage them to read it before signing it!
- Answer questions
- Make sure they check one of the boxes in the video release section
- Have participant sign and date the form and the copy
- Give the participant a copy of the informed consent

7. Vision Tests

Record the results for the 2 vision tests on the Vision Test Form

a) The first test is the Snellen eye chart test.

Take the participant over to the eye chart test area.
Line up their toes to the line on the floor (20 feet).

Participants can leave on their glasses if they wear them for driving.

Procedure: *Look at the wall and read aloud the smallest line you can comfortably read.*

If the participants get every letter on the first line they try correct have them try the next smaller line. Continue until they miss a letter. At that time, record the one that they were able to read in full (line above).
If they get the first line they attempt incorrect, have them read the previous line. Repeat as needed until they get one line completely correct. Record this acuity.
Participant must have 20/40 or better vision using both eyes to participate in the study.

b) Vision Test for Color Blindness.

Procedure:
Take the participant back to his/her desk.
Place the book containing the plates on the testing apparatus

Please hold the red end of this handle to your nose and read the number on the following plates.

Record the participant's answers on the Health Screening Form

8. Describe the Experiment

Read the following to the participant

We are now ready to go out to the vehicle where we will give you further instructions.

Answer all questions, once finished inform the participant that it is time to begin the study. Inform them you will be on the roadway for about an hour and a half and that it will be difficult to use a restroom during that time. Recommend they use the restroom before leaving.

E.2 Experimenter Protocol

1. **Orient driver to the vehicle**
    - Seat Adjustment
    - Mirror Adjustment
    - Gear Shift
    - Tell them they can control the HVAC, but that we won't be using any of the other buttons on the center stack.
    - Tell them not to turn the vehicle off

2. **Signal dispatch when ready**
    - Confirm with driver that they are ready

3. **Give directions**
    - To the Smart Road

4. **Read script to participant**

    The purpose of this study is to determine how well our occlusion goggles can simulate driver distraction for a series of future studies.

    Show them the occlusion goggles. Put the glasses on the participant.

    These are the occlusion goggles. You will be wearing them throughout the study. The goggles will go blank or occlude for about 2 seconds. (Demonstrate) *We will be occluding you at random intervals while you are driving up and down the road. While you are occluded, continue to drive normally. We will be collecting data such as lane position and speed maintenance as you drive.*

    We are both trained experimenters. We have taken every precaution possible to ensure your safety. We would like for you to maintain 35 mph while you are driving, including during periods of occlusion. You do not need to maintain 35 mph through the turnarounds. This is the upper turnaround. I will show you the lower turnaround as we approach it. Use a comfortable speed through these turnarounds. To help you maintain 35mph, we'll have you put the car in 3rd gear. You should obey all usual traffic rules and regulations at all times.

    The occlusions will occur at random intervals controlled by the computer. But for safety they will not occlude while you are in the turnarounds. If the goggles *do occlude during a turnaround, or if the occlusions ever last longer than 2 seconds please alert me so that I can reset the program. In the unlikely event that the goggles blink or act inconsistently, please inform me so that I can make any necessary adjustments. Also please hold any non-urgent conversation or questions until after the experiment. It's important that we focus on vehicle performance and data collection.*

Do you have any questions you'd like to ask before we begin?

5. Debrief after surprise DVI presentation

- Make sure they understand and sign new informed consent form
- Answer any questions about why the surprise was necessary

6. Complete All Trials

- Make periodic checks to see that the data acquisition is functional
- If problem arises re-run trial on following loop
- Make notes of all discrepancies and re-runs

7. Return to the building

- Guide participant to a parking location
- Walk back to the screening room
- Answer any questions

8. Pay the participant $20 per hour

- Ask them to sign the payment log

APPENDIX F: Questionnaire Responses

F.1 Verbal Responses

#P	Stop/Did Not Stop	Group	Notice anything unusual	(Yes) Describe what you noticed	(No) feel the car begin to slow down	Describe what the brakes did	Constant brake or pulses?	How many pulses	Extra experimenter notes
506	Stopped	600ms-1 pulse	Light about to turn yellow. Didn't press brake- everyone shifted forward "it stopped".			Thought there was something wrong, "thought someone pushed the brake", Reacted then when saw it turn yellow	No, I didn't, once brake hit- I hit		
507	Stopped	600ms-1 pulse	It was if brakes were applied automatically	Nose of the car dipped, light changed			Wasn't long enough to feel pulses, brake was applied then saw light so then I applied the brake		first brake was a surprise- but was not disconcerting, did not startle him
508	Stopped	600ms-1 pulse	It did go blank- anticipated		Oh yeah "who did that?"	felt like brakes applied unusually hard			Did not register as a warning, did not like that warning, realized it was the vehicle braking- did not realize front seat experimenter had a brake
509	Stopped	600ms-1 pulse	No		yes	Felt like someone put the brake on for me			Thought someone else was doing it or something was wrong with the

#P	Stop/Did Not Stop	Group	Notice anything unusual	(Yes) Describe what you noticed	(No) feel the car begin to slow down	Describe what the brakes did	Constant brake or pulses?	How many pulses	Extra experimenter notes
									car, or I hit something
511	Stopped	600ms-1 pulse	Yes	the car jerked, slowed down		felt like brakes "slammed on"	constant		
519	Stopped	600ms-1 pulse		the brakes caught		they didn't completely lock up, but they were "ahead of me"	constant brake or 1 long pulse		
520	Did Not Stop	600ms-1 pulse	The brakes hit before he hit them			had foot over brake & left from under foot (during occlusion)	a pulse		
549	Stopped	600ms-1 pulse	yeah	car jerked, like out of control			don't remember	2 brakes- pretty strong	
527	Stopped	600ms- 3 pulses	goggles went blank		Did notice car braking on own				
529	Stopped	600ms- 3 pulses	It tried to stop for me, something other than me put brake on				a pulse	1	seemed like he then had to push the brake harder
533	Stopped	600ms- 3 pulses	It was scary, reaction time was quick after it went		yes		constant brake		
535	Stopped	600ms- 3 pulses	It went off right as the light turned yellow, then car stopped itself				constant brake- seemed like ABS		
540	Stopped	600ms- 3 pulses	No, other than it was occluded saw car closing in		Yes, thank you for reminding me- outside of control		2 distinct braking events- first outside of control, second him doing it		
544	Stopped	600ms- 3	brakes came on				pulses	3	

