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Preliminary Studies in Haptic Displays for Rear-End Collision Avoidance System and Adaptive Cruise Control System Applications

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16. Abstract

One potential means of providing collision avoidance warnings to the driver is through haptic displays, i.e., displays that are "felt". In this report, various haptic display concepts for rear-end collision avoidance are presented and published research studies are reviewed. Then three small-scale studies of mono-pulse braking and active steering displays are reported.

Two parameter setting studies were conducted. The first study was conducted to determine the display parameter settings of a mono-pulse braking display. The second study examined the effects of active steering vibration amplitude, frequency, and duration on display detectability and appropriateness ratings. The results indicated that, over the ranges of vibration frequency, torque amplitude, and duration used, all of the displays were essentially equivalent in terms of driver response. Based on these results, it was suggested that active steering displays be reserved for future collision avoidance system integration for those situations that most likely require steering maneuvers for achieving a desirable outcome, i.e., for hazards in the lateral axis.

The third study sought to determine how drivers in a car following situation would react to a mono-pulse braking display under two different simulated rear-end collision avoidance warning scenarios. In a true positive (TP) condition, a lead vehicle was braking to a stop when the haptic braking display came on. In a false positive (FP) condition, the haptic display came on even though the lead vehicle was not slowing down. The TP data indicated that drivers, on average, modulated their braking according to the constraints of the lead vehicle coming to a stop rather than according to the jerk rate or duration of the mono-pulse braking display. In approximately one-third of the FP trials, inappropriate braking responses were recorded. The TP trial results suggest that in the presence of a decelerating lead vehicle, drivers will respond according to the constraints of the car following situation, not to the properties of a mono-pulse brake display itself. The results suggest guarded optimism that mono-pulse braking displays might be of use in rear-end collision avoidance applications.

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EXECUTIVE SUMMARY

One potential means of providing collision avoidance warnings to the driver is through haptic displays, i.e., displays that are “felt” through tactile, vestibular, or kinesthetic sensations and perceptions. In this report, various haptic display concepts for rear-end collision avoidance are presented and published research studies are reviewed. Then three small-scale studies of mono-pulse braking and active steering displays are reported.

The first study was conducted to determine the display parameter settings of a mono-pulse braking display. Three females (ages: 27, 36, and 50 years) and three males (ages 25, 39, and 56 years) served as test participants. The test participants received brief training on address entry into a commercially available route navigation system. The test participant then drove an instrumented vehicle on a skid pad at approximately 45 mph on dry pavement during daytime hours. Blocks of 12 trials each were completed of non-distraction (i.e., driving only) and distraction trials (i.e., driving while entering in destinations). During a trial (except for catch trials where no haptic display was presented) a mono-pulse braking event was presented at random times during the drive. As soon as the test participant noticed the braking event, they were to bring the vehicle to a controlled stop. Mono-pulse braking events were created by linear ramps of deceleration based on all combinations of three jerk rates (0.08 g/s, 0.20 g/s, and 0.32 g/s) and three durations (0.25 s, 0.65 s, and 1.0 s). Results from analyses of detection performance, accelerator release time, and subjective ratings of appropriateness indicated that if a single mono-pulse braking display is to be selected for further testing, it should be a 0.32 g/s jerk rate linearly ramped up for 0.65 seconds. Results from the stopping distance and maximum pedal force data indicated that the stronger the mono-pulse braking display, the harder the subsequent braking.

The second study examined the effects of active steering vibration amplitude, frequency, and duration on display detectability and appropriateness ratings. The same individuals who participated in the first pulse brake display study served as test participants in the second study and the test procedure was similar to that of the first study. Active steering displays (vibration of the handwheel) were created by selected combinations of five vibration frequencies (4, 6, 8, 10, and 12 Hz), five amplitudes (1.0, 1.2, 1.6, 1.8, and 2.2 Nm of torque), and five durations (0.50, 0.74, 1.00, 1.26, and

1.50 seconds). The results indicated that, over the ranges of vibration frequency, torque amplitude, and duration used, all of the displays were essentially equivalent in terms of driver response. This is perhaps best explained by the great sensitivity the hands possess. Unlike the findings of the first study, driver response was not reliably related to the magnitude of the active steering display. The discrepant findings are considered to result from the fact that active steering displays are not intrinsically associated with a braking response but pulse braking displays are. It is suggested that active steering displays be reserved for future collision avoidance system integration for those situations that most likely require steering maneuvers for achieving a desirable outcome, i.e., for hazards in the lateral axis.

The third study was undertaken to determine how drivers in a car following situation would react to a mono-pulse braking display in two different simulated rear-end collision warning system scenarios. In a true positive (TP) condition, a lead vehicle was braking to a stop when the haptic braking display came on. In a false positive (FP) condition, the haptic display came on even though the lead vehicle was not slowing down. Three females and four males who had not participated in previous pulse braking studies served as test participants. They engaged in car following at approximately 42 mph with a time headway of 2.0 seconds controlled by an adaptive cruise control (ACC) system. While car following, the test participants attempted to enter destinations into a commercially available route guidance system. The lead vehicle was a towed artificial rear-end of an automobile with brake lights disabled which periodically would brake at approximately 0.35 g to a complete stop. Haptic warnings were generated by means of a simple time-to-collision algorithm. The TP data indicated that drivers, on average, modulated their braking according to the constraints of the lead vehicle coming to a stop rather than according to the jerk rate or duration of the mono-pulse pulse braking display. In approximately one-third of the FP trials, uncalled-for or inappropriate braking responses were recorded. On average, higher jerk rates were associated with greater maximum decelerations and greater momentary drops in speed. However, these inappropriate braking responses were generally both mild and of short duration. The TP trial results suggest that in the presence of a decelerating lead vehicle, drivers will respond according to the constraints of the car following situation, not to the properties of a mono-pulse brake display itself. The results suggest a guarded optimism that mono-pulse braking displays might be of use in rear-end collision avoidance applications. Recommendations for further research are provided.

1.0 GENERAL INTRODUCTION TO HAPTIC DISPLAY RESEARCH FOR ADAPTIVE CRUISE CONTROL (ACC) AND REAR-END COLLISION AVOIDANCE SYSTEMS (CAS)

1.1 Background

Crash Avoidance Systems (CAS) technology to alleviate various crash problems represent a priority within the Intelligent Vehicle Initiative (IVI) portion of the U.S. Department of Transportation's Intelligent Transportation Systems (ITS) research program. To date, CAS technologies have been developed to address specific crash problems, such as rear-end crashes, lane change crashes, single vehicle roadway departure crashes, and backing crashes. The CAS concepts have emphasized driver alerting and warning rather than automatic vehicle control. However, the successful demonstrations of various Automated Highway System (AHS) concepts in San Diego, CA during the summer of 1997 suggest that automatic vehicle control could become a reality in the vehicles and roads of the future. Emerging technologies like Adaptive Cruise Control (ACC) with limited braking authority lie intermediate between warning systems and fully automatic vehicle control systems. In an ACC system with limited braking authority, the system modulates travel speed and inter-vehicle separation via throttle and perhaps downshifts according to setpoints provided by the driver. When necessary, such a system also applies service brakes up to some limit of authority. An ACC system with limited braking authority cannot brake to a full stop, but it is capable of doing more than just alerting the driver to an obstacle ahead.

IVI research has also raised the question of how best to integrate ITS subsystems into vehicles. The IVI program is to be a major focus of U.S. Department of Transportation research over the next several years. In line with the ITS initiative's emphasis on safety, a key priority in IVI research will be the integration of CAS technologies to provide comprehensive collision avoidance support to the driver. Also, convenience systems such as Adaptive Cruise Control (ACC) may merge or otherwise interact with rear-end CAS to provide both challenges to and opportunities for enhanced highway safety.

There is a need to better understand the most effective and efficient ways to display collision avoidance information to the driver in the ITS-equipped vehicle. Visual and auditory displays are the most commonly used or proposed CAS driver interfaces. Nevertheless, there remain other modes of communicating potentially life-saving crash avoidance information to the driver. One of these is the haptic mode, i.e., displays that are "felt" through tactile, vestibular, or kinesthetic means. Key concepts and issues associated with haptic displays for crash avoidance systems will be presented in this section. The emphasis will be on haptic displays that apply most directly to rear-end collision avoidance systems and ACC. However, the haptic display concepts to be discussed may serve more generally as a valuable display "infrastructure" for integrated collision avoidance systems within the overall IVI.

1.2 The Rear-end Crash Problem in the United States

Rear-end crashes are among the most numerous type of crash plaguing the driving public, comprising approximately 23 percent of all police-reported (PR) crashes in the United States (Knipling, Mironer, Hendricks, Tijerina, Everson, Allen, and Wilson, 1993). There are two basic kinematic subtypes of rear-end crashes. In the lead vehicle stopped (LVS) subtype, the lead vehicle is stopped or traveling very slowly for some period of time prior to the crash. Such conditions could arise for many reasons, such as when a lead vehicle stops in response to a traffic queue, a pedestrian crossing the road, to execute a left-turn, to check for a train at an at-grade railroad crossing, or to obey a traffic control device like a stop sign or traffic light. In the lead vehicle moving (LVM) subtype, the lead vehicle is in motion and is either slowing or traveling at a constant but slower speed than the subject vehicle (SV) at impact. This subtype might arise if the SV driver was following too closely and the LV driver suddenly braked. Such conditions would also arise if the SV driver encroached upon a substantially slower LV traveling at steady speed. Though estimates vary, the LVS subtype is the most prevalent and involves larger velocity differences between the LV and SV than those associated with the LVM case. In terms of crash contributing factors, by and large, driver inattention to the road scene ahead, along with following too closely, predominate.

Further review of the crash record indicates that drivers involved in rear-end crashes often exhibit no pre-crash avoidance maneuver (Volpe Center, 1998). When they do, braking is the most prevalent emergency response. Steering alone is less often used as a crash avoidance maneuver, as is steering and braking together. Allen (1994) presented a plot of obstacle headway time (his term) versus travel speed upon evasive maneuver onset. In this plot, there are distinct regions in the plot where the driver can safely only steer, safely only brake, safely do either (or both), or not avoid the crash. Interestingly, at higher initial SV travel speeds before braking, steering requires less time than braking. This suggests that there are scenarios for which steering is the best pre-crash avoidance maneuver, given that a safe trajectory can be found.

Allen's (1994) kinematic analysis might be reconsidered from a slightly different vantage point to determine if the same results are obtained. For example, Allen's evasive steering maneuver equation for maneuver time does not encompass the corrective reverse of steering input necessary to avoid an overshoot in the adjacent lane which could precipitate a road departure or perhaps an opposite direction crash. On the other hand, the sinusoidal acceleration model of a lane change maneuver given in Chovan, Tijerina, Alexander, and Hendricks (1994) provides a more complete model of the evasive steering maneuver. Peak acceleration in this model is given as:

$$A = \frac{2\pi(ILCD)}{t_{LC}^2}$$

where

A = Peak lateral acceleration for the lane change (i.e., evasive steering) maneuver, e.g., 0.6 g

$ILCD$ = the lateral inter-lane change distance traversed by the end of the maneuver (e.g., 10 ft)

t_{LC} = the lane change (i.e., evasive steering) maneuver completion time, in seconds.

By rearranging terms, one can solve for the evasive steering maneuver time, t_{LC}, given specific values of $ILCD$ and A:

$$t_{LC} = \sqrt{\frac{2\pi ILCD}{A}}$$

The braking maneuver time derivation presented by Allen (1994) contains an error; the 2 in the denominator should not be there. That is, the maneuver time, defined from the onset of braking until the vehicle comes to a complete stop should be given as

$$T_M = \frac{U_0}{a_x}$$

where

T_M = Maneuver time to brake to a full stop after onset of braking, in seconds.
U_0 = Initial Subject Vehicle travel velocity, in ft/s
a_x = Evasive maneuver braking deceleration applied, (e.g., 0.8 g)

Assuming Allen's value of 0.6g for peak lateral acceleration (A = (0.6)(32.2 ft/s^2 = 19.32 ft/s^2) and a 10 foot shift of lateral position for successful evasive steering (i.e., *ILCD* = 10 ft), the evasive steering maneuver time is t_{LC} = 1.80 seconds. For the evasive braking maneuver, Allen assumed a_x = (0.8)(32.2) = 25.76 ft/s^2. One can set $T_M = t_{LC}$ = 1.80 seconds to determine the crossover point, in terms of travel speed, U_0, between successful braking and successful steering. For these values, U_0 = 46.4 ft/s or approximately 32 mph, close to Allen's reported 35 mph value.

Figure 1.1 presents a modified version of Allen's (1994) Figure 2 plot. Given the stated assumptions and an LVS scenario, an initial velocity of 32 mph at the start of an evasive maneuver is critical to determine what that maneuver should be. Below 32 mph, a stopped obstacle 1.8 seconds of time headway ahead can be adequately handled by braking alone whereas adequate steering time would be unavailable. Above 32 mph, an evasive steering maneuver alone would be successful (provided that there is no other traffic or obstacles in the adjacent lane) yet braking alone would be insufficient to avoid a collision. Note that there remains a third, large region where the collision would be unavoidable and a fourth region where either evasive steering or braking would be feasible. A further important point is that braking prior to a collision will reduce the severity of the collision.

Taken as a set, these various results suggest the following:

- Rear-end CAS technology must be able to reliably detect a stopped or nearly stopped vehicle in the travel lane ahead with sufficient range to allow an inattentive driver to avoid the collision. The CAS must also be able to monitor the separation between the lead vehicle and the subject vehicle in a car following situation and alert the driver that he or she is following too closely or is encroaching upon a slower moving lead vehicle.

- Given that driver inattention is the predominant crash contributing or causal factor, driver alerting or warning is necessary, though not necessarily sufficient, to promote crash avoidance.
- Given that driving too closely is also a major crash contributor, rear-end CAS technology that promotes safer car following behavior is warranted.
- Given that drivers in rear-end crashes often do nothing in terms of evasive maneuvers, that drivers may brake when steering would have been more effective (or vice versa), and that while braking will not always avoid a crash it will reduce collision severity, rear-end CAS technology that promotes a more effective evasive maneuver seems warranted.

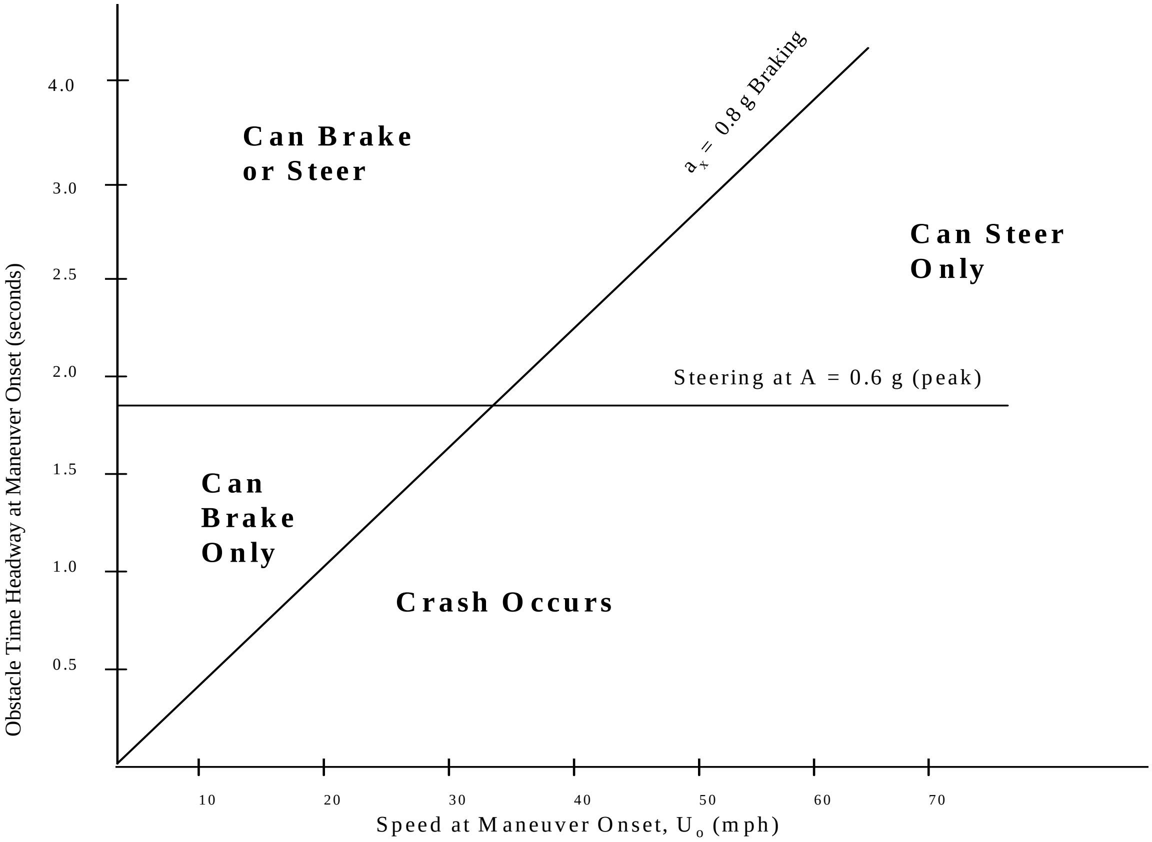


Figure 1.1. Feasible evasive maneuvers as a function of initial travel speed and obstacle time headway, assuming peak lateral acceleration of 0.6 g and longitudinal deceleration of 0.8 g (modified from Allen, 1994)

1.3 Crash Avoidance System (CAS) Functions

Tijerina (1995) has argued that effective CAS technology should, if possible, convey the following information to a driver in an efficient and timely manner:

- what the hazard is (at least categorically, e.g., rear-end, road departure, lane change),
- where the hazard is (e.g., ahead, to the right, to the left),
- what to do about it (e.g., brake, steer, both), and
- how to do it (e.g., steer in this direction, brake harder).

If a CAS does not indicate what the hazard is and where it is located (e.g., obstacle ahead in travel lane, object in right blind spot), the driver must spend precious time to search, detect, recognize, and identify the hazard. If a CAS does indicate what is wrong, then the driver may need less time to verify the hazard because he or she has been properly oriented on where to look.

Decisions must still be made about how best to deal with the situation. CAS technology that provides a recommended course of action could save the driver time. This concept, however, requires a high degree of intelligence on the part of the CAS. Beyond this, the driver must always have the option to select another course of action if it is deemed more appropriate.

The motivation to provide a wide range of driver support in the decision and response arenas rests on a sound theoretical foundation. In rare, terminus crash situations where time is limited, suggesting a viable response reduces or simplifies the decision tasks the driver must complete. Rasmussen (1983) speaks of skill-based, rule-based, and knowledge-based cognitive processing. Skill-based performance (e.g., lanekeeping, braking to avoid a looming obstacle) is fast, accurate, and relatively immune from deterioration in a broad range of contexts. Rule-based behavior (e.g., following traffic laws, defensive driving rules-of-thumb) is slower, and somewhat more susceptible to stress-related deterioration. Knowledge-based behavior (how to react to a crisis situation that has never been encountered before) is essentially problem solving for situations where there are no preplanned rules to follow. Knowledge-based behavior is slow, effortful, and error-prone. Suggesting what to do to maintain a safe field of travel (Gibson and Crooks, 1938) can push performance from knowledge-based behavior back down to rule-based or perhaps even skill-based behavior, thus, saving the driver time and effort. To a certain extent all CAS technologies must suggest or at least imply what to do to avoid a crash if they are not to confuse the driver and to be at all effective. In the realm of rear-end collision avoidance, there are many alternative responses (e.g., brake, steer left, steer right, brake and steer left, etc.). There is evidence in the crash record and the human factors literature that drivers do not necessarily do a good job of either generating or picking effective evasive actions.

The last class of information that might be conveyed by a truly intelligent CAS is how to best execute the selected evasive maneuver. Currently, concern exists with antilock brake systems (ABS) that a driver may underutilize or mis-use the system. This suggests that drivers do not necessarily always know how best to execute an emergency braking maneuver with this new technology. Drivers in a terminus crash situation often do not use the full braking capability of the vehicle. Brake assist systems are being developed and marketed that sense panic braking as distinct from normal braking to change the vehicle's braking response. Evidence from the human factors literature indicates that drivers do not use the full steering potential of the automobile (Wierwille, 1988). Stability enhancement systems that manage understeer and oversteer may alleviate this problem to some extent. These human performance shortcomings and technological supports suggest that advanced CAS devices might not only indicate the nature of the hazard, but suggest an effective evasive maneuver and even support maneuver execution. Taken to its logical conclusion, fully automated vehicle control systems would perform all of the CAS functions. The level of technology needed for truly robust fully automated vehicle control systems is still off in the future.

1.4 The Haptic System and Haptic Displays

Gibson (1966) defined the haptic system as "the sensibility of the individual to the world adjacent to his body". The term derives from the Greek word meaning "able to lay hold of" and operates when an individual feels things with the body or its extremities. Gibson points out that the receptor cells and units of the haptic system are tuned to mechanical energy, not chemical or photic energy. And, while touch is an important component of the haptic system, Gibson takes pains to point out that it is not just the sense of skin pressure alone. Mechanical energy is taken to include accelerations and decelerations that may be sensed through tissue compression changes and the vestibular system, as well as energy that impinges on the receptors of muscles, joints, and tendons. MacAdam (1995) points out that the haptic system is also sometimes referred to as the kinesthetic-tactile system.

One possible CAS display system is a haptic interface that the driver feels rather than sees or hears. A theoretical motivation for such displays is that they can contain high stimulus-response (S-R) compatibility (Wickens, 1992). In this case, the stimulus matches the sensory feedback produced by the intended response. For example, a steering response might be facilitated by a haptic display that involves steering wheel motion in the direction a driver should turn to avoid a collision.

The driver controls the vehicle and avoids collisions by appropriate inputs to the brake system, the accelerator, the steering wheel, the manual shifter, or some combinations of these. (Because of the proliferation of automatic transmissions in the fleet, manual downshifting is becoming an increasingly uncommon driver control input). These controls suggest some of the avenues by which haptic displays might be applied. There are also innovative control concepts that might be pursued for use in cars and trucks. Finally, other means of haptic display presentation may be pursued that do not operate on the vehicle controls at all. Table 1.1 presents some haptic display concepts that either have been or might be applied for collision avoidance in general and rear-end collision avoidance in particular.

Table 1.1 -- Candidate haptic display concepts for rear-end collision avoidance

Concept	Examples	Comments
Brake Displays	•CAS Warning via Pulse Braking; • High jerk rate or step change in decel that indicates automatic braking up to Adaptive Cruise Control (ACC) braking authority has been achieved and further manual braking is required; • Brake pedal force manipulations to prompt driver response.	•Pulse braking produces a short, sudden deceleration. The driver need not have a foot on the brake pedal or accelerator pedal. • High jerk rate as ACC braking authority is reached in attempt to deal with an obstacle; •For ACC automatic braking authority limit notification, a 2- 3 Hz ABS-type cycling could be applied to signify ACC braking limit is being reached. The driver need not have a foot on the brake or accelerator pedal. • ABS brake pedal feedback presumably falls within this category; foot on brake pedal needed
Accelerator Displays	•Active accelerator pedal that provides counterforce proportional to defined error (e.g., speed, instantaneous time headway, time-to-collision, etc.) or vibration for general alerting.	The active accelerator pedal assumes the driver has his or her foot on the accelerator. Use of conventional cruise control (CCC) or Adaptive Cruise Control (ACC) would result in the driver's foot most likely being off the accelerator pedal.
Steering Displays	•Directional torque of specified magnitude and duration; •Non-directional oscillation (e.g., vibration) of specified duration, amplitude, frequency, waveform;	• Directional torque active steering displays have been applied to lane change crash avoidance systems and to roadway departure crash avoidance systems (see literature review). In the present context, the directional steering wheel display would be used to facilitate an evasive steering maneuver (or steering and braking maneuver) in lieu of braking alone. • Non-directional active steering displays provide a generalized warning function but do not suggest an evasive maneuver; unrelated to braking events.
Innovative Controller Displays	• Raised Braille Dot display used by Fenton (1966) for car following and Jagacinski, Miller, and Gilson (1979), Jagacinski, Burke, and Gilson (1980); and Jagacinski, Flach, and Gilson (1983) for laboratory tracking task investigations.	This display was mounted in a joy stick handle. When the driver's hand was wrapped about this handle, a central wedge displaced forward (toward the driver's fingers) to indicate a need to back off or backward (toward the driver's palm) to indicate a need to catch up. Movement of the controller to bring the wedge flush with the handle nulled car following error.
Non-controller Displays	• Seat shakers to alert the driver; • Vibrating floor board to alert the driver; • Turn-signal stalk shakers to alert driver. •CAS Warning via forward pitch.	The first three concepts provide only general alerting; no indication of what is wrong or what to do about it. • Forward pitch is a key component of the braking sensation; used in simulators with limited throw. Active suspension could be used to alert the driver without actual deceleration of the vehicle. Alternatively, pitching driver's seat might suffice.

1.5 Previous Research on Haptic Displays

Haptic displays have been used for years in aviation. “Stick shakers” to alert the pilot of potential stalls have been in use since World War II. The earliest automotive application of a kinesthetic-tactile display was by Fenton (1966). In Fenton’s study of car following, a joystick was modified to provide headway information to the driver’s hand. If the driver was following too closely, a servo-driven joystick protrusion pushed out from the joystick handle toward the driver’s fingers. If the headway was greater than desired, the protrusion recessed through the joystick handle and in toward the driver’s palm. Both states were sensed primarily by the driver’s sense of touch. Drivers were able to maintain desired headway by keeping the joystick handle flush. Fenton (1966) reported success with this innovative display/control system.

Since Fenton’s pioneering research, there have been other applications of the haptic display concept to aviation (Gilson and Fenton, 1974), and tracking research (Burke, Gilson, and Jagacinski, 1980; Jagacinski, Flach, and Gilson, 1983; Jagacinski, Miller, and Gilson, 1979). In general, haptic displays show promise for various control applications as a form of workload relief. However, they are likely to be unfamiliar to drivers and therefore may require some practice. Furthermore, as the sole means of effecting control, haptic displays remain a poor second to visually guided control.

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

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

Godthelp and Schumann (1991) (see also Godthelp and Schumann, 1993) later evaluated the effects of the active accelerator pedal with error-proportional force feedback on speed control in a driving simulator. Test participants drove a simulated two-lane rural road, executed a lane change, and resumed driving at a requested speed that was perhaps different from the initial speed. Independent variables included the maneuver with or without speedometer information (termed speedometer occlusion) and with accelerator pedal characteristics at four levels: normal (passive) accelerator; speed-error proportional force feedback accelerator; feedback proportional to pedal position (not speed) accelerator; and a vibrating pedal (0.5 s at 10.0 Hz with 20 N magnitude). Results indicated that the accelerator that provided force feedback proportional to speed error was most effective in reducing speed errors.

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

Farber, Naab, and Schumann (1991) investigated the effectiveness of the active steering and accelerator pedal displays in a series of driving simulator and proving ground studies. The driving simulator scenarios included curve negotiation, overtaking, and car following. For curve driving, the active accelerator pedal reliably reduced speed through the curve but the use of a fixed duration (0.5 s) and fixed amplitude (2 Nm) directional torque shift did not significantly improve lateral control (as measured by lane standard deviation and median time-to-line crossing values). In the overtaking scenario, the CAS warned the driver attempting to pass a slower-moving lead vehicle that there was an oncoming vehicle. Thus, the goal of the CAS was to cancel the overtaking maneuver. The CAS support used, either a vibrating steering wheel (2.0 s at 10 Hz with 1 Nm amplitude) or a short directional torque steering wheel (0.5 s with torque shift of 2.5 Nm), was applied along with active accelerator pedal support. Results showed that the directional torque condition was reliably better than either no support or a vibrating steering wheel in terms of maximum lateral position to the left lane achieved prior to the driver canceling the overtaking maneuver. It was speculated that the amplitude of the vibrating steering wheel was too weak to capture the driver's attention, suggesting that the 1.2 Nm value found by Farber, Farber, et al. (1991) should be considered an absolute minimum. In the car following scenario, the lead vehicle suddenly braked but the brake lights did not come on. The active accelerator with fixed duration force (1 sec duration, 225 N force increment superimposed upon regular gas-pedal force) was clearly superior to the condition with no driver support in terms of the number of rear-end crashes avoided. Finally, the discrete directional steering torque (0.8 s with 3 Nm magnitude) was compared to no steering support and to a continuous steering wheel display that provided directional torque proportional to error (up to 3 Nm of torque maximum) on a closed course driven in an instrumented vehicle. In terms of curve negotiation, the two active steering approaches showed no significant differences in lane standard deviation, steering angle changes, or mean speed through the curve. There was a reliable increase in speed standard deviation for the discrete active steering display relative to the continuous support or no support.

Schumann, Godthelp, Farber, and Wontorra (1993) reported on a fixed base driving simulator study to examine the effectiveness of an active steering display to abort a lane change maneuver. The driver performed a lane change maneuver which was signaled by a short period where the visual scene was occluded. The lane change was then attempted with full vision or with vision occluded. During the lane change maneuver, the haptic displays activated to tell the driver to cancel the maneuver because of a vehicle in the adjacent lane. The CAS displays were auditory (0.5 s tone), vibrating steering wheel (0.5 s duration at 10 Hz with 1.2 Nm magnitude), vibrating steering wheel as before but duration lasting until lateral speed to the right (in the direction of a corrective steering maneuver) was greater than 1 m/s, and a directional torque to the right of fixed duration (0.5 s) and magnitude (2.4 Nm). The lane change maneuver is considered to be open-loop or pre-programmed (McRuer, Allen, Wier, and Klein, 1977) and so should be relatively hard to cancel once it has been initiated. Results indicated no significant effects of display modality on maximum steering wheel angle to the left and to the right, or maximum steering velocity to the left and to the right. This was interpreted to indicate that the steering control actions had not been disturbed. Response times were reliably shorter to the constant torque, directional steering wheel display, while the minimum lateral distance to the center line (lane line) was greater.

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

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

Tijerina, Jackson, Pomerleau, Romano, and Petersen (1996) applied various haptic display concepts to the problem of single vehicle road departure crash avoidance. The purpose of the study was to evaluate the following items from a driver-oriented perspective. Sixty-four volunteers participated at the Iowa Driving Simulator (IDS), a six-degree-of-freedom, moving-base simulator with a wide field-of-view image generation system. Sixteen of the participants were randomly assigned to serve in a control group without CAS support; the remaining 48 participants were randomly assigned to groups of 16 in each of three CAS Interface groups: auditory, haptic (active steering wheel or active accelerator pedal), or combined-modality. Within the CAS groups, participants were further assigned to different levels of four factors: directionality of CAS display (directional or non-directional), Onset (early CAS onset or late CAS onset), and Algorithm (Time-to-Line-Crossing [TLC] versus Time-to-Trajectory Divergence [TTD]) for lanekeeping.

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

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

Most recently, two reports have presented information on haptic braking displays. Bittner, Lloyd, Nowak, and Wilson (1999) introduced a haptic display concept for intersection collision avoidance warning. This is described as a series of three short pulses intended to mimic the feel of rumble strips. To achieve this effect, the authors designed an auxiliary brake system that includes additional calipers mounted on each wheel, an auxiliary hydraulic system placed in the trunk of the vehicle, and supporting actuators and controllers. No human factors studies with this system are reported in the paper.

Kiefer, LeBlanc, Palmer, Salinger, Deering, and Shulman (1999) report on an interesting series of studies of rear-end collision avoidance using a single-pulse braking haptic display as a driver warning. The pulse braking display consisted of a brief (approximately 600 msec) braking event involving a peak deceleration of 0.24 g. The pulse brake display was combined with a high-head-down visual display (HHDD) or with a non-speech auditory tone in a series of test track trials. The trials involved following a surrogate vehicle (artificial car) either stopped in the travel lane or being towed at approximately 30 mph. Test participants in the moving trials were instructed to maintain a normal time headway and the surrogate lead vehicle would occasionally brake at between 0.36 and 0.38g. Other driver displays included in the tests included a head-up display (HUD) combined with a non-speech tone, a HHDD combined with a non-speech tone, a HHDD combined with a an auditory speech (“Warning, Warning, Warning”) display. For both surprise (i.e., unexpected) and alerted (i.e., expected) trials, the pulse braking + HHDD display was associated with the slowest average brake reaction times as compared to auditory + visual displays. Inclusion of a coincident auditory display improved this somewhat, though HUD + non-speech auditory displays and HHDD+non-speech auditory displays were associated with faster responding. The authors concluded that the pulse brake alert provided some “vehicle slowing” advantage during the reaction time interval. They nonetheless caution about a number of unresolved issues with pulse braking displays. These issues include alert activation on slippery surfaces, onset delays or display “sluggishness,” consequences of lurching the driver out of the normal seated position, and driver annoyance and acceptance issues.

Pulse braking displays may be effective in alerting the driver to a forward obstacle. On the other hand, concern has been voiced that if the pulse braking is not designed correctly, the driver may assume that the vehicle will stop of its own accord, the driver may react inappropriately and execute a dangerous maneuver, or the driver may become distracted or confused as to the true state of affairs and delay appropriate intervention. The hands are very sensitive and perhaps an active steering display (e.g., handwheel vibration) would serve as a useful means of driver warning. However, many (perhaps more) of the same issues exist. A variety of research needs remain in the area of haptic displays. Some of the more salient issues are introduced below.

1.6 Issues for Haptic Display Research

The following questions have been identified as important to the evaluation of haptic display suitability for crash avoidance research. Each will be discussed in turn below.

What are the most suitable haptic displays for rear-end crash avoidance applications?