#P	Stop/Did Not Stop	Group	Notice anything unusual	(Yes) Describe what you noticed	(No) feel the car begin to slow down	Describe what the brakes did	Constant brake or pulses?	How many pulses	Extra experimenter notes
		pulses							
546	Stopped	600ms- 3 pulses	yes	car brake on its own			1 hard brake	1	
547	Stopped	600ms- 3 pulses	yeah	felt like my brakes were on before I put them on			pulses	2	
553	Stopped	600ms- 3 pulses	yes	car braked on its own			1 hard brake		
525	Stopped	380ms- 3 pulses	Guy was following, missed the line		No				
531	Stopped	380ms- 3 pulses	the car started braking				pulses	2 or 3	
532	Stopped	380ms- 3 pulses	yeah felt car slowing down for me				1 pulse		"Oh wow, did you do that?"
545	Did not stop	380ms- 3 pulses	Think there was a blank out		brake		pulses	2 or 3	
548	Stopped	380ms- 3 pulses	yeah	brakes hit themselves			ABS	1 or 2	
554	Did not stop	380ms- 3 pulses	the brakes felt like someone hit the brakes & went through red light				felt like constant then let up		
566	Stopped	380ms- 3 pulses	felt like someone else was helping me brake				constant		
567	Stopped	380ms- 3 pulses	yeah the occlusion went off when it was green, then the car stopped- just as it stopped occlusion cleared				it was pulses- felt it then I hit brake	1	
536	Stopped	160ms-3 pulses	yes	felt like the car started braking before I hit the brake			like constant brake- was about 1 second		
550	Stopped	160ms-3 pulses	yeah	juttering with the accelerator, uneveness, like engine was dying,					

#P	Stop/Did Not Stop	Group	Notice anything unusual	(Yes) Describe what you noticed	(No) feel the car begin to slow down	Describe what the brakes did	Constant brake or pulses?	How many pulses	Extra experimenter notes
				no normal					
552	Stopped	160ms-3 pulses	yeah	car was putting on its own brake			pulses	2	
555	Stopped	160ms-3 pulses	yeah	felt like it was stopping itself			pulse- then it made me want to brake	1	
560	Stopped	160ms-3 pulses	the blackout thing happened before I was supposed to stop for light		yeah- car began to slow down & thing blacking out				
563	Stopped	160ms-3 pulses	yeah	Did you do it? (to front seat experimenter)			pulses	2	
568	Stopped	160ms-3 pulses	Why did it jerk? Like I didn't have control				pulses	2 or 3	
571	Stopped	160ms-3 pulses	Car malfunctioned	it cut in & out, either electrically or gas, obviously planned		I was doing the braking		2 or 3	
522	Stopped	160ms-continuous pulses	Car hit brakes on its own					1	
523	Stopped	160ms-continuous pulses	Felt him (front seat experimenter) brake				constant		
524	Stopped	160ms-continuous pulses	uh-huh	something wanted to stop me before I pressed the brake pedal			pulses	2	
528	Stopped	160ms-continuous pulses	yeah	started stopping on its own, took several seconds to stop			pulses	3	
530	Stopped	160ms-continuous pulses	There was a guy behind, the things occluded		When I didn't slow down when it was occluded- it				

#P	Stop/Did Not Stop	Group	Notice anything unusual	(Yes) Describe what you noticed	(No) feel the car begin to slow down	Describe what the brakes did	Constant brake or pulses?	How many pulses	Extra experimenter notes
					slowed down for me, I don't know if I put on the brakes first, felt like it braked during the occlusion				
538	Stopped	160ms-continuous pulses	Yes, I did	When it blanked out couldn't tell if light was changing- made it difficult to stop	yes, I did		felt more like a jerk		
539	Stopped	160ms-continuous pulses	The brakes seemed to work themselves				pulses	2	
543	Stopped	160ms-continuous pulses	Yes	it grabbed as if stopping on its own			pulses	3	
574	Stopped	600ms- 3 pulse + Aud	Said "stop" & the car stopped				constant brake		
575	Stopped	600ms- 3 pulse + Aud	yelling stop, did the car slow down on its own at all " I don't know"	Definitely felt it slow down on its own			constant		
578	Stopped	600ms- 3 pulse + Aud	Thought I saw flash, heard person say stop		"yeah"		constant		
579	Stopped	600ms- 3 pulse + Aud	Car alarm, the car kind of jerked itself said "stop"				Don't know maybe pulses		
580	Stopped	600ms- 3 pulse + Aud	No		Heard person saying "stop", might have been some braking sensation				

#P	Stop/Did Not Stop	Group	Notice anything unusual	(Yes) Describe what you noticed	(No) feel the car begin to slow down	Describe what the brakes did	Constant brake or pulses?	How many pulses	Extra experimenter notes
					wasn't really sure				
581	Stopped	600ms- 3 pulse + Aud	Caution light coming on, told me to stop, sort of stopped on its own				pulses		
582	Stopped	600ms- 3 pulse + Aud	Pulling in the car, did hear person say "stop", felt like car braking				constant kind of like it wanted to stop itself		
584	Stopped	600ms- 3 pulse + Aud	Yeah- flash or something traffic light tweaked red, wondering first where voice came from		when voice said stop, noticed a jerk in the car, a hesitation in the transmission, transmission went into another gear				