Referring back to Table 1.1, it is clear that many different haptic display concepts can be generated (no doubt including others not listed in the table and combinations thereof) to address the rear-end CAS application. These concepts might be filtered by a number of criteria, including initial feasibility of implementation. From this standpoint, active accelerator pedals might be considered technically feasible. However, the active accelerator pedal is not of use when the driver has conventional cruise control (CCC) or Adaptive Cruise Control (ACC) engaged. This is because the driver will most likely have the foot off the accelerator pedal and so will be unable to perceive the haptically displayed information. Thus, the active accelerator pedal may be desirable for rear-end CAS but it is not likely to be a sufficient haptic display if CCC or ACC are engaged. Pulse braking appears technically feasible since it is merely an extension of the ACC with limited braking authority. The implementation of an active brake pedal is also technically feasible. An examination of brake pedal feedback is already a part of the ABS research being conducted by the National Highway Traffic Safety Administration and no further comment is provided here. Active steering wheel displays are technically feasible for use as collision warnings. Forward collision avoidance might involve handwheel vibration when a forward obstacle or hazard is detected. Directional torque is also technically feasible but requires sensing of the adjacent lanes if such displays are to prompt an evasive steering response in a safe manner. Thus, the active steering wheel display should be considered most properly as part of an integrated, comprehensive crash avoidance system suite. Innovative car following displays like that developed by Fenton (1966) appear quite attractive to address the following-too-closely scenario. However, Fenton's implementation replaced the steering wheel with a joystick... a design option unlikely to be adopted by automotive manufacturers in the near term. On the other hand, handicapped drivers without the use of their legs make use of assistive devices to control brakes and throttle by hand. One such assistive device is a single lever that the driver pushes forward to brake and pulls back to accelerate. Perhaps an electro mechanically-modified hand controller like this could be implemented for rear-end CAS use. Finally, the use of non-directional displays like a seat shaker or floor board shaker are technically feasible. For example, subwoofers may be used to generate an output that is felt rather than heard. A forward-pitch display might be technically feasible with an active suspension system or perhaps some seat-pan angle adjustment device. Such an arrangement would have to be fast acting, however, and is currently speculative only.

In summary, then, it appears that the active accelerator pedal and pulse braking display, taken together, appear most promising from the standpoint of practical near-term implementation for rear-end CAS applications. The active steering display should be considered in the context of IVI as part of a comprehensive crash avoidance system suite as an intermediate-term rather than near-term goal. Innovative haptic displays for the hands suitable for car following are currently not available but might be implemented through the assistive technologies that help drivers without the use of their legs to remain mobile. Finally, non-controller haptic displays that make use of seat or floor board vibration are implementable. A haptic display that creates a short duration forward pitch of the vehicle is perhaps feasible through some form of active suspension change but is not considered near-term. Far-term implementations, not discussed here, involve automatic vehicle control systems.

Should the haptic display effect vehicle control directly?

This question arises only with haptic displays that are integrated into a controller (e.g., steering wheel, brakes, accelerator pedal, etc.). With conventional mechanical linkages, applying a torque on the steering wheel would, depending on magnitude and duration, eventually change heading angle and then vehicle lateral position. Similarly, application of a force on the accelerator pedal or brake pedal would, depending on magnitude and duration, affect the vehicle's accelerations and decelerations. With the advent of drive-by-wire technology, it is possible to bypass the mechanical linkages between controls and vehicle subsystems and provide haptic displays that do not, in themselves, affect vehicle dynamics. Instead, such displays could provide a haptic stimulus and, when the driver applied a force or torque modification, the drive-by-wire system would re-engage the control linkages. Such drive-by-wire concepts will require substantial development before they are introduced to the driving public and are not, therefore, considered a near-term alternative haptic displays.

For the active accelerator pedal research reported earlier, the counterforce on the gas pedal would (if not counteracted by the driver) slow the vehicle down because of the mechanical linkages that existed between the pedal and the throttle. With drive-by-wire technology, a counterforce could be applied that did nothing to the travel speed. The driver would then have to ease off of the pedal or pull the foot off their pedal (and, presumably onto the brake pedal) for the system to re-engage. Both conventional and drive-by-wire approaches could be compared and contrasted along the dimensions of driver acceptance, crash avoidance performance, and nuisance alarm effects.

For the pulse brake display, momentary application of the service brakes would actually decelerate the vehicle. On the other hand, if a forward-pitch display concept were implemented, vehicle deceleration might be mimicked momentarily without decelerating the vehicle. Like the active accelerator pedal example, both kinds of pulse braking display could be implemented to determine their effects on driver acceptance, crash avoidance performance, and nuisance alarm reactions.

For the active steering wheel, a torque applied to the steering wheel or shaft would, eventually change the heading angle and lane position with conventional mechanical linkages. With drive-by-wire, however, a directional or vibrational torque could be applied without affecting vehicle heading or lane position. Only when the driver applied an additional torque would the system engage.

The value of such concepts remains to be seen. For the active steering wheel, in particular, drive-by-wire technology might allow for improved vehicle control. For example, an evasive steering maneuver might be facilitated by providing what is termed "display quickening" into the steering wheel. A quickened display is one that presents a single indicator of tracking error (e.g., desired ILCD and t_{LC} based on a sinusoidal acceleration pattern) which is created by a weighted combination of the current error position, velocity, and acceleration. It presents, in essence, where the system will likely be in the future if it is not controlled or nulled out. Quickened displays are a form of predictive display that have proven to be useful in controlling systems of second order or higher (Wickens, 1992).

What are the characteristics of a haptic display that ensure fast and accurate perception on the part of the driver?

If a display is to be useful, it must first be detectable. Table 1.1 presents the set of candidate haptic display concepts outlined above and indicates the characteristics that can play a part in their detectability. As a rule, the characteristics span the range of settings for the following attributes:

Duration
Magnitude
Direction (Motion Stereotypes)

Directionality (e.g., vibration versus directional display)
Onset and Offset Profile
Periodicity
Effects of gloves, snow boots, heavy coats, and other "attenuators" on haptic display efficacy.

There are numerous test procedures that could be applied to determine the threshold settings for relevant display characteristics that guarantee, say, 95% detection among a pool of test participants. On the other hand, some preliminary work exists for some haptic displays (e.g., see review of previous research) that could be used to guide selection of a range of values that would be suitable for testing in an experimental rather than psychophysical framework. The evaluation of haptic display parameters to ensure detectability is, therefore, a high priority for CAS research.

How well does the haptic display work compared to visual or auditory displays for rear-end crash avoidance applications?

Once a set of detectable (and, hopefully, driver-acceptable) haptic display configurations have been identified, the next step is a comparison study to examine their efficacy when compared to auditory or visual displays. (Presumably, combinations of displays such as haptic+auditory would also be allowed). This portion of the research program would examine driver behavioral and performance reactions when presented with a haptic display while driving. It is envisioned that a test track study would be conducted that made use of a lead vehicle (perhaps a surrogate lead vehicle like that prepared for the CAMP program). The test participant, driving a suitably equipped vehicle, would follow the lead vehicle. The lead vehicle would vary its travel speed for car following, and brake at levels similar to those used in the CAMP first human factors study. There would also be a need to examine emergency braking to a stopped vehicle (or obstacle surrogate), presumably in a test track setting.

Does vision dominate haptic displays?

What if there is a mismatch between the visual input the driver receives and the haptic or kinesthetic-tactile display that the driver concurrently receives? There is evidence from basic perceptual research that vision dominates in such instances. For example, Rock (1984) reported on a study in which subjects viewed a cube lying on top of a cloth through a minifying lens. They judged the cube to be about half its objective size (correct, given the minification power of the lens). Then the subjects touched the cube without looking at it and correctly judged the size to be its true, objective size. But, when both looking at the cube through the minifying lens and simultaneously feeling it through the underlying cloth, subjects reported the size of the cube to be about half its objective size. This indicates that, given conflicting tactile and visual information, vision dominates. Perhaps the same phenomenon will apply for any mismatch between the driver's visual input and haptic inputs. Given that vision is superior to the haptic perceptions and the driver's judgement should take precedence over a machine-generated indication, visual dominance may be expected to have safety–positive consequences.... if it holds. There is a need to determine if in fact dominance holds and, in the event of a conflict between displayed and visually perceived information, the time or response accuracy costs associated with resolving the conflict.

One potential advantage of the haptic display is that it promotes faster responses than a visual stimulus. Unfortunately, visual dominance can have a deleterious effect on this facilitative property. Klein and Posner (1974) found that the reaction time to a stimulus that was multimodal (i.e., both a light and a proprioceptive displacement of a limb) was slower than the reaction time to a proprioceptive stimulus (a haptic display) alone. This result has been interpreted to suggest that the light captured attention and slowed down the more rapid processing of the haptic information. Posner, Nissen, and Klein, (1976) have proposed that visual dominance arises because vision captures attention less effectively than touch. As Rosenbaum (1991) points out, someone tapping on your shoulder is sure to get your attention but you may overlook someone waving to you. An attentional bias favoring vision may help compensate for the stronger alerting capacity of touch.

There are several implications of this basic research that merit verification in the application of haptic displays to CAS. First, if there is a mismatch between vision and the haptic display, vision should dominate. Given that the driver's vision is likely to be much more powerful for assessing a situation than a machine-generated haptic display, this should benefit safety in the event the haptic display system is malfunctioning in some manner. Second, the research of Posner and his colleagues leads to a research hypothesis that redundant visual and haptic displays may reduce to some extent the beneficial effects of haptic displays in terms of shorter reaction times.

1.7 Research Objectives

The initial studies to be described in this report addressed the following questions for pulse braking:

- What levels of mono-pulse braking duration and jerk rate support the detection of pulse braking events?
- Do the best levels of pulse braking duration and jerk rate change depending on whether or not the driver is driving only or driving while engaged in a demanding in-vehicle task?
- What combination(s) of duration and jerk rate do drivers consider most appropriate for CAS applications?

A similar set of questions were addressed for active steering displays, i.e.,:

- What levels of active steering vibration amplitude, frequency, and duration best support the detection of pulse braking events?
- Do the best levels of active steering display amplitude, frequency, and duration change depending on whether or not the driver is driving only or driving while engaged in a demanding in-vehicle task?
- What combination(s) of amplitude, frequency, and duration do drivers consider most appropriate for CAS applications?

A set of three studies were conducted to meet these objectives as well as other ad hoc objectives that arose from the results of the first study. The first study was designed to select parameters for a detectable pulse braking display. The second study was designed to select display parameters for an active steering display that warned the driver by means of handwheel vibration. In both of these studies, response surface methodology was applied to the study design (see Appendix A for an introduction to this type of study design and modeling approach). The purpose of the third study was to use rear-end CAS scenarios to examine the preferred concepts identified in the first two studies. All three studies are described in subsequent sections of this report.

1.8 Conclusions Regarding Haptic Research Considerations and Approach

It has been suggested that the haptic display research should be directed toward finding out what are the characteristics of a haptic display that are detectable and distinguishable from other roadway haptic cues in a variety of vehicle types. It has furthermore been indicated that the research should indicate the haptic display designs that are not objectionable to the driver from a comfort and acceptance point of view and quickly interpreted by the driver as crash warning information. Once the basic characteristics are determined, then some type of performance testing would be useful to see how well such a display works as a warning display, compared to auditory and/or visual displays, or combinations of displays.

These goals appear reasonable but prior experience with such displays compels the authors to make the following observations. To the extent that they serve as useful food-for-thought that leads to a more fruitful direction for the planned research, so much the better.

1. Haptic displays may not be created equal. We must be open to indications that, for example, a good haptic display for a LVS may of necessity be somewhat different than for an LVM scenario.

2. Haptic displays that employ braking or steering, if reserved for imminent crash warning situations only, should be infrequent but alarming. As such, drivers may not find them comfortable because it is not a comfortable situation to be in. Drivers may, nonetheless, find them acceptable because of their infrequency and perceived value in crash avoidance.

3. Haptic displays will almost certainly require some learning on the part of the driver. For example, a haptic display should not be confused for a system that automatically brakes

to a full stop. Nor should the haptic display be considered a sign of brake system failure. Distinguishing these types of confusions is important.

4. The individual properties of haptic displays for different automobiles may need to be tailored to those automobiles. Large, heavy autos may need very different kinds of haptic display characteristics to achieve the same "psychophysically equivalent" effect as a haptic display in a small, light automobile. This has implications in building off existing psychophysical studies conducted in Europe (see literature review above) and in extrapolating the findings in this study to other vehicles.

5. Distinguishing haptic cues from other roadway cues may or may not be a necessity. If the haptic cue promotes the appropriate crash avoidance response in the driver, whether or not it is the same as something else in the road environment (that would prompt the same type of response) may be beside the point. Some researchers (e.g., Kiefer, et al, 1999) indicate that a CAS warning should not be confusable with other cues in the driving environment. However, the authors disagree on principle. For example, a directional car horn sound in a lane change CAS can be very effective and prompt an appropriate crash avoidance response. This is precisely because it is like the real-world driving cues for a lane change conflict most people are already familiar with. That a false alarm may prompt an inappropriate response is, in the authors' opinion, no excuse for providing the driver with an artificial, sub-optimal display.

It is clear that there are many directions that a program in haptic displays for rear-end CAS applications can go. This report contains preliminary test results for what should most properly be considered pilot studies for a series of more in-depth studies that support the evolution of haptic displays for collision avoidance.

2.0 REAR-END COLLISION AVOIDANCE SYSTEM MONO-PULSE BRAKING HAPTIC DISPLAY PARAMETER SETTING STUDY

2.1 Introduction

There is a need to better understand the most effective and efficient ways to display haptic collision warning information to the driver in the rear-end collision avoidance system equipped vehicle. This is through the haptic mode, i.e., through displays that are felt rather than heard or seen. This chapter presents of a small-scale screening study to determine the display parameter settings of a mono-pulse braking display that might be used as the driver-vehicle interface for rear-end collision avoidance systems or Adaptive Cruise Control (ACC) systems with braking authority. Other concepts for providing haptic cues for collision avoidance through braking use a series of short pulses (analogous to the feel of rumble strips) (Bittner, Lloyd, Nowak, and Wilson, 1999). However, this concept requires an auxiliary brake system while the mono-pulse brake display used in the current study was accomplished through use of the standard foundation brakes of the test vehicle.

2.2 Method

2.2.1 Test Participants

Six (6) individuals, three females (ages: 27, 36, and 50 years) and three males (ages 25, 39, and 56 years), served as volunteer test participants. All individuals were in the employ of the Transportation Research Center (TRC) Inc. No special compensation was provided for participation. Test participants were unaware of the nature of the research prior to participation.

2.2.2 Apparatus

A 1995 4-door Chevrolet Lumina, with automatic transmission was used as the test vehicle. Cruise control was disabled for the test drives. The vehicle was equipped with MicroDAS instrumentation (Barickman, 1998) to capture speed, longitudinal acceleration, accelerator pedal position, and brake pedal force. The Visteon Magellan™ route guidance system (formerly the Zexel Navmate™) was installed and mounted on a gooseneck pedestal within easy reach of the driver. This device was used for the driver to enter address destinations during a portion of the data collection session.

Pulse braking was produced in the following manner. The Lumina had installed in it a torque motor (PMI Motion Technologies Model No. U9D-E) attached by means of a wire cable and pulley to the arm of the brake pedal. Upon application of a command signal provided by means of a GRID laptop computer, the torque motor provided a force on the brake pedal that generated the nominal jerk rate and duration required for a given trial.

The equipment that effected the pulse braking events produced some audible noise that might confound the results of the study. To alleviate this problem, each test participant during the actual driving phase of the study wore headphones (Optimus Model PRO-135) over which a compact disc (CD) of ocean surf sounds was played by means of a CD player (Sony Model D-E30ZCK). Each test participant had an opportunity to select the volume level that was comfortable but the levels chosen were always sufficient to mask any actuator sounds from the pulse braking equipment.

All trials were conducted on the TRC skid pad. This is a multilane (5 lanes plus 2 bump course lanes of asphalt) concrete course, with approximately 1 mile (1.6 km) of straightaway and banked turnaround loops (310 ft or 94 m radius curves) at either end. At times, other traffic not involved with the pulse braking study was also present on the skid pad.

2.2.3 Procedure

The test participant read the informed consent form (see Appendix B) which outlined the general purpose of the study. The test participant was given an opportunity to ask questions of the experimenter. The test participant was escorted to the test vehicle and oriented to it. The experimenter then provided the test participant with instruction on the manner in which to enter street address destinations into the route guidance system. This in-vehicle task had previously been shown to impose significant distraction to the driver (Tijerina, Parmer, and Goodman, 1998). The test vehicle was then driven to the TRC skid pad for testing.

Upon reaching the skid pad the test participant was read the instructions provided in Appendix C. These instructions were carefully worded to emphasize a quick response while leaving undefined the magnitude of the braking deceleration that, to the driver, constituted the response to the pulse braking event.

The test participant then drove 45 mph (72 kph) through one circuit of the skid pad for familiarization. This was followed by two blocks of 12 trials each, where a single trial constituted travel in one direction on the skid pad. After the vehicle was brought to a complete stop, the test participant would rate the acceptability of the pulse braking display as a rear-end collision avoidance system warning by means of a 7-point rating scale contained in Appendix D.

For half of the test participants, one block of trials was carried out while the driver was entering street addresses into the route guidance system. After a short break, the other block of trials was carried out while the driver was driving only. The order of the two blocks of trials was reversed for the other half of the test participants. Each block was composed of 9 trials with various haptic pulse braking events and 3 ‘catch trials’, i.e., trials in which no pulse braking display was presented. The order of trials was randomized across the ensemble of test participants with the caveat that the last trial was never a catch trial and catch trials were not run back-to-back.

2.2.4 Independent variables

The two pulse braking display parameters manipulated for this study were jerk rate (J) and Duration (D). The nominal levels used are provided in Table 2.1. As can be seen from Figure 2.1 and Table 2.1, three levels each of jerk rate and duration were factorially combined. A third factor, distraction condition (driving only vs. destination entry while driving) was also manipulated as a blocking variable.