F.2 Open-ended Question Responses

P#	Stopped/Did Not Stop	Group	First thought	Happening
506	Stopped	600ms-1 pulse	Something was wrong or I did something wrong in the study. There could have been a vehicle approaching	I did something wrong which needed the correction of another person in the car. (like when getting Driver's License test).
507	Stopped	600ms-1 pulse	Unexpected	No idea
508	Stopped	600ms-1 pulse	An emergency just occurred	Didn't know
509	Stopped	600ms-1 pulse	I thought something was wrong with the car.	Still thought something was wrong with the car
511	Stopped	600ms-1 pulse	the car motor may have stopped	testing had made it do that
519	Stopped	600ms-1 pulse	Just wondered what it was, caught me a little off guard	Either to help me or the experimenters were stopping the car for safety reasons
520	Did Not Stop	600ms-1 pulse	I was crossing lanes or doing something wrong	The car was stalling out or malfunctioning, didn't really think it was a warning until I saw the light.
549	Stopped	600ms-1 pulse	I just wondered what was going on	Didn't have a clue!
527	Stopped	600ms- 3 pulses	Wasn't sure what was going on	I thought the car was equipped with pedals on the passenger side like drivers education cars and the passenger pressed the break.
529	Stopped	600ms- 3 pulses	The brakes jammed or the car malfunctioned. I did not know the light had changed, so I did not think of the braking as a warning.	Something was wrong with the car or with the brakes
533	Stopped	600ms- 3 pulses	Oh I need to stop	I thought something was wrong with the car
535	Stopped	600ms- 3 pulses	I thought they installed an automatic stop device so I would not run a red light	The car was coming to a stop I knew it was not a car malfunction
540	Stopped	600ms- 3 pulses	Surprise	The experiment was over
544	Stopped	600ms- 3 pulses	That I was to stop the car	part of the test
546	Stopped	600ms- 3 pulses	scared	I thought someone in the vehicle saw the light turn red
547	Stopped	600ms- 3 pulses	I though the brake was being applied for me	I thought I had done something wrong
553	Stopped	600ms- 3 pulses	I felt that the vehicle was having problems	that an occurrence was happening with which I had very little control
525	Stopped	380ms- 3 pulses	I thought that the car was slowing down a bit quicker than usual when I decelerated, and felt a need to slow down gradually incase the light changed	That the care was lowing down quicker than usual. It was kind of like a premonition.
531	Stopped	380ms- 3 pulses	I was wondering if the light was changing, and if I would be able to stop	That I was going through the light and it was red
532	Stopped	380ms- 3 pulses	Distracted, scared	Not sure, but figured the light was changing or I

P#	Stopped/Did Not Stop	Group	First thought	Happening
				had done something wrong
545	Did not stop	380ms- 3 pulses	I didn't know what to think, so I stayed the course…. In other words, don't panic!	The car was acting crazily!
548	Stopped	380ms- 3 pulses	Felt like ABS system coming on	Brakes were locking up
554	Did not stop	380ms- 3 pulses	something was wrong	not sure- I guess I was a little confused
566	Stopped	380ms- 3 pulses	Sara in the back seat was braking for me. Glad it was there so I could make red light	Sara was worried I wouldn't stop and but would start into intersection
567	Stopped	380ms- 3 pulses	I instantly looked at the traffic light to see if it had turned while the occlusion was on.	I thought the experimenter had a separate brake like the student driver cars, and she was pressing it.
536	Stopped	160ms-3 pulses	I thought the light had unexpectedly turned red and the researchers were stopping the car to avoid hitting another car	See above, while I wasn't entirely sure why the vehicle was stopping, I immediately hit the brake.
550	Stopped	160ms-3 pulses	problem with engine	thought engine was misfiring
552	Stopped	160ms-3 pulses	I recognized it a signal that the light was changing, I considered accelerating to make the light until I felt the signal; then was surprised at how easy it was to brake in time	see above
555	Stopped	160ms-3 pulses	it at first scared me, but then I realized it was probably part of the study	I thought the car was falling apart
560	Stopped	160ms-3 pulses	That the study was controlling my moves, even though I had anticipated what was going to happen at the intersection, and I didn't like it!	same as above
563	Stopped	160ms-3 pulses	There was a red light and the passenger braked since I could not see.	The passenger was braking
568	Stopped	160ms-3 pulses	I thought Sarah was braking from the rear seat	
571	Stopped	160ms-3 pulses	Planned car malfunction	car malfunction
522	Stopped	160ms- continuous pulses	I thought that I did not see the red light and the person next to me had her own break pedal which she hit	I thought the car was coming to a stop
523	Stopped	160ms- continuous pulses	that I didn't stop soon enough so the passenger was stopping me before I ran the light	that the passenger was using his break
524	Stopped	160ms- continuous pulses	I thought of pressing on the brake pedal to stop	The car was drawing my attention to a problem
528	Stopped	160ms- continuous pulses	I thought the light had turned and the girl in the back seat was doing it for me	The car was stopping by itself
530	Stopped	160ms- continuous pulses	oh good- because the light was changing & I couldn't see it	End of experiment, or that I'd failed to respond adequately just before road.
538	Stopped	160ms- continuous pulses	Something wrong with car	brakes locking

P#	Stopped/Did Not Stop	Group	First thought	Happening
539	Stopped	160ms-continuous pulses	Didn't know for sure what it was	some kind of warning
543	Stopped	160ms-continuous pulses	Thought the light would change	uncertain
574	Stopped	600ms-3 pulses + Aud	That I should also break as well and that there may have been something wrong	I thought the car was going to stop all by itself because I had done something wrong
575	Stopped	600ms-3 pulses + Aud	Approaching vehicle, or change in stop light	Car was stopping, due to oncoming traffic or stop light
578	Stopped	600ms-3 pulses + Aud	There was a need to stop, I felt it about the same time as the light turned and the voice said stop	I wasn't sure. I thought it was something to do with the test
579	Stopped	600ms-3 pulses + Aud	I thought the light was changing but I wondered why I couldn't control the car more myself	the car was stopping on its own
580	Stopped	600ms-3 pulses + Aud	Possible vehicle tendency	no idea
581	Stopped	600ms-3 pulses + Aud	Needed to stop	that I need to stop quickly
582	Stopped	600ms-3 pulses + Aud	It seemed too soon for me	The car was in control
584	Stopped	600ms-3 pulses + Aud	Transmission had dropped into another gear- surprised	car was immediately slowing down & responding to signal & my interaction to signal- good brakes?

APPENDIX G: Data Analysis Results

G.1 Fisher's Exact test of the zones for those who stopped

Haptic Conditions vs. Baseline

The FREQ Procedure

Table of Group by Zone2

Group(Group) Zone2(Zone2)

Frequency Percent Row Pct Col Pct	AfterStopBar	BeforeStopBar	Total
Baseline	4 9.52 100.00 13.33	0 0.00 0.00 0.00	4 9.52
Haptic Conditions (Collapsed)	26 61.90 68.42 86.67	12 28.57 31.58 100.00	38 90.48
Total	30 71.43	12 28.57	42 100.00

Fisher's Exact Test

Cell (1,1) Frequency (F)	4
Left-sided Pr <= F	1.0000
Right-sided Pr >= F	0.2448
Table Probability (P)	0.2448
Two-sided Pr <= P	0.3082

Haptic Conditions vs. Auditory ("STOP") + Visual

The FREQ Procedure
Table of Group by Zone2

Group(Group)   Zone2(Zone2)

Frequency / Percent / Row Pct / Col Pct	AfterStopBar	BeforeStopBar	Total
Aud (STOP) + Visual	10	6	16
	18.52	11.11	29.63
	62.50	37.50	
	27.78	33.33	
Haptic Conditions (Collapsed)	26	12	38
	48.15	22.22	70.37
	68.42	31.58	
	72.22	66.67	
Total	36	18	54
	66.67	33.33	100.00

Fisher's Exact Test

Cell (1,1) Frequency (F)	10
Left-sided Pr <= F	0.4524
Right-sided Pr >= F	0.7713
Table Probability (P)	0.2237
Two-sided Pr <= P	0.7560

Haptic Conditions vs. Auditory (CAMP) + Visual

The FREQ Procedure

Table of Group by Zone2

Group(Group) Zone2(Zone2)

Frequency Percent Row Pct Col Pct	AfterStopBar	BeforeStopBar	Total
Aud (CAMP) + Visual	10 20.83 100.00 27.78	0 0.00 0.00 0.00	10 20.83
Haptic Conditions (Collapsed)	26 54.17 68.42 72.22	12 25.00 31.58 100.00	38 79.17
Total	36 75.00	12 25.00	48 100.00

Fisher's Exact Test

Cell (1,1) Frequency (F)	10
Left-sided Pr <= F	1.0000
Right-sided Pr >= F	0.0389
Table Probability (P)	0.0389
Two-sided Pr <= P	0.0481

Haptic Phase I vs Phase II

The FREQ Procedure

Table of Group by Zone2

Group(Group) / Zone2(Zone2) Frequency Percent Row Pct Col Pct	AfterStopBar	BeforeStopBar	Total
Haptic Phase I	26 56.52 68.42 86.67	12 26.09 31.58 75.00	38 82.61
Haptic Phase II	4 8.70 50.00 13.33	4 8.70 50.00 25.00	8 17.39
Total	30 65.22	16 34.78	46 100.00

Fisher's Exact Test

Cell (1,1) Frequency (F)	26
Left-sided Pr <= F	0.9173
Right-sided Pr >= F	0.2738
Table Probability (P)	0.1911
Two-sided Pr <= P	0.4211

G.2 ANOVAs Between All Haptic Conditions:

TAR

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	0.097759	0.02444	1.96	0.1234
Error	33	0.411062	0.012456		
Corrected Total	37	0.508821			

ReactionTime

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	0.209878	0.052469	0.83	0.5169
Error	33	2.090757	0.063356		
Corrected Total	37	2.300634			

TPB

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	0.907449	0.226862	0.36	0.8371
Error	33	20.95597	0.635029		
Corrected Total	37	21.86342			

TBPB

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	0.44567	0.111418	0.21	0.9291
Error	33	17.23012	0.522125		
Corrected Total	37	17.67579			

ABT

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	0.206706	0.051676	0.81	0.5288
Error	33	2.109465	0.063923		
Corrected Total	37	2.316171			

MaxDecel

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*	
Group	4	0.048766	0.012192	3.03	0.0313	*
Error	33	0.1329	0.004027			
Corrected Total	37	0.181667				

* p<0.10

AvgDecel

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*	
Group	4	0.011393	0.002848	2.85	0.0391	*
Error	33	0.032975	0.000999			
Corrected Total	37	0.044368				

* p<0.10

DistanceBSB

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	4	452.7831	113.1958	1.67	0.1807
Error	33	2238.214	67.82466		
Corrected Total	37	2690.997			

RDP

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	4	0.007693	0.001923	2.05	0.1106
Error	33	0.031016	0.00094		
Corrected Total	37	0.038709			

SpeedDifferential

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	4	10.90186	2.725466	1.38	0.2636
Error	33	65.38274	1.981295		
Corrected Total	37	76.2846			

G.3 ANOVAs for Across All Haptic Conditions: Age, Gender, Age X Gender

TAR

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*	
Age	1	0.046938	0.046938	3.65	0.0646	*
Gender	1	0.017201	0.017201	1.34	0.2557	
Age*Gender	1	0.008307	0.008307	0.65	0.4273	
Error	34	0.437566	0.01287			
Corrected Total	37	0.508821				