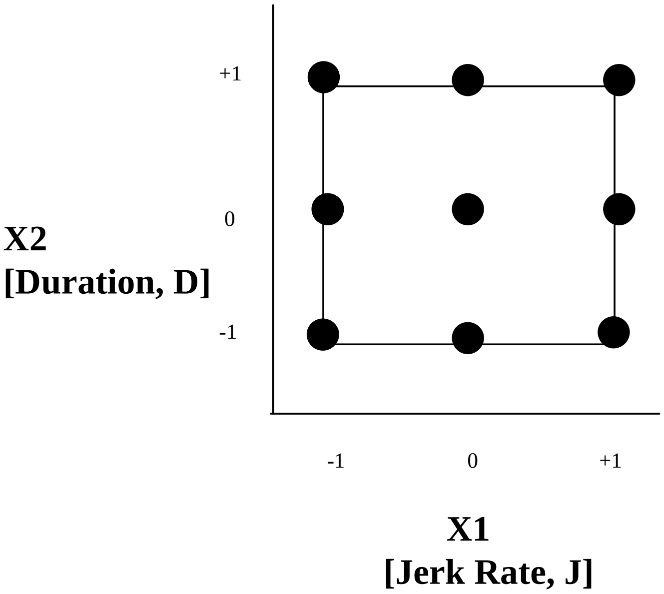


Figure 2.1 -- Pulse Braking Study Central Composite Design, Alpha = 1

Table 2.1 -- Coding Scheme for 2-Factor Pulse Braking Central Composite Design

Treatment	Coded		Uncoded	
Comb.	X1	X2	J (g/s)	D (s)
1	-1	-1	0.08	0.25
2	-1	+1	0.08	1.00
3	+1	-1	0.32	0.25
4	+1	+1	0.32	1.00
5	0	0	0.20	0.65
6	+1	0	0.32	0.65
7	-1	0	0.08	0.65
8	0	+1	0.20	1.00
9	0	-1	0.20	0.25

2.2.5 Dependent (Response) Variables

The following response variables were used:

- Detection Accuracy (count): The number of test participants out of six who responded to the pulse braking event. Without detection, none of the remaining response variables could be collected.
- Accelerator Release Time (AccelRT, seconds): The time interval from the onset of the pulse braking event until the test participant took his or her foot off the accelerator pedal.
- Total Stopping Distance (StopDist, m): The total distance traveled from pulse braking onset until the vehicle came to a complete stop. Note that the stopping distance was corrected using the formula in SAE J299 for minor variations about the nominal 45 mph (72 kph) travel speed the test participant was directed to maintain. The correction formula is accurate for speed variations of up to 3.2 kph. The total stopping distance represents the global braking response to the pulse braking event, i.e., the effects of the pulse braking display plus the driver braking response.
- Brake Stopping Distance (BrakDist, m): The total distance traveled from driver braking onset until the vehicle came to a complete stop. This provides an indication as to how the test participant stopped the vehicle after the pulse braking display was presented.
- Maximum Brake Pedal Force (PedalF, ft-lbs): The peak force applied by the driver to the brake pedal during the stopping maneuver, as measured from load cells attached to the brake treadle. This provides an indication of the braking effort exerted by the test participant in stopping the vehicle.
- Subjective Assessment of Acceptability as a Warning Display for Rear-end Collision Avoidance (Ratings): This was taken as a first step toward assessing the acceptability of a pulse braking display for its intended purpose. See Appendix C for the rating scale.

2.2.6 Data Analysis Approach

The levels of jerk rate and duration included in the study were established through pilot testing of various options. The goal was to arrive at jerk rates and durations the combinations of which would span the range of detectability and acceptability. Specifically, pilot testing uncovered a lower value of jerk rate and duration which would sometimes lead to missed detections and acceptability ratings of "much too soft" and upper values of jerk rate and duration that would always lead to detection but would sometimes be judged as "much too strong." Furthermore, the combinations of jerk rate and duration were selected such that the maximum deceleration achieved by the mono-pulse braking system would be within the range of braking authorities envisioned for adaptive cruise control systems.

The choice of three levels each of jerk rate and duration was made to allow for up to a quadratic response surface to be fitted to the numeric response variables. The combinations of levels of the two variables represent a face-centered central composite design suitable for fitting up to a quadratic polynomial by means of linear regression techniques and the analysis of variance. Williges (1981) provides more details about the central composite design approach.

The steps in the data analysis were as follows:

- The analysis involved both regression modeling and the analysis of variance on the regression weights. The Statistical Analysis System Version 6.12 (SAS, 1996) PROC GLM procedure was used throughout for the regression and Analysis of Variance (ANOVA) modeling. The Type III (simultaneous) Sums of Squares was used for all ANOVA tables and significance testing to accommodate missing data.
- All analyses were carried out on coded variables rather than natural variables. This has the advantage of simplifying the models as well as making the magnitudes of the fitted beta-weights more directly comparable. The linear transformation used for the coded variables was:

$$\text{X[Coded Value]} = \frac{\text{original value} - \left[\dfrac{\text{range minimum } + \text{ maximum}}{2}\right]}{\{\left[\text{range maximum } - \text{ minimum}\right] / 2\ \}}$$

- Examination of all possible combinations of X1, X2, $X1^2$, $X2^2$, and X1*X2 factors (i.e., linear, quadratic, and cross-product terms) were examined using the all-possible regressions approach with adjusted R^2 (an estimate of the proportion of variation in the response variable accounted for by the predictors) as the criterion. This was used to select the 'best' subset of models for further consideration.
- Modeling the 'best' subset of models both with and without test participant effects was carried out by using binary (0, 1) indicator variables to represent the test participant ("subject") effects. In general, for n subjects, n-1 indicator variables are needed and each consumes one degree of freedom in the regression model. In human factors research, it is not uncommon to find that individual differences among test participants is the largest single source of variation in a response.
- Generally, the alpha level of significance was reduced to $\alpha = 0.10$ for consideration of individual beta weights.

2.3 Results

The results will be presented for each of the response measures of interest. See Appendix E and Appendix F for the detailed results of regression modeling efforts for the distraction and non-distraction trials respectively.

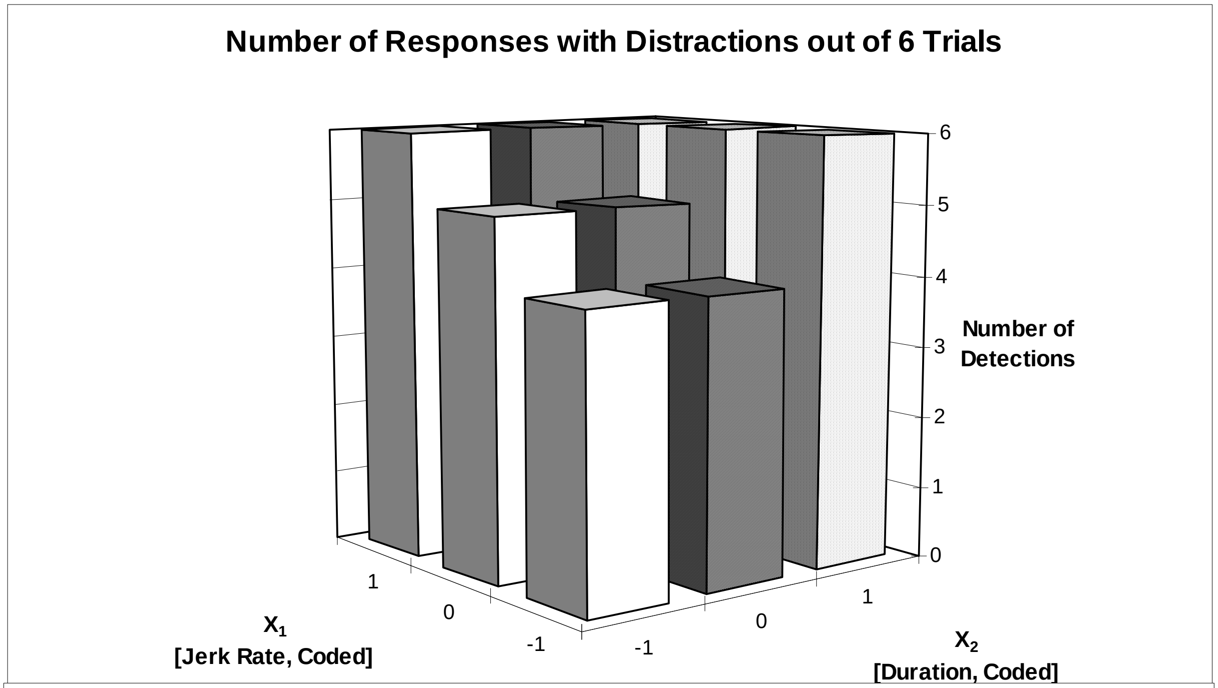
2.3.1 Accuracy of Detection

Figure 2.2 presents 3-D bar charts indicating the number of test participants out of six who responded correctly to each of the nine pulse braking events. Consistent across both distracted and non-distracted trials is a number of missed detections at the lowest levels of jerk rate and duration. Across both conditions only the highest jerk rate and the middle or highest event duration produced perfect detection. Surprisingly, the block of trials without distraction was associated with more missed detections than the block of trials completed with the destination entry distraction task. One possible explanation for this was that test participants exerted more effort to attend to a possible pulse braking event when they were obviously under greater distraction. This is considered to be an artifact of the experimental methods used; it cannot be assumed that being distracted while driving will always promote greater sensitivity to pulse braking or other types of warning displays. It nonetheless remains an interesting hypothesis for future evaluation.

2.3.2 Accelerator Release Time (AccelRT)

For the distraction trials, no statistically significant models were found for AccelRT as a function of jerk rate or duration. All variation in accelerator release time after pulse brake onset appears attributable to random variation during the distraction condition. For the non-distracted trials, only a linear effect of jerk rate was successfully fitted to AccelRT. That is, no other linear, quadratic, or cross-product terms added significantly to the model. The linear model of AccelRT as a function of jerk rate had an $R^2 = 0.19$ without subjects included in the model and an $R^2 = 0.47$ with subject effects terms in the model. Thus, about 19% of the variability in AccelRT is related to jerk rate, an additional 28% of the variability is related to stable differences among test participants, and over half of the variability remains unaccounted for, i.e., is error variance in the model.

Figure 2.3 shows the mean AccelRT values for each of the nine pulse braking events. Note the general trend for AccelRT to decrease with increasing jerk rates. In general the AccelRT measure proved not to be particularly diagnostic. It appears that chance factors had a greater effect on the variation in this response measure than either of the two pulse braking display parameters or individual differences among test participants (subjects).



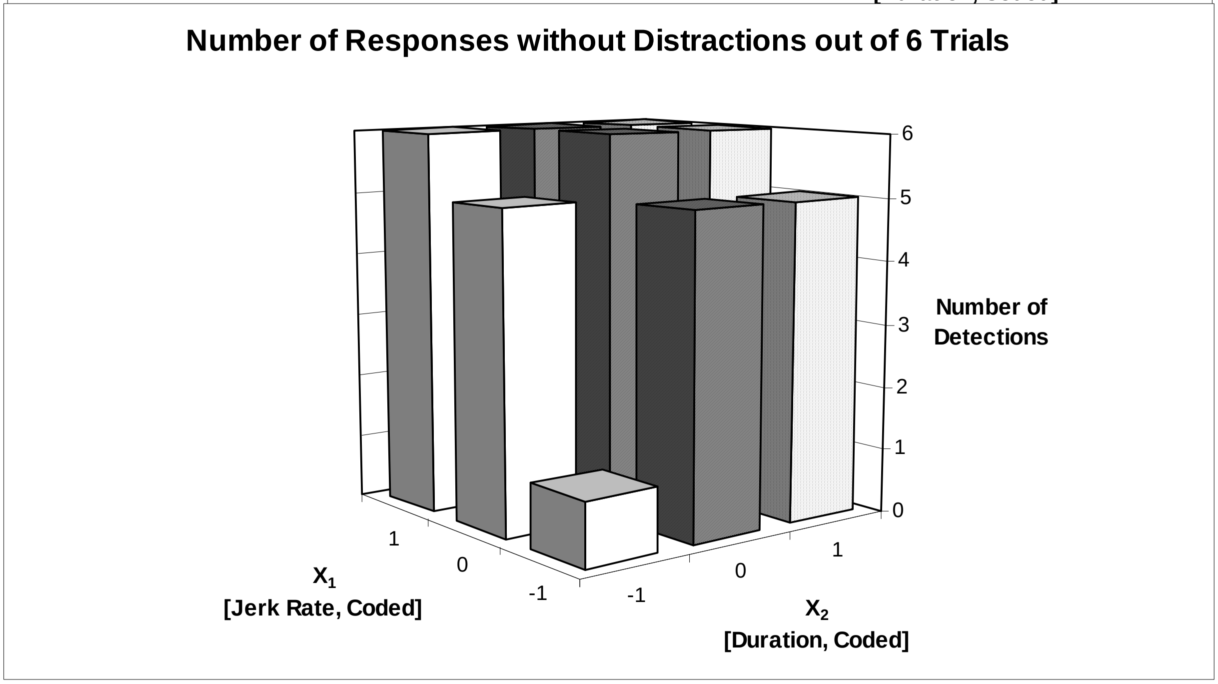
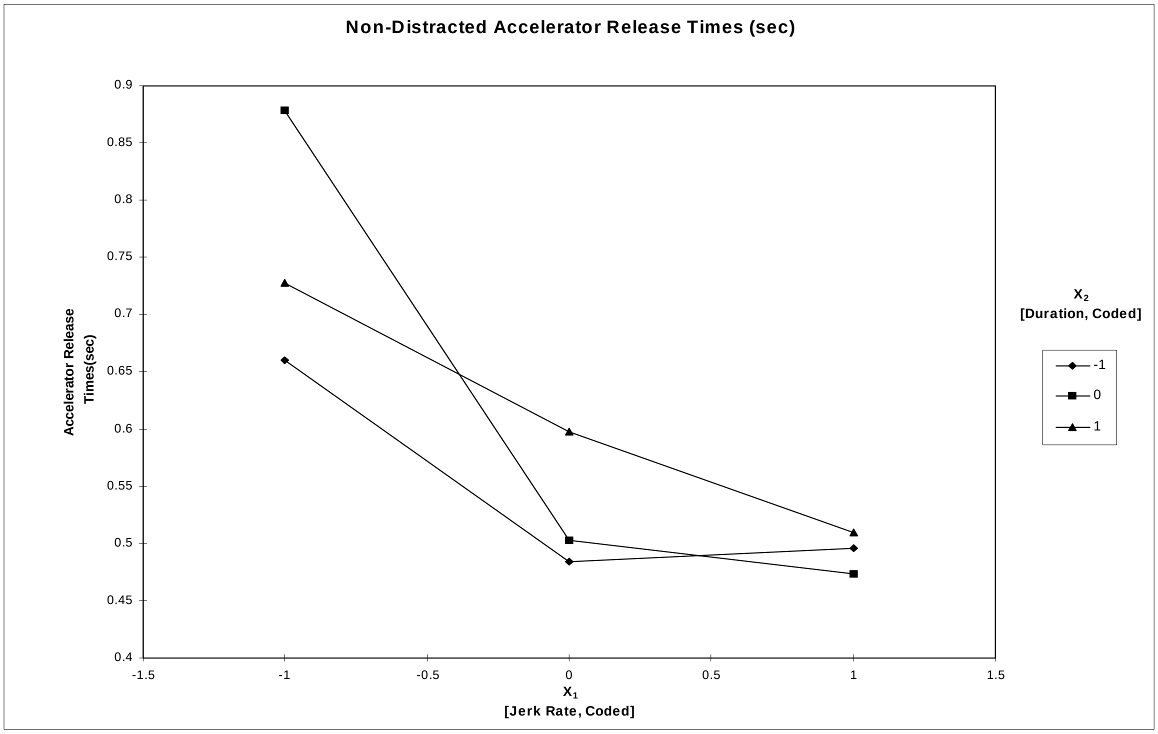


Figure 2.2 -- Number of test participants out of six responding to Pulse Braking Events as a function of Jerk Rate and Duration (Coded Values), in Distracted and Non-Distracted Trials



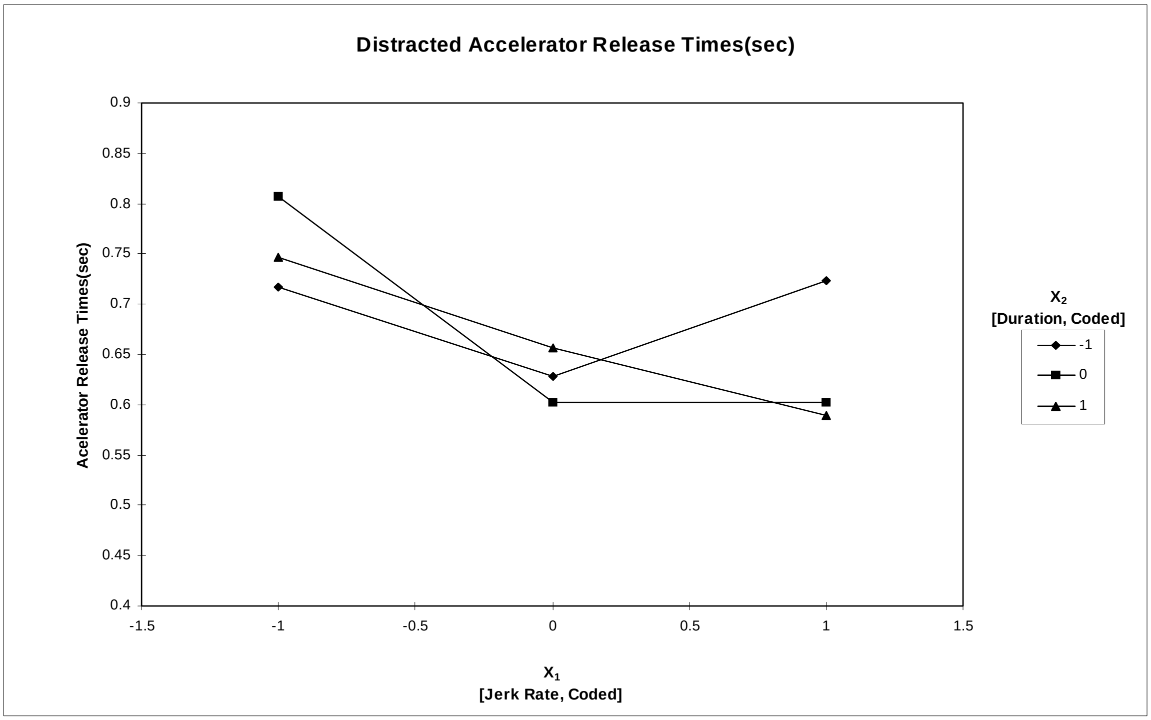


Figure 2.3 -- Mean AccelRT as a function of Jerk Rate and Duration (Coded Values), Distracted and Non-Distracted Trials

2.3.3 Total Stopping Distance

Test participants were instructed ahead of time that they were to bring the vehicle to a "controlled stop" if they noticed a pulse braking display. Pilot testing had suggested that, regardless of the instruction, drivers would brake harder (and stop in a shorter distance) the more noticeable the display. Such a relationship between the magnitude of the stimulus display and the magnitude of the response has not been reported before with haptic displays.

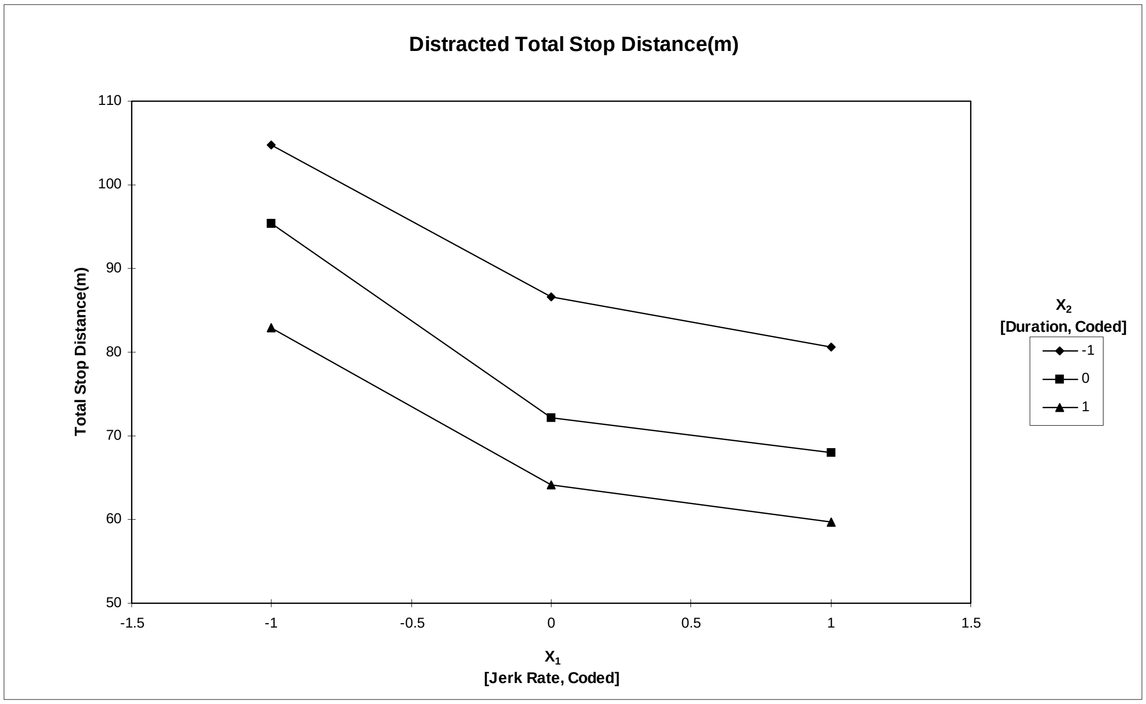
Figure 2.4 shows the mean stopping distances as a function of jerk rate and duration (coded values) for both distraction and non-distraction trials. The figure suggests linear trends toward shorter stopping distances as jerk rate and duration increase. There was no appreciable interaction between jerk rate and duration; variations from parallel lines represent chance variation. This pattern holds for both distraction and non-distraction data sets. Indeed, regression analysis produced the following "best model" for the distraction condition (X1 is coded jerk rate; X2 is coded duration):

$$Totstop = 79.1 - 12.2X_1 - 11.0X_2; R^2 = 0.38, se = 16.8$$

If test participants are included in the model, the proportion of variability in the response variable increases to $R^2 = 0.80$ Thus, 80% of the variation in stopping distance is accounted for by a linear model of jerk rate and duration, along with subject effects.

The "best" linear model for the non-distraction condition is similar to that for the distraction condition.

$$Totstop = 84.6 - 15.3X_1 - 10.7X_2; R^2 = 0.37, se = 18.2$$



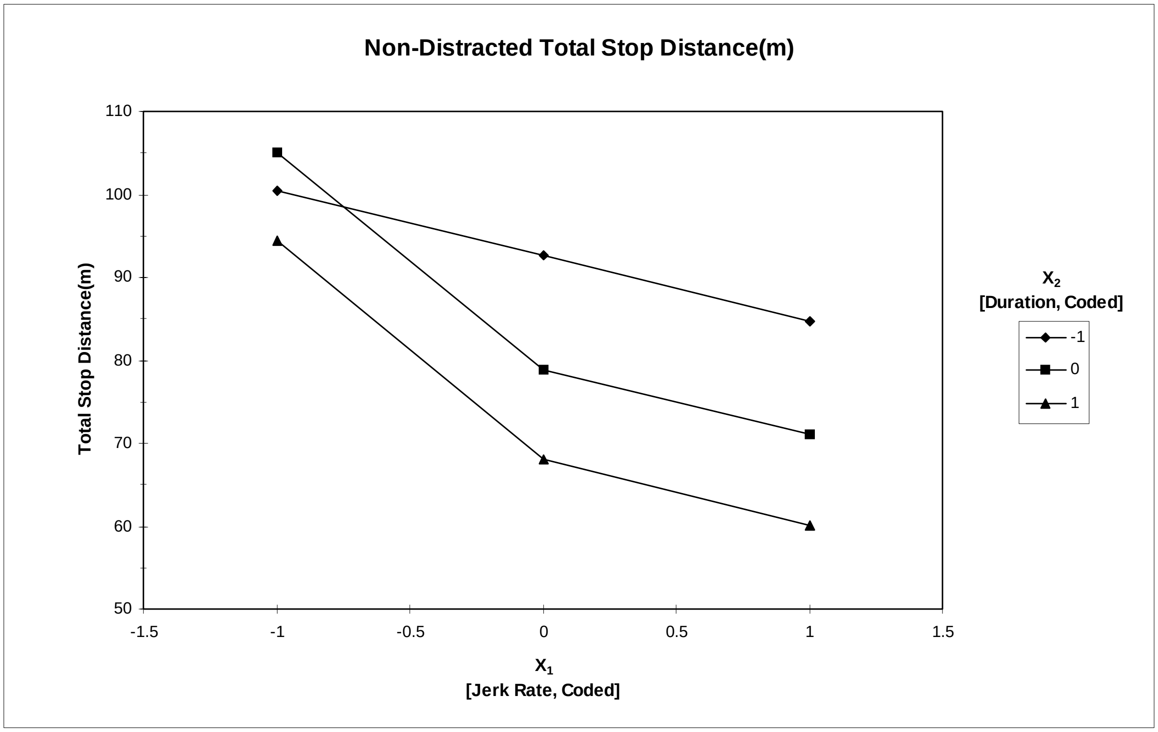


Figure 2.4 -- Total Stopping Distance as a function of Pulse Braking Jerk Rate and Duration (Coded Variables), Distracted and Non-Distracted Conditions

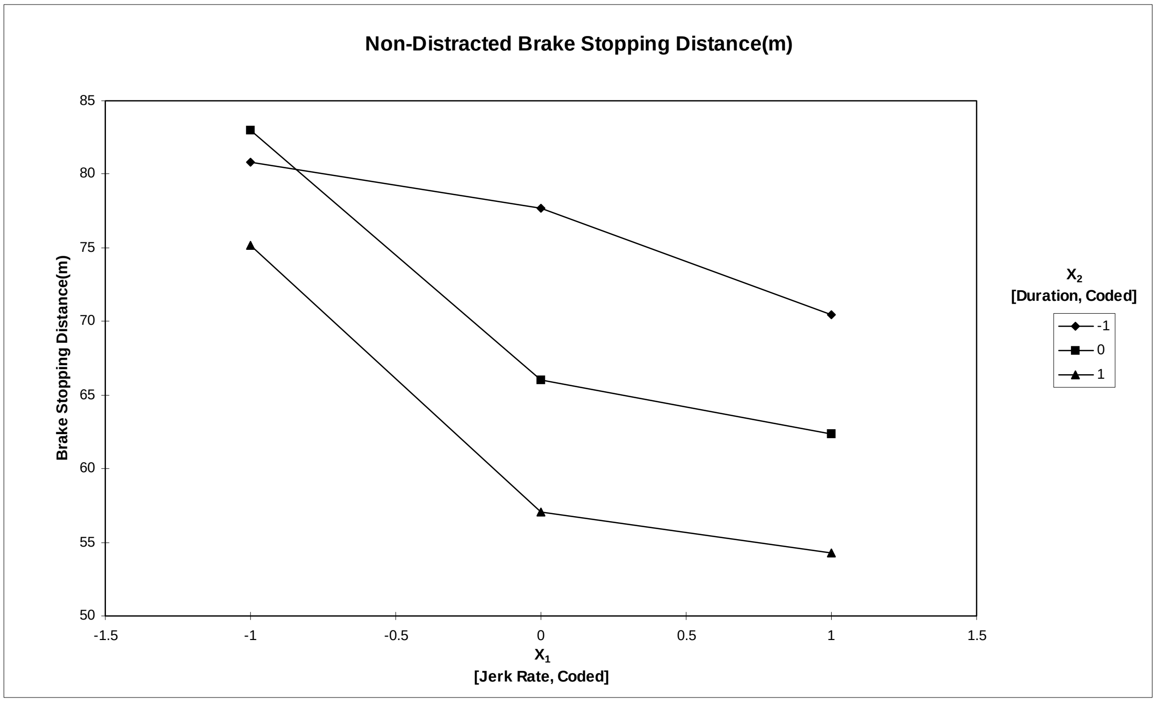
Again, no quadratic or cross product terms were statistically significant. If subject effects are included in the regression model, the proportion of variability in the response variable accounted for by the model jumps to $R^2 = 0.86$, or 86%.

These results are remarkable from at least two standpoints. First, human factors data from field experiments seldom exhibit such high proportions of response variance accounted for by the data analysis model. Second, even though the test participants were not instructed to respond in any particular way while bringing the vehicle to a controlled stop, clearly there was a substantial effect of the magnitude of the pulse braking display on the subsequent stopping maneuver. Such an effect has not been previously reported in the open literature, to the authors' knowledge. The implications of this effect will be discussed later.

It must be acknowledged that the total stopping distance response reflects both the driver's response and the effects of the pulse braking display itself. To examine how the driver stopped the vehicle in response to the pulse braking display, the brake stopping distance was analyzed as well.

2.3.4 Brake Stopping Distance

Figure 2.5 presents the mean brake stopping distances as a function of jerk rate and duration (coded values) for both distracted and non-distracted conditions, respectively. By including subject effects into the model, the percentage of variability in brake stopping distance grows to 79% and 87% for distracted and non-distracted conditions, respectively. Thus, the effect of a greater stimulus magnitude producing a stronger braking response holds even after the effects of the pulse braking display itself have been partialled out. The general trend is toward shorter brake stopping distances with greater jerk rates and longer duration pulse braking events.



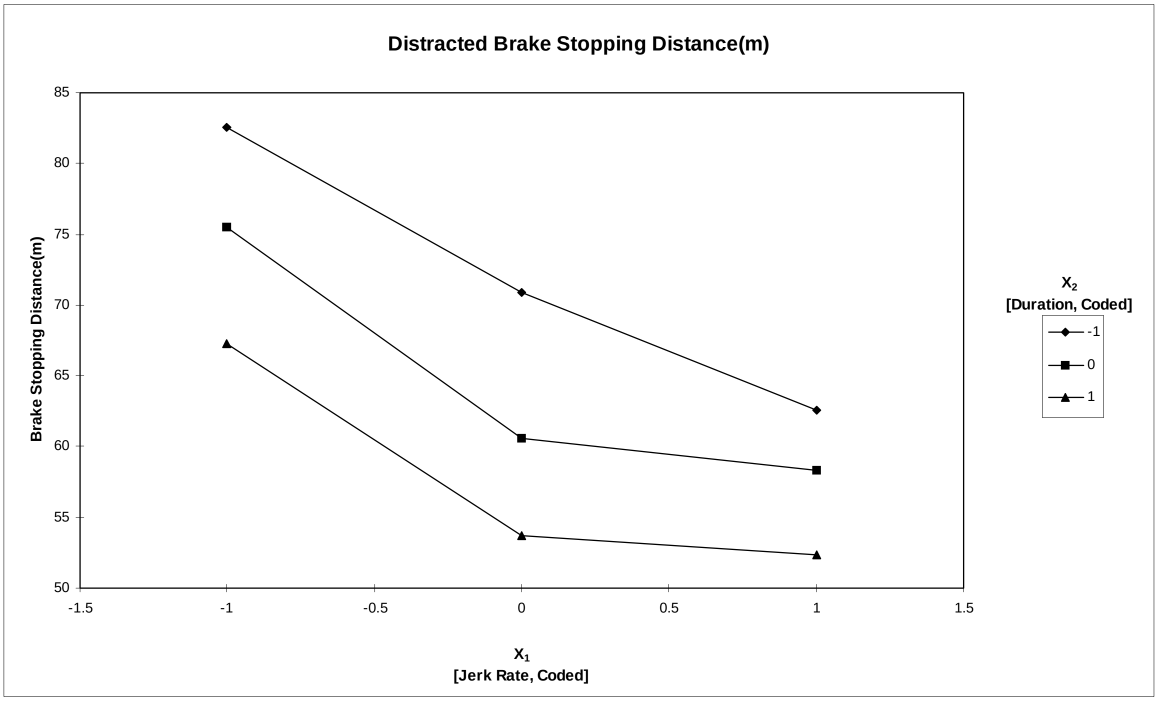


Figure 2.5 -- Mean Brake Stopping Distance as a function of Jerk Rate and Duration (Coded Values), Distracted and Non-Distracted Conditions

2.3.5 Maximum Pedal Force Exerted

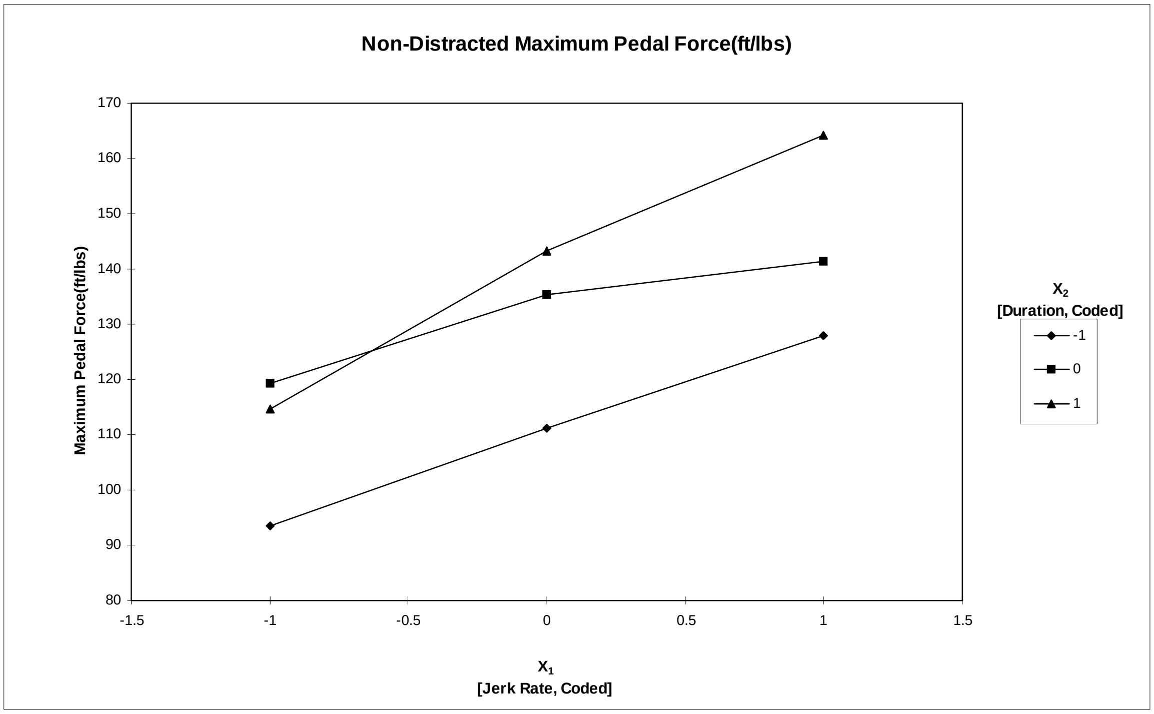
The force applied to the brake pedal is another indication of the effort the driver is exerting to make the braking maneuver. Figure 2.6 shows the mean maximum pedal force for each combination of jerk rate and duration of pulse braking event. Regression analysis revealed the percentage of variance in this response accounted for by a 'best' regression model for distraction trials was $R^2 = 0.16$ for a linear model that included both jerk rate and duration. Inclusion of Subject effects to the linear model led to a considerable increase in $R^2 = 0.87$. For non-distraction trials, the "best" regression model was again linear in jerk rate and duration, with $R^2 = 0.14$. Inclusion of subject effects in the linear model increased the proportion of variance accounted for to $R^2 = 0.83$. The general trend is for greater peak brake pedal force applications with greater jerk rate and longer duration pulse braking events.