*p<0.10

ReactionTime

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*	
Age	1	0.370573	0.370573	6.6	0.0147	*
Gender	1	0.000367	0.000367	0.01	0.936	
Age*Gender	1	0.02203	0.02203	0.39	0.5351	
Error	34	1.907902	0.056115			
Corrected Total	37	2.300634				

*p<0.05

TPB

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Age	1	0.366421	0.366421	0.6	0.4442
Gender	1	0.028082	0.028082	0.05	0.8316
Age*Gender	1	0.668082	0.668082	1.09	0.3032
Error	34	20.78444	0.611307		
Corrected Total	37	21.86342			

TBPB

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Age	1	1.17E-05	1.17E-05	0	0.9962
Gender	1	0.036678	0.036678	0.07	0.7892
Age*Gender	1	0.44931	0.44931	0.89	0.3523
Error	34	17.17489	0.505144		
Corrected Total	37	17.67579			

ABT

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Age	1	0.153738	0.153738	2.44	0.1278
Gender	1	0.012545	0.012545	0.2	0.6585
Age*Gender	1	0.003281	0.003281	0.05	0.821
Error	34	2.145886	0.063114		
Corrected Total	37	2.316171			

MaxDecel

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*	
Age	1	0.021076	0.021076	4.82	0.035	*

Gender	1	0.009748	0.009748	2.23	0.1446
Age*Gender	1	0.001732	0.001732	0.4	0.5333
Error	34	0.148644	0.004372		
Corrected Total	37	0.181667			

* p<0.05

AvgDecel

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Age	1	0.003288	0.003288	2.89	0.0983
Gender	1	0.00088	0.00088	0.77	0.3854
Age*Gender	1	0.001627	0.001627	1.43	0.2401
Error	34	0.038693	0.001138		
Corrected Total	37	0.044368			

DistanceBSB

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***	
Age	1	4.632679	4.632679	0.07	0.7949	
Gender	1	47.30484	47.30484	0.7	0.4084	
Age*Gender	1	356.1969	356.1969	5.28	0.0279	*
Error	34	2295.444	67.51305			
Corrected Total	37	2690.997				

*p<0.05

RDP

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***	
Age	1	0.004661	0.004661	4.88	0.034	*
Gender	1	0.000141	0.000141	0.15	0.7036	
Age*Gender	1	0.001464	0.001464	1.53	0.2242	
Error	34	0.032486	0.000955			
Corrected Total	37	0.038709				

*p<0.05

SpeedDifferential

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Age	1	4.296576	4.296576	2.03	0.1629
Gender	1	0.041965	0.041965	0.02	0.8887
Age*Gender	1	0.12626	0.12626	0.06	0.8083
Error	34	71.81165	2.112107		
Corrected Total	37	76.2846			

G.4 ANOVAs for Between Warning Type

TAR

Source	df	Type III SS	MS	F value	P value	
Warning Type	6	0.492278	0.082046	4.87	0.0004	*
Error	57	0.959622	0.016835			
Corrected Total	63	1.4519				

*p<0.05

ReactionTime

Source	df	Type III SS	MS	F value	P value	
Warning Type**	2	0.399808	0.199904	4.57	0.0141	*
Error	61	2.667778	0.043734			
Corrected Total	63	3.067586				

* p<0.05 **Haptic Conditions Collapsed

TPB

Source	df	Type III SS	MS	F value	P value
Warning Type	6	2.107997	0.351333	0.79	0.5787
Error	57	25.22935	0.44262		
Corrected Total	63	27.33734			

TBPB

Source	df	Type III SS	MS	F value	P value
Warning Type	6	0.653381	0.108897	0.29	0.9399
Error	57	21.48412	0.376914		
Corrected Total	63	22.1375			

ABT

Source	df	Type III SS	MS	F value	P value	
Warning Type	6	0.663292	0.110549	2.7	0.0224	*
Error	57	2.334369	0.040954			
Corrected Total	63	2.997661				

*p<0.05

MaxDecel

Source	df	Type III SS	MS	F value	P value	
Warning Type	6	0.514859	0.08581	16.15	<.0001	*
Error	57	0.302937	0.005315			
Corrected Total	63	0.817796				

*p<0.05

AvgDecel

Source	df	Type III SS	MS	F value	P value	
Warning Type	6	0.215604	0.035934	19.41	<.0001	*
Error	57	0.105516	0.001851			
Corrected Total	63	0.32112				

* p<0.05

DistanceBSB

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***	
Warning Type	6	1471.241	245.2069	2.52	0.0311	
Error	57	5545.585	97.29097			
Corrected Total	63	7016.827				

RDP

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***	
Warning Type	6	0.321229	0.053538	45.37	<.0001	*
Error	57	0.067255	0.00118			
Corrected Total	63	0.388484				

*p<0.05

G.5 ANOVAs for Subjective Factors

Effectiveness

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	5.816396	1.454099	0.45	0.7744
Error	36	117.3056	3.258488		
Corrected Total	40	123.122			

Urgency

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	8.20122	2.050305	0.95	0.4469
Error	36	77.75	2.159722		
Corrected Total	40	85.95122			

Likeable

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	6.435976	1.608994	0.57	0.6841
Error	36	101.125	2.809028		
Corrected Total	40	107.561			

Annoying

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*	
Group	4	39.93835	9.984587	5.42	0.0016	*
Error	36	66.30556	1.841821			
Corrected Total	40	106.2439				

*p<0.05

Expected

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	18.3689	4.592226	1.09	0.3768
Error	36	151.875	4.21875		
Corrected Total	40	170.2439			

Timing

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	8.222561	2.05564	1.24	0.313
Error	36	59.875	1.663194		
Corrected Total	40	68.09756			

Comfort

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	5.509294	1.377324	0.7	0.6005
Error	33	65.35913	1.98058		
Corrected Total	37	70.86842			

Control

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	6.241541	1.560385	0.56	0.6901
Error	33	91.23214	2.76461		
Corrected Total	37	97.47368			

Safety

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	14.12839	3.532097	1.34	0.2738
Error	36	94.84722	2.634645		
Corrected Total	40	108.9756			

Trustworthy

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	10.3447	2.586174	0.97	0.4393
Error	28	74.625	2.665179		
Corrected Total	32	84.9697			

Reliable

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	4	13.2197	3.304924	1.86	0.1454
Error	28	49.75	1.776786		
Corrected Total	32	62.9697			

G.6 ANOVAs for Additional Trials: Within Haptic Conditions

Effectiveness

Source	df	Type III SS	MS	F value	P value
Between					
Part*Group(Age*Gender)	151	274.3855	1.817123		
Within					
Group	3	1.162892	0.387631	0.21	0.8871
Corrected Total	154	275.5484			

Urgency

Source	df	Type III SS	MS	F value	P value
Between					
Part*Group(Age*Gender)	151	295.7638	1.9587		
Within					
Group	3	0.984621	0.328207	0.17	0.9181
Corrected Total	154	296.7484			

Likeable

Source	df	Type III SS	MS	F value	P value
Between					
Part*Group(Age*Gender)	151	377.2352	2.498246		
Within					
Group	3	0.274515	0.091505	0.04	0.9906
Corrected Total	154	377.5097			

Annoying

Source	df	Type III SS	MS	F value	P value
Between					
Part*Group(Age*Gender)	151	387.2613	2.564645		
Within					
Group	3	2.648351	0.882784	0.34	0.7934
Corrected Total	154	389.9097			

Trustworthy

Source	df	Type III SS	MS	F value	P value
Between					
Part*Group(Age*Gender)	125	211.2255	1.689804		
Within					
Group	3	0.355905	0.118635	0.07	0.9757
Corrected Total	128	211.5814			

Reliable

Source	df	Type III SS	MS	F value	P value
Between					
Part*Group(Age*Gender)	125	190.3028	1.522423		
Within					
Group	3	1.278563	0.426188	0.28	0.8398
Corrected Total	128	191.5814			

G.7 ANOVAs for Subjective Factors Between Phase I and Phase II

Between the 600ms- 3pulses Condition and Haptic + Auditory Condition

Effectiveness

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	1	0.20915	0.20915	0.07	0.7966
Error	15	45.55556	3.037037		
Corrected Total	16	45.76471			

Urgency

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	1	6.183824	6.183824	1.9	0.1885
Error	15	48.875	3.258333		
Corrected Total	16	55.05882			

Likeable

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	1	1.882353	1.882353	0.74	0.4023
Error	15	38	2.533333		
Corrected Total	16	39.88235			

Annoying

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	1	2.562092	2.562092	1.15	0.3015
Error	15	33.55556	2.237037		
Corrected Total	16	36.11765			

Expected

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	1	13.59559	13.59559	3.72	0.073
Error	15	54.875	3.658333		
Corrected Total	16	68.47059			

Timing

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	1	0.264706	0.264706	0.11	0.7427
Error	15	35.5	2.366667		
Corrected Total	16	35.76471			

Comfort

Source	***df***	***Type III SS***	***MS***	***F value***	***P value***
Group	1	4.003268	4.003268	1.54	0.234
Error	15	39.05556	2.603704		

Corrected Total	16	43.05882

Control

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	1	0.066176	0.066176	0.02	0.8862
Error	15	46.875	3.125		
Corrected Total	16	46.94118			

Safety

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	1	18.13807	18.13807	4.85	0.0437
Error	15	56.09722	3.739815		
Corrected Total	16	74.23529			

Trustworthy

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	1	5.0625	5.0625	1.63	0.2219
Error	14	43.375	3.098214		
Corrected Total	15	48.4375			

Reliable

Source	*df*	*Type III SS*	*MS*	*F value*	*P value*
Group	1	6.25	6.25	1.84	0.1962
Error	14	47.5	3.392857		
Corrected Total	15	53.75			

G.8 Post-hoc Results

Haptic Conditions: MaxDecel

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	MaxDecel LSMEAN	LSMEAN Number
600ms- 1 pulse	-0.49785714	1
600ms- 3 pulses	-0.52200000	2
380ms- 3 pulses	-0.51516667	3
160ms- 3 pulses	-0.58312500	4
160ms- continuous pulses	-0.47925000	5

i/j	1	2	3	4	5
1		0.754907	0.490267	2.59614	-0.56653
		0.9415	0.9877	0.0943	0.9790
2	-0.75491		-0.2043	1.982235	-1.38635
	0.9415		0.9996	0.2967	0.6404
3	-0.49027	0.204305		1.982867	-1.04797
	0.9877	0.9996		0.2964	0.8311
4	-2.59614	-1.98223	-1.98287		-3.27367
	0.0943	0.2967	0.2964		0.0197
5	0.566529	1.386348	1.047966	3.273674	
	0.9790	0.6404	0.8311	0.0197	

Haptic Condition: AvgDecel

Group	AvgDecel LSMEAN	LSMEAN Number
600ms- 1 pulse	-0.32878217	1
600ms- 3 pulses	-0.32786767	2
380ms- 3 pulses	-0.35085432	3
160ms- 3 pulses	-0.36811853	4
160ms- continuous pulses	-0.32349940	5

i/j	1	2	3	4	5
1		-0.05741	1.255055	2.404405	-0.32291
		1.0000	0.7197	0.1394	0.9975
2	0.057406		1.379723	2.620487	-0.28439
	1.0000		0.6445	0.0896	0.9985
3	-1.25506	-1.37972		1.011273	-1.60235
	0.7197	0.6445		0.8483	0.5065
4	-2.4044	-2.62049	-1.01127		-2.82303
	0.1394	0.0896	0.8483		0.0575
5	0.322905	0.284391	1.602349	2.823034	
	0.9975	0.9985	0.5065	0.0575	