2.3.6 Subjective Assessments

The last dependent measure was the rating of each pulse braking event in terms of its perceived suitability as a rear-end collision warning display. The test participants answered the subjective assessment question below after each detected pulse braking event:

"Please judge the appropriateness of the haptic event as a warning display on the following 7-point scale":

1___ Much too soft
2___ Moderately soft
3___ Slightly soft
4___ Just right
5___ Slightly hard
6___ Moderately hard
7___ Much too hard



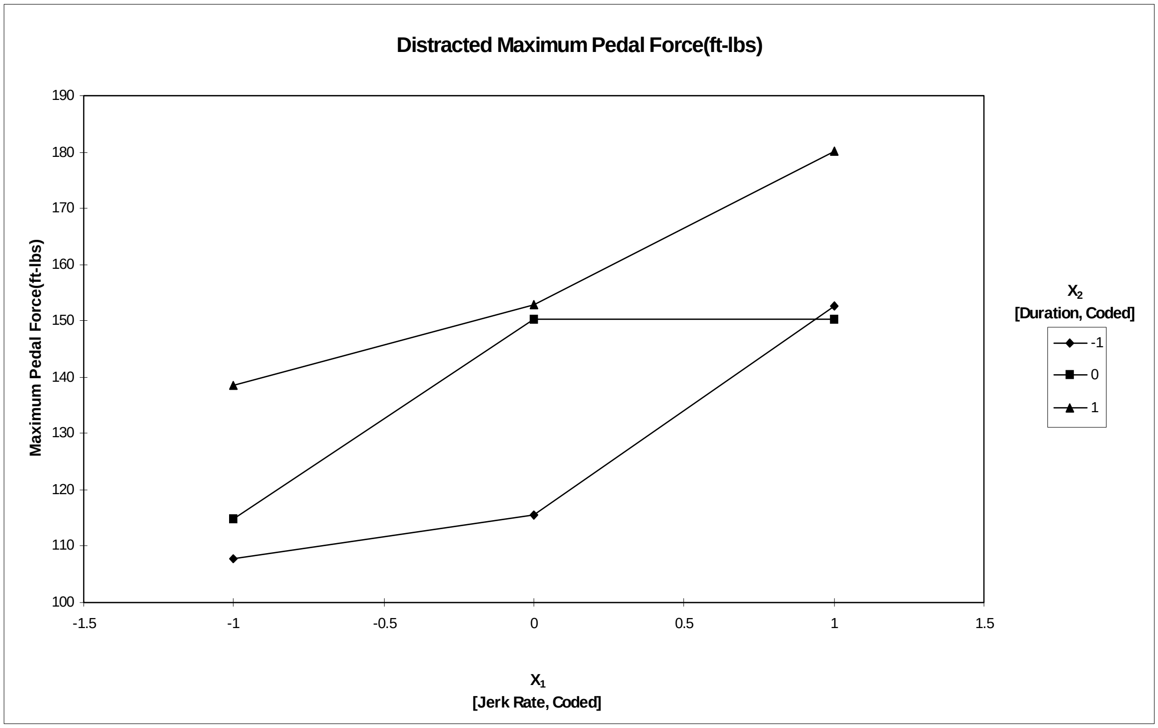


Figure 2.6 -- Mean Maximum Pedal Force as a Function of Jerk Rate and Duration (Coded Values), Distracted and Non-Distracted Conditions

Such judgements must be interpreted with caution. The rating process is generally noisy and the ratings were provided after only a single exposure in a given condition of distraction or non-distraction. With these caveats, the following logic for interpretation is offered. What is desired is identification of a combination of jerk rate and duration that promotes the most ratings of "Just right". Ratings of "Slightly soft" or "Slightly hard" are next most preferable, with the latter being the more suitable of the two for collision warning displays. Ratings of "Much too soft" and "Much too hard" might be construed as unacceptable. Ratings of "Moderately soft" and "Moderately hard" might be interpreted as less desirable than ratings in the middle range.

Table 2.2 contains the individual ratings for each combination of jerk rate and duration of the pulse braking displays used in the study. Consider the distraction data first. If one sums the number of ratings at or about the ideal point (i.e., ratings of 3, 4, 5), then the highest level of jerk rate with the lowest or middle level of duration are the best from a subjective standpoint. Given the rule that a warning display, if not "just right" should err on the side of being "slightly hard", then pulse braking display with the highest jerk rate and the middle level of duration is preferred.

Consider next the non-distraction data. By summing the number of ratings at or about the ideal point (i.e., ratings of 3, 4, 5), then the highest level of jerk rate combined with the middle level of duration represents the "best" combination from a subjective standpoint.

2.4 Conclusions of Mono-Pulse Braking Haptic Display Parameter Setting Study

The results of this parameter setting study revealed a number of interesting phenomena. Perhaps the most surprising one was that, within the scope of the study, all response functions were linear. While the study design made it possible to fit up to a quadratic response function to the quantitative response measures, in no case was such a function justified from a statistical standpoint, even using more lax alpha levels of 0.10. It was originally thought that a quadratic response surface would allow for determination of a mathematically optimal response. Purely linear response functions require that another strategy be applied.

Table 2.2 -- Individual Ratings of Appropriateness of Pulse Braking Display as a Warning Display, Distraction and Non-Distraction Trials, N=6

Distraction Trials

	Duration, X2			
Jerk Rate, X1	Codes	-1	0	+1
	-1	0, 0, 1, 1, 1, 1	0, 0, 2, 2, 3, 4	1, 2, 2, 2, 3, 3
	0	0, 2, 2, 2, 3, 4	2, 3, 3, 4, 6, 6	3, 4, 5, 6, 6, 7
	+1	3, 3, 3, 3, 4, 4	3, 4, 4, 5, 5, 7	4, 6, 6, 7, 7, 7

Non-Distraction Trials

	Duration, X2			
Jerk Rate, X1	Codes	-1	0	+1
	-1	0, 0, 0, 0, 0, 1	0, 1, 1, 2, 2, 2	0, 1, 3, 3, 3, 4
	0	0, 1, 2, 2, 2, 3	2, 3, 3, 4, 5, 5	1, 4, 5, 5, 6, 6
	+1	0, 1, 1, 2, 3, 4	2, 4, 4, 4, 5, 6	4, 5, 6, 6, 6, 7

Notes:

The following rating scale was used:

> “Please judge the appropriateness of the haptic event as a warning display on the following 7-point scale”:

1___ Much too soft
2___ Moderately soft
3___ Slightly soft
4___ Just right
5___ Slightly hard
6___ Moderately hard
7___ Much too hard

A scale value of 0 in the above table indicates a missed detection.

Second, it is clear that individual differences among test participants accounted for a substantial proportion of the variability in a given response measure. It is not uncommon that individual differences serve as the main source of response variability in a human factors study. The regression equations that included subject effects accounted for up to 79% to 87% of variability, a remarkable result given the noise usually inherent in field study research. Perhaps the simplicity of the detection task underlies this outcome.

Third, the data more or less consistently point to the combination of high-jerk-rate and middle-duration as the most suitable single pulse braking display for further evaluation. This combination had the following properties across the distraction and non-distraction trials:

- Detection by all test participants. This is considered critical since a display that cannot be reliably detected is problematic as a warning display.
- The most positive subjective assessments (e.g., the most ratings of "Just right", followed by "Slightly hard" and "Slightly soft"). This is considered important as a precursor to driver acceptance.
- Effectively the shortest driver response latencies (as indicated by trends in accelerator release times). While the differences in accelerator release times were generally not statistically significant for the distraction trials, the general trend was toward shorter reaction times with stronger (i.e, higher jerk rate, longer duration) displays. The selected high jerk rate, middle duration pulse braking display was associated with the shortest (or practically the shortest) response latencies.

Fourth, the data clearly and consistently show a phenomenon that has heretofore not been reported for haptic displays (to the authors' knowledge). The magnitude of the pulse braking display had a consistent impact on the magnitude of the driver's braking response. In general, the higher the jerk rate and the longer the pulse braking event duration, the harder the driver braked to bring the vehicle to a controlled stop. Care was taken in the instructions provided to the test participant to be neutral about the nature of the braking maneuver. This finding suggests both opportunities and problems for the mono-pulse braking display concept for rear-end collision warning.

The opportunity uncovered by this result is that it may be possible to prompt more appropriate responses from the driver depending on the severity of the conflict between the subject vehicle and the principal other vehicle. That is, if the sensed conditions are such that a more aggressive braking maneuver is required, a stronger mono-pulse braking display may promote this. There is evidence that drivers in crash-imminent situations do not fully utilize the braking capability of the vehicle. This is the motivation behind, for example, some newly developed "smart" brake systems which sense "panic braking" by means of brake pedal throw and automatically provide a higher pedal force gain in such circumstances. If the trends in the current study are any indication, variable-magnitude mono-pulse braking displays may alleviate the problem of insufficient braking to at least some extent. Furthermore, the mono-pulse braking display does have some effect on the vehicle itself and so the display may contribute to the eventual evasive braking maneuver.

The problem posed by the pattern of results is what may happen when a false positive indication arises. There exists the possibility that a driver startled by the mono-pulse braking display may instinctively brake hard. If so, this behavior might precipitate a chained rear-end collision with the host vehicle being struck from behind by another vehicle. (Note that such a problem might also arise in the event of a true rear-end crash hazardous situation). A false positive when the driver is attempting to clear an intersection may put the host vehicle in the path of another vehicle. A false positive indication while negotiating the tracks at an at-grade railroad crossing may cause the driver to brake suddenly while straddling the tracks. And so on.

The third study described in this report examined driver response to mono-pulse braking displays for both true-positive and false-positive conditions. Assessment in the true-positive condition provides an assessment of the efficacy of the mono-pulse braking display to alert the driver to a crash hazard. Assessment in the false-positive condition provides an assessment of how the driver will respond to a false warning. The false-positive condition might be assessed through two different scenarios. In one scenario, the subject vehicle is following a lead vehicle when the false positive warning is issued yet the lead vehicle is not slowing down. In a second scenario, the subject vehicle is not in car following when a false positive warning is issued; here there is no object to focus attention onto.

2.5 Final Recommendations for Mono-Pulse Braking Haptic Display Parameter Setting Study

The purpose of this initial research was to arrive at mono-pulse braking parameter settings that would result in a display suitable for subsequent testing. Based on the results of this study, it is recommended that a 0.32 g/s jerk rate applied for 0.65 seconds be used as the mono-pulse braking display concept for further evaluation.

An unexpected finding also arose from this testing. Results from the stopping distance and maximum pedal force data indicate that the magnitude of the pulse braking display influenced the magnitude of the driver's stopping behavior. In short, the stronger the mono-pulse braking display, the harder the subsequent braking. The third study described in this report further investigated this phenomenon in a car following setting as described in Section 4.0.

3.0 REAR-END COLLISION AVOIDANCE SYSTEM ACTIVE STEERING HAPTIC DISPLAY PARAMETER SETTING STUDY

3.1 Introduction

Another way to display haptic collision warning information to the driver in the of a rear-end collision avoidance system equipped vehicle is by active steering. This chapter presents the results of a small-scale screening study to determine the display parameter settings of an active steering haptic display. Such a display vibrates the steering wheel to get the driver's attention to a hazard.

3.2 Method

3.2.1 Test Participants

Six (6) individuals, three females (ages: 27, 36, and 50 years) and three males (ages 25, 39, and 56 years), served as volunteer test participants. These were the same individuals which participated in the mono-pulse braking haptic display parameter setting study. All individuals were in the employ of the TRC No special compensation was provided for participation. Test participants were unaware of the nature of the research prior to participation.

3.2.2 Apparatus

A 1995 4-door Chevrolet Lumina (the same vehicle as was used in the mono-pulse braking haptic display parameter setting study), with automatic transmission was used as the test vehicle. Cruise control was disabled for the test drives. The vehicle was equipped with MicroDAS instrumentation (Barickman, 1998) to capture speed, longitudinal acceleration, accelerator pedal position, and brake pedal force. The Visteon Magellan™ route guidance system was installed and mounted on a gooseneck pedestal within easy reach of the driver. This device was used for the driver to enter address destinations during a portion of the data collection session.

The active steering display was produced in the following manner. The Lumina had installed in it a torque motor (PMI Motion Technologies Model No. U9D-E), mounted beneath the dashboard and secured to the wall of the footbox by bolts. The torque was transmitted via a roller chain and sprockets affixed to the steering column and the torque motor shaft. Upon application of a command signal provided by means of a GRID laptop computer, the torque motor provided a torque on the steering column in a given direction (clockwise, counterclockwise) that generated the nominal frequency, amplitude, and duration required for a given trial (see Independent Variables section below).

The torque levels for the active steering display were measured during pre-testing by means of a load cell. The steering wheel column was restrained from rotation by a rigid bar mounted in the vehicle. The rigid bar was attached to the steering wheel by means of a load cell. The load cell (Transducers Inc. Model: BTC-FF62-CS-300#) was calibrated using a 14 pound weight. The moment arm of the steering wheel was measured to calculate torque. All the levels of the active steering display were played back and the torque levels were measured.

The equipment that generated the active steering displays produced some audible noise that might confound the results of the study. To alleviate this problem, each test participant during the actual driving phase of the study wore headphones (Optimus Model PRO-135) over which a compact disc (CD) of ocean surf sounds was played by means of a CD player (Sony Model D-E30ZCK). Each test participant had an opportunity to select the volume level that was comfortable but the levels chosen were always sufficient to mask any actuator sounds from the active steering display equipment.

All trials were conducted on the TRC skid pad. As stated previously, this is a multilane (5 lanes plus two bump course lanes of asphalt) concrete course, with approximately 1 mile (1.6 km) of straightaway and banked turnaround loops (310 ft or 94 m radius curves) at either end. At times, other traffic not involved with the pulse braking study was also present on the skid pad in other lanes.

3.2.3 Procedure

The test participant read the informed consent form (see Appendix G) which outlined the general purpose of the study. The test participant was given an opportunity to ask questions of the experimenter. The test participant was escorted to the test vehicle and oriented to it. The experimenter then provided the test participant with instruction on the manner in which to enter street address destinations into the route guidance system. This in-vehicle task had previously been shown to impose significant distraction to the driver (Tijerina, Parmer, and Goodman, 1998). The test vehicle was then driven to the TRC skid pad for testing.

Upon reaching the skid pad the test participant was read the instructions provided in Appendix H. These instructions were carefully worded to emphasize a quick response while leaving undefined the magnitude of the braking deceleration that, to the driver, constituted the response to the active steering event.

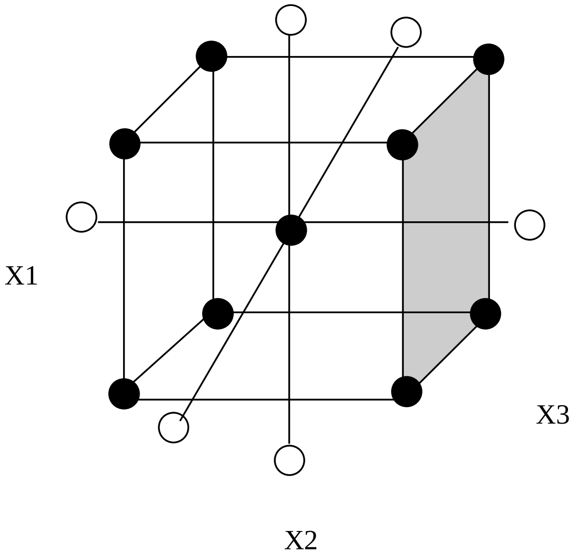
The test participant then drove 45 mph (72 kph) through one circuit of the skid pad for familiarization. This was followed by two blocks of 20 trials each, where a single trial constituted travel in one direction on the skid pad. After the vehicle was brought to a complete stop during a trial, the test participant would rate the acceptability of the active steering display as a rear-end collision avoidance system warning by means of a set of rating scales contained in Appendix I.

For half of the test participants, one block of trials was carried out while the driver was entering street addresses into the route guidance system. After a short break, the other block of trials was carried out while the driver was driving only. The order of the two blocks of trials was reversed for the other half of the test participants. Each block was composed of 15 trials with various haptic active steering displays and 5 ‘catch trials’, i.e., trials in which no active steering display was presented. The order of trials was randomized across the ensemble of test participants with the caveat that the last trial was never a catch trial and catch trials were not run back-to-back.