Age Groups: TAR

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Age	TAR LSMEAN	H0:LSMean1=LSMean2 t Value	Pr > |t|
O	0.35388889	1.91	0.0646
Y	0.28350000		

Age Groups: ReactionTime

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Age	ReactionTime LSMEAN	H0:LSMean1=LSMean2 t Value	Pr > |t|
O	0.88277778	2.57	0.0147
Y	0.68500000		

Age X Gender: DistanceBSB

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Age	Gender	DistanceBSB LSMEAN	LSMEAN Number
O	F	-0.64044444	1
O	M	-9.00677778	2
Y	F	-7.47150000	3
Y	M	-3.57430000	4

i/j	1	2	3	4
1		2.159969	1.809416	0.777122
		0.1551	0.2866	0.8642
2	-2.15997		-0.40667	-1.43896
	0.1551		0.9769	0.4846
3	-1.80942	0.406666		-1.06058
	0.2866	0.9769		0.7154
4	-0.77712	1.438959	1.060581	
	0.8642	0.4846	0.7154	

Age Groups: RDP

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Age	RDP LSMEAN	H0:LSMean1=LSMean2 t Value	Pr > |t|
O	0.36652924	2.21	0.0340
Y	0.34434723		

Warning Type: TAR

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	TAR LSMEAN	LSMEAN Number
Aud (CAMP) + Visual	0.53200000	1
Aud (STOP) + Visual	0.41000000	2
600ms- 1 pulse	0.22857143	3
600ms- 3 pulses	0.30777778	4
380ms- 3 pulses	0.36666667	5
160ms- 3 pulses	0.37500000	6
160ms- continuous pulses	0.30875000	7

i/j	1	2	3	4	5	6	7
1		2.332494	4.745351	3.761061	2.467535	2.550913	3.627334
		0.2469	0.0003	0.0069	0.1908	0.1611	0.0104
2	-2.33249		3.085589	1.890792	0.697644	0.622952	1.802112
	0.2469		0.0464	0.4947	0.9922	0.9958	0.5522
3	-4.74535	-3.08559		-1.21132	-1.91302	-2.18053	-1.19397
	0.0003	0.0464		0.8869	0.4804	0.3221	0.8936
4	-3.76106	-1.89079	1.211316		-0.86114	-1.06621	-0.01542
	0.0069	0.4947	0.8869		0.9768	0.9353	1.0000
5	-2.46754	-0.69764	1.913018	0.861136		-0.11892	0.826509
	0.1908	0.9922	0.4804	0.9768		1.0000	0.9812
6	-2.55091	-0.62295	2.180527	1.066208	0.118922		1.021182
	0.1611	0.9958	0.3221	0.9353	1.0000		0.9470
7	-3.62733	-1.80211	1.193972	0.01542	-0.82651	-1.02118	
	0.0104	0.5522	0.8936	1.0000	0.9812	0.9470	

Warning Type: ReactionTime

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	ReactionTime LSMEAN	LSMEAN Number
Aud (CAMP) + Visual	0.92500000	1
Aud (STOP) + Visual	0.67062500	2
Haptic Conditions (Collapsed)	0.77868421	3

i/j	1	2	3
1		3.017434	1.968577
		0.0102	0.1287
2	-3.01743		-1.73383
	0.0102		0.2010
3	-1.96858	1.733831	
	0.1287	0.2010	

Warning Type: ABT

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	ABT LSMEAN	LSMEAN Number
Aud (CAMP) + Visual	0.39300000	1
Aud (STOP) + Visual	0.26062500	2
600ms- 1 pulse	0.44285714	3
600ms- 3 pulses	0.53555556	4
380ms- 3 pulses	0.31500000	5
160ms- 3 pulses	0.45000000	6
160ms- continuous pulses	0.51750000	7

i/j	1	2	3	4	5	6	7
1		1.622677	-0.49992	-1.53314	0.746385	-0.59379	-1.29697
		0.6685	0.9988	0.7239	0.9889	0.9968	0.8505
2	-1.62268		-1.98711	-3.26052	-0.56128	-2.1611	-2.93139
	0.6685		0.4339	0.0292	0.9976	0.3326	0.0682
3	0.499925	1.987114		-0.90894	1.135614	-0.0682	-0.71267
	0.9988	0.4339		0.9697	0.9143	1.0000	0.9913
4	1.533138	3.260521	0.90894		2.067864	0.870047	0.183614
	0.7239	0.0292	0.9697		0.3853	0.9756	1.0000
5	-0.74639	0.561276	-1.13561	-2.06786		-1.23522	-1.85282
	0.9889	0.9976	0.9143	0.3853		0.8773	0.5192
6	0.593795	2.161099	0.068198	-0.87005	1.235216		-0.66709
	0.9968	0.3326	1.0000	0.9756	0.8773		0.9939
7	1.296973	2.931392	0.712671	-0.18361	1.852825	0.667093	
	0.8505	0.0682	0.9913	1.0000	0.5192	0.9939	