3.2.4 Independent variables

The three active steering display parameters manipulated for this study were Frequency (F), Amplitude (A), and Duration (D). The nominal levels and combinations used are provided in Figure 3.1. The combinations used constitute a 3-factor central composite design. A fourth factor, distraction condition (driving only vs. destination entry while driving) was also manipulated as a blocking variable.

Second-order, Central Composite Study Design in 3 Variables, X1, X2, X3



	Coded			Uncoded (Natural)		
Treatment	X1	X2	X3	F(Hz)	A(Nm)	D(s)
1	+1	+1	+1	10	1.8	1.26
2	+1	-1	+1	10	1.2	1.26
3	+1	+1	-1	10	1.8	0.74
4	+1	-1	-1	10	1.2	0.74
5	-1	+1	+1	6	1.8	1.26
6	-1	-1	+1	6	1.2	1.26
7	-1	+1	-1	6	1.8	0.74
8	-1	-1	-1	6	1.2	0.74
9	+1.9	0	0	12	1.6	1.00
10	-1.9	0	0	4	1.6	1.00
11	0	+1.9	0	8	2.2	1.00
12	0	-1.9	0	8	1.0	1.00
13	0	0	+1.9	8	1.6	1.50
14	0	0	-1.9	8	1.6	0.50
15	0	0	0	8	1.6	1.00

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + e$$

Figure 3.1 -- Central Composite Design for Active Steering Study

3.2.5 Dependent (Response) Variables

The following response variables were used:

- Detection Accuracy (count): The number of test participants out of six who responded to the active steering event. Without detection, none of the remaining response variables could be collected.
- Accelerator Release Time (AccelRT, seconds): The time interval from the onset of the active steering event until the test participant took his or her foot off the accelerator pedal.
- Brake Reaction Time (BrakeRT, seconds): The time interval from the onset of the active steering event until the test participant pressed the brake pedal. It represents an important measure of brake initiation.
- Total Stopping Distance (StopDist, m): The total distance traveled from active steering onset until the vehicle came to a complete stop. Note that the stopping distance was corrected using the formula in SAE J299 for minor variations about the nominal 45 mph (72 kph) travel speed the test participant was directed to maintain. The correction formula is accurate for speed variations of up to 3.2 kph. The total stopping distance represents the global braking response to the active steering event.
- Brake Stopping Distance (BrakDist, m): The total distance traveled from driver braking onset until the vehicle came to a complete stop. This provides an indication as to how the test participant stopped the vehicle after the pulse braking display was presented.
- Maximum Brake Pedal Force (PedalF, ft-lbs): The peak force applied by the driver to the brake pedal during the stopping maneuver, as measured from load cells attached to the brake treadle. This provides some indication of the effort the driver exerted in bringing the vehicle to a controlled stop.
- Subjective Assessments of Acceptability as a Warning Display for Rear-end Collision Avoidance (Ratings): This was taken as a first step toward assessing the acceptability of an active steering display for its intended purpose. See Appendix I.

3.2.6 Data Analysis Approach

The levels of active steering vibration frequency, amplitude, and duration included in the study were established through pilot testing of various options. The combinations of levels of the three variables represent a central composite design suitable for fitting a quadratic polynomial by means of linear regression techniques and the analysis of variance. Williges (1981) provides more details about the central composite design approach.

The steps in the data analysis were as follows:

- The analysis involved both regression modeling and the analysis of variance on the regression weights. The Statistical Analysis System Version 6.12 (SAS, 1996) PROC GLM procedure was used throughout for the regression and Analysis of Variance (ANOVA) modeling. The Type III (simultaneous) Sums of Squares was used for all ANOVA tables and significance testing to accommodate missing data.
- All analyses were carried out on coded variables rather than natural variables. This has the advantage of simplifying the models as well as making the magnitudes of the fitted beta-weights more directly comparable. The relationship between coded variables and nominal levels of the three active steering parameters is provided in Figure 3.1.
- Examination of all possible combinations of X1, X2, X3, $X1^2$, $X2^2$, $X3^2$, X1*X2, X1*X3, and X2*X3 factors (i.e., linear, quadratic, and cross-product terms) were examined using the all-possible regressions approach with adjusted R^2 (an estimate of the proportion of variation in the response variable accounted for by the predictors) as the criterion. This was used to select the ‘best’ subset of models for further consideration. In addition, only “best models” that accounted for at least 5 percent of the variability in a given response measure were considered of interest. If such an independent variable (or set of variables) were identified, regression methods were used to determine if the associated beta weights were statistically significant. Generally, the alpha level of significance was reduced to $\alpha = 0.10$ for consideration of individual beta weights.
- Modeling the ‘best’ subset of models both with and without test participant effects was carried out by using binary (0, 1) indicator variables to represent the test participant

("subject") effects. In general, for n subjects, n-1 indicator variables are needed and each consumes one degree of freedom in the regression model. In human factors research, it is not uncommon to find that individual differences among test participants is the largest single source of variation in a response.

3.3 Results for Rear-End Collision Avoidance System Active Steering Haptic Display Parameter Setting Study

The results will be presented for each of the response measures of interest. See Appendix J and Appendix K for the detailed results of regression modeling efforts for the distraction and non-distraction trials respectively.

3.3.1 Accuracy of Detection (counts of missed detections)

There were no missed detections of any active steering displays in either the distracted or undistracted conditions. This attests to the sensitivity of the hands and the driver's ability to notice vibrations over a wide range of parameter settings.

3.3.2 Accelerator Release time (AccelRT, seconds)

For the distraction condition, the main effects of two active steering display variables, X2 (Amplitude) and X3 (Duration), accounted for approximately 9% of the variability in this response. The inclusion of individual difference effects (i e., test participant effects) along with X2 and X3 main effects increased the proportion of variance accounted for to only 29%. Approximately 71% of the variability in the response remains unaccounted for.

The results for the no distraction condition indicated that variable X2 (Amplitude) alone accounted for approximately 11% of the variability in accelerator release time. Addition of individual differences effects in the model along with X2 increased the proportion of response variability to 39%. Again, little of the variability in the accelerator release time was accounted for by variations in active display parameters.

The means and standard deviations for the accelerator release data are provided in Tables 3.1 and 3.2. The general conclusion suggested by this pattern of results is that all active steering displays were above threshold for discrimination. Under such circumstances, it is common for performance to plateau with respect to further increases in stimulus magnitude. It is only when stimulus magnitude is increased greatly that performance again changes... often declining.

Table 3.1 -- Distraction Data Set: Mean Accelerator Release Times by Active Steering Treatment

	Coded Levels			Mean	
Treatment	X1	X2	X3	ACCELRT	ACCELSD
1	1.0	1.0	1.0	0.41	0.07
2	1.0	-1.0	1.0	0.45	0.07
3	1.0	1.0	-1.0	0.46	0.07
4	1.0	-1.0	-1.0	0.47	0.06
5	-1.0	1.0	1.0	0.41	0.06
6	-1.0	-1.0	1.0	0.47	0.09
7	-1.0	1.0	-1.0	0.47	0.08
8	-1.0	-1.0	-1.0	0.46	0.05
9	1.9	0.0	0.0	0.41	0.09
10	-1.9	0.0	0.0	0.43	0.01
11	0.0	1.9	0.0	0.42	0.05
12	0.0	-1.9	0.0	0.50	0.10
13	0.0	0.0	1.9	0.41	0.08
14	0.0	0.0	-1.9	0.45	0.04
15	0.0	0.0	0.0	0.44	0.13

Table 3.2 -- No Distraction Data Set: Mean Accelerator Release Times by Active Steering Treatment

	Coded Levels			Mean	
Treatment	X1	X2	X3	ACCELRT	ACCELSD
1	1.0	1.0	1.0	0.34	0.09
2	1.0	-1.0	1.0	0.45	0.10
3	1.0	1.0	-1.0	0.38	0.10
4	1.0	-1.0	-1.0	0.44	0.10
5	-1.0	1.0	1.0	0.32	0.04
6	-1.0	-1.0	1.0	0.44	0.12
7	-1.0	1.0	-1.0	0.39	0.09
8	-1.0	-1.0	-1.0	0.43	0.16
9	1.9	0.0	0.0	0.40	0.12
10	-1.9	0.0	0.0	0.39	0.05
11	0.0	1.9	0.0	0.34	0.07
12	0.0	-1.9	0.0	0.43	0.05
13	0.0	0.0	1.9	0.43	0.12
14	0.0	0.0	-1.9	0.37	0.06
15	0.0	0.0	0.0	0.40	0.06

3.3.3 Brake Reaction Time (BrakeRT, seconds)

The means and standard deviations in brake reaction time for each of the treatment combinations are provided in Tables 3.3 and 3.4. For the distraction condition, no statistically significant models were found as a function of the active steering display variables of X1 (Frequency), X2 (Amplitude), or X3 (Duration). Individual differences among test participants accounted for approximately 49% of the variability in maximum pedal force. The remaining 51% of response variation is due to unknown sources of variability or random variation.

Table 3.3 -- Distraction Data Set: Brake Reaction Time Means and Standard Deviations

	Coded Levels			Mean	
Treatment	X1	X2	X3	BRAKERT	BRAKRTSD
1	1.0	1.0	1.0	0.77	0.22
2	1.0	-1.0	1.0	0.79	0.09
3	1.0	1.0	-1.0	0.78	0.15
4	1.0	-1.0	-1.0	0.79	0.10
5	-1.0	1.0	1.0	0.69	0.11
6	-1.0	-1.0	1.0	0.78	0.08
7	-1.0	1.0	-1.0	0.81	0.21
8	-1.0	-1.0	-1.0	0.77	0.12
9	1.9	0.0	0.0	0.73	0.18
10	-1.9	0.0	0.0	0.73	0.12
11	0.0	1.9	0.0	0.73	0.10
12	0.0	-1.9	0.0	0.82	0.19
13	0.0	0.0	1.9	0.73	0.11
14	0.0	0.0	-1.9	0.75	0.12
15	0.0	0.0	0.0	0.76	0.07

Table 3.4 -- No Distraction Data Set: Brake Reaction Time Means and Standard Deviations

	Coded Levels		Mean		
Treatment	X1	X2	X3	BRAKERT	BRAKRTSD
1	1.0	1.0	1.0	0.74	0.31
2	1.0	-1.0	1.0	0.84	0.21
3	1.0	1.0	-1.0	0.69	0.16
4	1.0	-1.0	-1.0	0.83	0.24
5	-1.0	1.0	1.0	0.69	0.20
6	-1.0	-1.0	1.0	0.80	0.13
7	-1.0	1.0	-1.0	0.78	0.31
8	-1.0	-1.0	-1.0	0.81	0.24
9	1.9	0.0	0.0	0.70	0.09
10	-1.9	0.0	0.0	0.76	0.09
11	0.0	1.9	0.0	0.62	0.12
12	0.0	-1.9	0.0	0.84	0.21
13	0.0	0.0	1.9	0.73	0.09
14	0.0	0.0	-1.9	0.74	0.12
15	0.0	0.0	0.0	0.72	0.10

For the no distraction condition, Display variable X2(Amplitude) accounted for only 8% of the variation in observed brake reaction time. Inclusion of test participant effects increased the proportion of brake reaction time variation accounted for to 61%. Thus, most of the known sources of variation reside in individual differences among the test participants. Much brake reaction time variability (39%) remains unaccounted for. The interpretation of this pattern of effects is similar to that offered for the accelerator release time data, i.e., all displays were above threshold and this minimized the effects of active steering display parameter variations.

3.3.4 Total Stopping Distance (TotStop, m)

Tables 3.5 and 3.6 present the means and standard deviations for total stopping distance associated with each of the active steering display treatments for distraction and no distraction conditions, respectively. No statistically significant effects were found as a function of the active steering display variables of Frequency, Amplitude, or Duration for either the distraction or no distraction conditions. Thus, the variations in means provided in the tables do not go beyond those attributable to random variation in the models examined.

On the other hand, the results are quite significant when individual differences are considered. In the distraction condition, individual differences among test participants (i.e., test subject effects) accounted for approximately 81% of the variability in total stopping distance. The remaining variation in total stopping distance appears attributable to unknown sources of variability or random variation. In the no distraction condition, individual differences among test participants accounted for approximately 85% of the variability in total stopping distance. The remaining variation is associated with unknown sources of variability or random variation.

3.3.5 Brake Stopping Distance (Brkstop, m)

Tables 3.7 and 3.8 present the means and standard deviations for brake stopping distance associated with each of the active steering display treatments for distraction and no distraction conditions, respectively. No statistically significant effects were found as a function of the active steering display variables of Frequency, Amplitude, or Duration for either distraction or no distraction conditions.

Table 3.5 -- Distraction Data Set: Total Stopping Distance Means and Standard Deviations

	Coded Levels			Mean	
Treatment	X1	X2	X3	Totstop	TotstopSD
1	1.0	1.0	1.0	84.3	25.0
2	1.0	-1.0	1.0	90.0	20.9
3	1.0	1.0	-1.0	84.7	20.4
4	1.0	-1.0	-1.0	86.5	20.5
5	-1.0	1.0	1.0	82.0	16.6
6	-1.0	-1.0	1.0	82.5	14.5
7	-1.0	1.0	-1.0	80.1	18.0
8	-1.0	-1.0	-1.0	84.8	21.4
9	1.9	0.0	0.0	81.2	16.8
10	-1.9	0.0	0.0	80.5	15.3
11	0.0	1.9	0.0	80.2	16.4
12	0.0	-1.9	0.0	86.8	19.3
13	0.0	0.0	1.9	75.3	21.1
14	0.0	0.0	-1.9	83.8	19.9
15	0.0	0.0	0.0	85.6	21.0

Table 3.6 -- No Distraction Data Set: Total Stopping Distance Means and Standard Deviations

	Coded Levels			Mean	
Treatment	X1	X2	X3	Totstop	TotstopSD
1	1.0	1.0	1.0	67.2	17.5
2	1.0	-1.0	1.0	72.0	14.4
3	1.0	1.0	-1.0	67.7	13.5
4	1.0	-1.0	-1.0	69.6	14.9
5	-1.0	1.0	1.0	67.8	14.7
6	-1.0	-1.0	1.0	63.0	14.1
7	-1.0	1.0	-1.0	69.6	16.0
8	-1.0	-1.0	-1.0	72.2	15.2
9	1.9	0.0	0.0	66.7	15.3
10	-1.9	0.0	0.0	68.9	17.1
11	0.0	1.9	0.0	65.3	16.1
12	0.0	-1.9	0.0	67.7	15.2
13	0.0	0.0	1.9	70.2	16.5
14	0.0	0.0	-1.9	68.8	12.2
15	0.0	0.0	0.0	67.5	12.4

For the distraction condition, individual differences among test participants accounted for approximately 81% of the variability in brake stopping distance. The remaining variation in brake stopping distance appears attributable to unknown sources of variability or random variation. For the no distraction condition, individual differences among test participants accounted for approximately 87% of the variability in brake stopping distance. The remaining variation in is brake stopping distance is associated with unknown sources of variability or random variation.

Table 3.7 -- Distraction Data Set: Brake Stopping Distance Means and Standard Deviations

	Coded Levels			Mean	
Treatment	X1	X2	X3	Brkstop	BrkstopSD
1	1.0	1.0	1.0	71.9	22.7
2	1.0	-1.0	1.0	76.3	18.4
3	1.0	1.0	-1.0	69.6	19.9
4	1.0	-1.0	-1.0	72.6	18.8
5	-1.0	1.0	1.0	69.7	13.9
6	-1.0	-1.0	1.0	68.9	13.0
7	-1.0	1.0	-1.0	64.7	14.7
8	-1.0	-1.0	-1.0	70.4	19.4
9	1.9	0.0	0.0	68.3	13.7
10	-1.9	0.0	0.0	67.5	12.8
11	0.0	1.9	0.0	68.2	15.6
12	0.0	-1.9	0.0	71.7	18.0
13	0.0	0.0	1.9	63.3	17.9
14	0.0	0.0	-1.9	70.5	18.8
15	0.0	0.0	0.0	72.5	20.1

Table 3.8 -- No Distraction Data Set: Brake Stopping Distance Means and Standard Deviations

	Coded Levels			Mean	
Treatment	X1	X2	X3	Brkstop	BrkstopSD
1	1.0	1.0	1.0	67.2	17.5
2	1.0	-1.0	1.0	72.0	14.4
3	1.0	1.0	-1.0	67.7	13.5
4	1.0	-1.0	-1.0	69.6	14.9
5	-1.0	1.0	1.0	67.8	14.7
6	-1.0	-1.0	1.0	63.0	14.1
7	-1.0	1.0	-1.0	69.6	16.0
8	-1.0	-1.0	-1.0	72.2	15.2
9	1.9	0.0	0.0	66.7	15.3
10	-1.9	0.0	0.0	68.9	17.1
11	0.0	1.9	0.0	65.3	16.1
12	0.0	-1.9	0.0	67.7	15.2
13	0.0	0.0	1.9	70.2	16.5
14	0.0	0.0	-1.9	68.8	12.2
15	0.0	0.0	0.0	67.5	12.4

3.3.6 Maximum Pedal Force Applied During Braking (Maxpedf, ft-lb)

Tables 3.9 and 3.10 present the means and standard deviations for maximum pedal force associated with each of the active steering display treatments for distraction and no distraction conditions, respectively. In the distraction condition, no statistically significant models were found as a function of the active steering display variables of Frequency, Amplitude, or Duration. Individual differences among test participants accounted for approximately 68% of the variability in maximum pedal force. The remaining 32% of response variation is due to unknown sources of variability or random variation.