Warning Type: MaxDecel

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	MaxDecel LSMEAN	LSMEAN Number
Aud (CAMP) + Visual	-0.67630000	1
Aud (STOP) + Visual	-0.70381250	2
600ms- 1 pulse	-0.49785714	3
600ms- 3 pulses	-0.52200000	4
380ms- 3 pulses	-0.51516667	5
160ms- 3 pulses	-0.58312500	6
160ms- continuous pulses	-0.47925000	7

i/j	1	2	3	4	5	6	7
1		0.936191	-4.96689	-4.6065	-4.28018	-2.69444	-5.69831
		0.9650	0.0001	0.0004	0.0013	0.1184	<.0001
2	-0.93619		-6.23418	-5.98544	-5.40546	-3.82316	-7.11374
	0.9650		<.0001	<.0001	<.0001	0.0057	<.0001
3	4.966894	6.23418		0.657143	0.426775	2.259929	-0.49316
	0.0001	<.0001		0.9944	0.9995	0.2813	0.9989
4	4.606505	5.98544	-0.65714		-0.17785	1.725527	-1.20681
	0.0004	<.0001	0.9944		1.0000	0.6022	0.8887
5	4.280181	5.40546	-0.42678	0.177846		1.726078	-0.91225
	0.0013	<.0001	0.9995	1.0000		0.6019	0.9691
6	2.694445	3.823163	-2.25993	-1.72553	-1.72608		-2.84972
	0.1184	0.0057	0.2813	0.6022	0.6019		0.0830
7	5.698313	7.113736	0.493162	1.20681	0.91225	2.84972	
	<.0001	<.0001	0.9989	0.8887	0.9691	0.0830	

Warning Type: AvgDecel

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	AvgDecel LSMEAN	LSMEAN Number
Aud (CAMP) + Visual	-0.45777983	1
Aud (STOP) + Visual	-0.45192128	2
600ms- 1 pulse	-0.32878217	3
600ms- 3 pulses	-0.32786767	4
380ms- 3 pulses	-0.35085432	5
160ms- 3 pulses	-0.36811853	6
160ms- continuous pulses	-0.32349940	7

i/j	1	2	3	4	5	6	7
1		-0.33779	-6.08393	-6.57162	-4.81255	-4.39331	-6.5796
		0.9999	<.0001	<.0001	0.0002	0.0009	<.0001
2	0.337786		-6.31567	-6.91988	-4.90695	-4.49817	-6.89313
	0.9999		<.0001	<.0001	0.0002	0.0006	<.0001
3	6.083933	6.315666		-0.04218	0.922095	1.766528	-0.23724
	<.0001	<.0001		1.0000	0.9675	0.5754	1.0000
4	6.571618	6.919882	0.042177		1.01369	1.925285	-0.20894
	<.0001	<.0001	1.0000		0.9488	0.4726	1.0000
5	4.812547	4.906948	-0.9221	-1.01369		0.742987	-1.17725
	0.0002	0.0002	0.9675	0.9488		0.9891	0.8998
6	4.39331	4.498168	-1.76653	-1.92528	-0.74299		-2.0741
	0.0009	0.0006	0.5754	0.4726	0.9891		0.3817
7	6.5796	6.893129	0.23724	0.208944	1.177254	2.074097	
	<.0001	<.0001	1.0000	1.0000	0.8998	0.3817	

Warning Type: RDP

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	RDP LSMEAN	LSMEAN Number
Aud (CAMP) + Visual	0.53197709	1
Aud (STOP) + Visual	0.46544950	2
600ms- 1 pulse	0.33640005	3
600ms- 3 pulses	0.34796210	4
380ms- 3 pulses	0.35203440	5
160ms- 3 pulses	0.37939143	6
160ms- continuous pulses	0.35633421	7

i/j	1	2	3	4	5	6	7
1		4.804521	11.5536	11.6593	10.14436	9.364777	10.77989
		0.0002	<.0001	<.0001	<.0001	<.0001	<.0001
2	-4.80452		8.290414	8.20876	6.897157	5.785833	7.336011
	0.0002		<.0001	<.0001	<.0001	<.0001	<.0001
3	-11.5536	-8.29041		-0.66791	-0.8181	-2.41827	-1.1213
	<.0001	<.0001		0.9938	0.9821	0.2101	0.9189
4	-11.6593	-8.20876	0.667913		-0.22494	-1.88301	-0.50159
	<.0001	<.0001	0.9938		1.0000	0.4997	0.9987
5	-10.1444	-6.89716	0.818103	0.22494		-1.47469	-0.23178
	<.0001	<.0001	0.9821	1.0000		0.7583	1.0000
6	-9.36478	-5.78583	2.41827	1.883007	1.474689		1.342493
	<.0001	<.0001	0.2101	0.4997	0.7583		0.8289
7	-10.7799	-7.33601	1.121299	0.501594	0.231782	-1.34249	
	<.0001	<.0001	0.9189	0.9987	1.0000	0.8289	

Haptic Condition: Annoying

The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Group	Annoying LSMEAN	LSMEAN Number
600ms- 1 pulse	4.75000000	1
600ms- 3 pulses	2.22222222	2
380ms- 3 pulses	2.62500000	3
160ms- 3 pulses	4.37500000	4
160ms- continuous pulses	3.75000000	5

i/j	1	2	3	4	5
1		3.83316	3.131592	0.552634	1.473691
		0.0042	0.0267	0.9809	0.5856
2	-3.83316		-0.61078	-3.2645	-2.31675
	0.0042		0.9725	0.0191	0.1631
3	-3.13159	0.610778		-2.57896	-1.6579
	0.0267	0.9725		0.0959	0.4718
4	-0.55263	3.264505	2.578958		0.921057
	0.9809	0.0191	0.0959		0.8869
5	-1.47369	2.316745	1.657902	-0.92106	
	0.5856	0.1631	0.4718	0.8869	

VITA

Sarah Brown was born in Norton, VA and was raised in Big Stone Gap, VA. She received her B.S. degree in Industrial and Systems Engineering from Virginia Tech in 2002. In 2001, she began working at the Virginia Tech Transportation Institute (VTTI) as a data reductionist for a lane change research project. Her interest in Human Factors continued into her graduate studies. While working towards her M.S. degree in Industrial and System Engineering in the Human Factors option area, she worked as a Graduate Research Assistant at VTTI. She worked on a project funded by NHTSA for intersection collision avoidance violation warning development. Her research interests are transportation, safety, and product design. She is an active member of the Human Factors and Ergonomics Society and the American Society of Safety Engineers.