Table 3.9 -- Distraction Data Set: Maximum Pedal Force Means and Standard Deviations

	Coded Levels			Mean	
Treatment	X1	X2	X3	MaxPedf	MaxPedfSD
1	1.0	1.0	1.0	112	49
2	1.0	-1.0	1.0	125	37
3	1.0	1.0	-1.0	131	37
4	1.0	-1.0	-1.0	126	23
5	-1.0	1.0	1.0	122	45
6	-1.0	-1.0	1.0	119	23
7	-1.0	1.0	-1.0	137	31
8	-1.0	-1.0	-1.0	130	46
9	1.9	0.0	0.0	118	21
10	-1.9	0.0	0.0	120	38
11	0.0	1.9	0.0	123	39
12	0.0	-1.9	0.0	122	36
13	0.0	0.0	1.9	130	38
14	0.0	0.0	-1.9	125	50
15	0.0	0.0	0.0	139	45

In the no distraction condition, active steering amplitude (X2) accounted for approximately 8% of the variability in maximum pedal force. Inclusion of test participant effects along with active steering display amplitude (X2) accounted for approximately 61% of the variability in response. It appears from this data that only a small amount of response variability can be attributed to active steering display parameter levels.

Table 3.10 -- No Distraction Data Set: Maximum Pedal Force Means and Standard Deviations

	Coded Levels			Mean	
Treatment	X1	X2	X3	MaxPedf	MaxPedfSD
1	1.0	1.0	1.0	129	44
2	1.0	-1.0	1.0	115	32
3	1.0	1.0	-1.0	126	31
4	1.0	-1.0	-1.0	121	43
5	-1.0	1.0	1.0	121	33
6	-1.0	-1.0	1.0	126	49
7	-1.0	1.0	-1.0	127	30
8	-1.0	-1.0	-1.0	113	25
9	1.9	0.0	0.0	124	50
10	-1.9	0.0	0.0	121	54
11	0.0	1.9	0.0	120	51
12	0.0	-1.9	0.0	131	43
13	0.0	0.0	1.9	118	53
14	0.0	0.0	-1.9	122	21
15	0.0	0.0	0.0	116	32

3.3.7 Subjective Ratings

After each active steering display had resulted in the driver bringing the vehicle to a control stop, each test participant was asked to rate the haptic display in terms of three dimensions:

- Vibration (too slow, about right, too fast)
- Strength (too weak, about right, too strong)
- Duration (too short, about right, too long)

The data were examined to determine what haptic steering display combinations had been judged "about right" on all three dimensions by half of the test participants or more. The following treatment combinations were rated "about right" on all three dimensions simultaneously for the following parameter combinations by half or more of the test participants in distracted and non-distracted conditions, respectively (Treatment numbers are from Table 1):

- Treatment 1 (X1= +1; X2= +1, X3= +1), 4 of 6 test participants, Distracted;
- Treatment 3 (X1= +1; X2= +1, X3= -1), 3 of 6 test participants, Distracted;
- Treatment 13 (X1= 0; X2= 0, X3= +1.9), 3 of 6 test participants, Distracted;
- Treatment 14 (X1= 0; X2= 0, X3= -1.9), 3 of 6 test participants, Distracted;

- Treatment 3 (X1= +1; X2= +1, X3= -1), 5 of 6 test participants, Non-Distracted;
- Treatment 5 (X1= +1; X2 = -1; X3= -1), 3 of 6 test participants, Non-Distracted;
- Treatment 13 (X1= 0; X2= 0, X3= +1.9), 4 of 6 test participants, Non-Distracted;

If one seeks to identify the combinations of frequency, amplitude, and duration that are judged most favorably on all dimensions in both non-distracted and distracted conditions, Treatments 3 and 13 appear most promising. That is, test participants appear to favor an active steering display vibration frequency of 8 to 10 Hz, and an amplitude of 1.6 to 1.8 Nm. The range of preferred display durations is relatively large, from 0.74 seconds to 1.5 seconds.

3.4 Conclusions of Rear-End Collision Avoidance System Active Steering Haptic Display Parameter Setting Study

The results of this parameter setting study indicated that, over the ranges of vibration frequency, torque amplitude, and duration used, all of the displays were essentially equivalent in terms of driver response. This is perhaps best explained by the great sensitivity the hands possess. All active steering displays tested were above the sensory threshold. As a consequence, variations in the display parameters had no substantial effects on any of the measured response variables. No parameter main effect or combinations of main effects accounted for more than approximately 11% of the variability in a response. Most of the variability was attributable to test participant effects or unidentified sources of variation.

An unexpected result was found in the mono-pulse braking study conducted to set the parameters for that display. The pulse braking parameter setting study protocol was virtually identical to the present study. As in this study, test participants were given a neutrally worded instruction: "...as soon as you notice a pulse braking event, bring the vehicle to a controlled stop...". The surprising result was that test participants braked harder in response to stronger pulse braking displays. By contrast, this effect is noticeably absent in the present study. There were no statistically reliable indications that drivers varied their braking maneuver as a function of the active steering display settings. The discrepant findings might arise because active steering displays are not intrinsically associated with a braking response but pulse braking displays are. Because variations in the active steering display are associated with lateral motion, not longitudinal decelerations, it is not surprising that they would be considered somewhat independent of the braking maneuver.

By way of recommendations, the authors suggest that active steering displays not be considered further as a warning for rear-end collision avoidance. It is likely that, given appropriate instruction and practice, drivers would respond appropriately to an active steering display in a rear-end conflict situation. However, there is a need for collision avoidance system display configuration management. In the future, integrated driver collision avoidance support might present several displays to alert or warn a driver of several kinds of crash hazards. In such a context, it seems prudent to consider the scope of integrated collision avoidance in the following terms:

- alerts and warnings to hazards in the forward longitudinal axis (e.g., rear-end crash hazard; road departure at a curve due to excessive speed; signalized and unsignalized straight crossing paths intersection crash hazards; at-grade railroad crossing crash hazard),
- alerts and warnings to hazards in the lateral axis (e.g., lane change crash hazard; single-vehicle road departure on straightaways; left-turn-across-path intersection hazard; opposite direction crash hazards during overtaking maneuvers on undivided roadways); and
- alerts and warnings to hazards in the rearward longitudinal axis (e.g., backing collision avoidance).

It appears sensible to reserve active steering displays for those situations that most likely require steering maneuvers for achieving a desirable outcome, i.e., for hazards in the lateral axis. Pulse braking and related haptic displays (e.g., active accelerator pedal) might be most appropriate for hazards that most likely require acceleration or deceleration for their successful resolution, i.e., the longitudinal axis. As our understanding of collision avoidance grows, perhaps appropriately designed and allocated haptic displays will provide benefit for assisting the driver in completing combined steering and braking collision avoidance maneuvers. By applying early configuration management of haptic display allocations now, the groundwork for maximizing effectiveness in the future is laid. This philosophy may be extended for auditory, visual, and multi-modality driver displays as well.

4.0 A Test Track Evaluation of Rear-End Collision Avoidance System Mono-Pulse Braking Haptic Displays In Car Following

4.1 Introduction

The purpose of the third study was to use rear-end CAS scenarios to evaluate the preferred concepts identified in the first two studies, i.e., the "ideal" parameter values for the two types of haptic displays. Based on the results of the pulse braking study, it was recommended that a 0.32 g/s jerk rate applied for 0.65 seconds be used as the mono-pulse braking display concept for further evaluation. Active steering displays are not intrinsically associated with a braking response but pulse braking displays are. The active steering display appears to be more naturally associated with lateral motion, not longitudinal decelerations. Therefore, active steering displays were not examined as a potential warning for rear-end collision avoidance in this third study. Thus, this section presents the results of a small-scale study to examine the effects of short duration, single pulse (mono-pulse) braking as a haptic warning suitable for applications to rear-end collision avoidance systems and limit performance of Adaptive Cruise Control (ACC) with braking authority.

An unexpected finding arose from previous testing with mono-pulse braking displays as described in Section 2 of this report. In that study, test participants drove an instrumented car without any lead vehicle present. The test participants were instructed to brake to a controlled stop whenever a pulse braking display was noticed by the test participant. Results indicated that the magnitude of the pulse braking display had a consistent impact on the magnitude of the driver's braking response. In general, the higher the jerk rate and the longer the pulse braking event duration, the harder the driver braked to bring the vehicle to a controlled stop. This occurred despite care taken to be neutral about the nature of the braking maneuver in the test participant instructions. This finding suggests both opportunities and problems for the mono-pulse braking display concept for rear-end collision warning.

The opportunity uncovered by this result is that it may be possible to prompt more appropriate braking responses from the driver depending on the severity of the conflict between the subject vehicle and the principal other vehicle. That is, if the sensed conditions are such that a more aggressive braking maneuver is required, a stronger mono-pulse braking display may promote this. There is evidence that drivers in crash-imminent situations do not fully utilize the braking capability of the vehicle. This is the motivation behind, for example, some newly developed “smart” brake systems which sense “panic braking” by means of brake pedal throw and automatically provide a higher pedal force gain in such circumstances. If the trends noted in Section 2 are any indication, variable-magnitude mono-pulse braking displays may alleviate the problem of insufficient braking to at least some extent. Furthermore, the mono-pulse braking display does itself slow the vehicle somewhat during the driver’s reaction time interval and so may contribute to the success of the evasive braking maneuver.

The problem posed by the pattern of results is what may happen when a false positive indication arises. There exists the possibility that a driver startled by the mono-pulse braking display may instinctively brake hard. If so, this behavior might precipitate a chained rear-end collision with the host vehicle being struck from behind by another vehicle. (Note that such a problem might also arise in the event of a true rear-end crash hazardous situation). A false positive when the driver is attempting to clear an intersection may put the host vehicle in the path of another vehicle. A false positive indication while negotiating the tracks at an at-grade railroad crossing may cause the driver to brake suddenly while straddling the tracks.

Given the potential safety impacts of this finding (both safety-positive and safety-negative), as well as the fact that active steering would not be examined in the third study, it was deemed feasible and worthwhile to expand the third study to examine multiple parameter settings of the pulse braking display, rather than just one value pair. This would provide the opportunity to assess whether the previous study results, as describe in Section 2.0 of this report, which related magnitude of braking maneuver to magnitude of mono-pulse braking display were an artifact of the test situation. In particular, it was thought that the presence of a lead vehicle would eliminate this effect. Drivers in car following appear to react to lead vehicle deceleration based on above-threshold optical looming stimuli (Mortimer, 1990). Thus, in “true positive” cases (i.e., cases where the lead vehicle is braking and the pulse brake display comes on), magnitude of optical looming rather than the magnitude of a pulse braking display should determine the braking behavior of the driver. By extension, it was hypothesized that in “false positive” cases (i.e., cases where the lead vehicle is present but not braking and the pulse brake display comes on), drivers would not make inappropriate braking maneuvers once they appreciated the fact that the lead vehicle was not slowing down.

4.2 Method

4.2.1 Test Participants

Seven (7) individuals served as volunteer test participants: three females (ages: 21, 41, and 61 years) and four males (ages 20, 22, 42, and 65 years). All individuals were in the employ of the TRC No special compensation was provided for participation. Test participants were unaware of the nature of the research prior to participation and had not participated in previous pulse braking studies.

4.2.2 Apparatus

A 1995 4-door Chevrolet Lumina, with automatic transmission was used as the test vehicle. The vehicle was equipped with MicroDAS instrumentation (Barickman, 1998) to capture speed, longitudinal acceleration, accelerator pedal position, and brake pedal force. In addition, a ControlLaser 2000™ headway sensor was implemented to capture range and range rate information during car following. A Kalman filter was developed for this sensor to improve range estimates and these were subsequently differentiated to arrive at range rate values. All range and range rate data reported herein, along with measures derived from them, are based on the Kalman-filtered data.

The Visteon Magellan™ route guidance system was installed and mounted on a gooseneck pedestal within easy reach of the driver. This device was used for the driver to enter address destinations during a portion of the data collection session. Prior research (Tijerina, Parmer, and Goodman, 1998) had indicated that destination entry while driving imposed a considerable distraction to the driver.

Pulse braking was produced in the following manner. The Lumina had installed in it a torque motor (PMI Motion Technologies Model No. U9D-E) attached by means of a wire cable and pulley to the arm of the brake pedal. Upon application of a command signal provided by means of a GRID laptop computer, the torque motor provided a force on the brake pedal that effected the nominal jerk rate and duration required for a given trial.

The equipment that effected the pulse braking events produced some audible noise that might confound the results of the study. To alleviate this problem, each test participant during the actual driving phase of the study wore headphones (Optimus Model PRO-135) over which a compact disc (CD) of ocean surf sounds was played by means of a CD player (Sony Model D-E30ZCK). Each test participant had an opportunity to select the volume level that was comfortable but the levels chosen were always sufficient to mask any actuator sounds from the pulse braking equipment.

All trials were conducted on the TRC skid pad. During these trials, the subject vehicle (SV) followed behind a towed surrogate lead vehicle (LV). The surrogate LV was a fiberglass mockup of the rear end of a 1997 Taurus. The surrogate LV was towed behind a 1996 4-door Honda Accord, equipped with conventional cruise control, by means of a 40 foot long collapsible beam. The beam was designed to collapse up to 9 feet in the event of a collision. The towed surrogate vehicle was designed to sustain impacts up to 10 mph without damage, and more importantly, without injuring the test participant or researchers. The surrogate LV and the towing vehicle both drove with brake lights disabled. This decision was based on prepilot testing that indicated brake lights served as a second, potentially confounding driver warning and, therefore, should not be used during this testing.

An adaptive cruise control system was implemented on a GRID laptop computer to help ensure that similar initial conditions of car following were achieved from trial to trial. The Kalman-filtered ControlLaser 2000™ headway measurements were used as the inputs to the adaptive cruise control system. Additional throttle control was available to the experimenter via laptop computer control to provide for additional management of car following. The adaptive cruise control system was set for a speed of approximately 45 mph and a car following time headway of 2.0 seconds, nominal. Time headway variations were generally in the range of 1.9 to 2.1 seconds of time headway.

In order to evaluate the mono-pulse braking display as a warning, a warning algorithm was needed. Pilot testing had revealed that drivers generally braked earlier than a late-onset warning such as that produced by the NHTSA warning algorithm proposed by Burgett, et al. (1998) and modified by

Pham (1999). Logically, if one wished to assess the impact of a mono-pulse braking display on driver behavior, the display would have to be presented prior to the onset of the driver's response. Attempts to adjust the NHTSA algorithm for earlier onset proved unsuccessful for reasons not entirely clear. Therefore a simple rule for warning onset was implemented. Specifically, all lead vehicle braking events were staged to occur with a nominal 0.35 g braking, This braking event was performed by a TRC driver monitoring a calibrated brake pedal force meter installed in the towing vehicle. Once a braking event began, the haptic brake warning was initiated when the time-to-collision (TTC) value was 25 seconds or less. Pilot testing had indicated that this onset rule would occur prior to SV braking in most instances. An even earlier onset proved infeasible because such TTC values were within the range of dither produced by speed variations in the cruise control systems used in the testing.

4.2.3 Procedure

The test participant read the informed consent form (see Appendix L) which outlined the general purpose of the study. The test participant was given an opportunity to ask questions of the experimenter. The test participant was escorted to the test vehicle and oriented to it. The experimenter then provided the test participant with instruction on the manner in which to enter street address destinations into the route guidance system. This in-vehicle task had previously been shown to impose significant distraction to the driver (Tijerina, Parmer, and Goodman, 1998). The test vehicle was then driven to the TRC skid pad for testing.

Upon reaching the skid pad the test participant was read the instructions provided in Appendix M. These instructions were carefully worded to emphasize a quick response while leaving undefined the magnitude of the braking response. The test participant was instructed to car follow the surrogate lead vehicle. The test participant was informed that the adaptive cruise control system would maintain an initial separation but that in the event the lead vehicle braked to a stop, the test participant was responsible for bringing the host vehicle to a safe stop. The emphasis in the skid pad instructions was to avoid collision with the surrogate lead vehicle.

The test participant then drove approximately 45 mph (72 kph) through one circuit of the skid pad for familiarization. A total of eight (8) practice braking events were presented without the pulse brake warnings or the destination entry task. The purpose of these practice braking events were to familiarize the test participant with the braking capabilities of the test vehicle and the braking events themselves (e.g., that the lead vehicle did not have brake lights). This was followed by a series of 24 trials nominal, where a single trial constituted travel in one direction on the skid pad. These included 9 true positive (TP) trials (i.e., trials in which the surrogate lead vehicle braked, pulse braking display came on), 9 false positive (FP) trials (i.e, trials in which the surrogate lead vehicle did not brake, but pulse braking display came on), and 6 true negative (TN) trials (i.e., trials in which the surrogate lead vehicle did not brake, pulse braking display did not come on). No false negative (FN) trials were deliberately run (i.e., trials in which the surrogate lead vehicle brakes but pulse braking display does not come on). However, instances where the pulse braking event was not noticed or was anticipated by the driver constitute *de facto* false negative events.

After the pulse braking display was presented (in true positive and false positive trials), the test participant was asked to indicate whether or not he or she noticed the display and, if so, rate the appropriateness of the pulse braking display as a rear-end collision avoidance system warning by means of a 7-point rating scale described later.

The ordering of trials for the test participant was quasi-randomized for each. However, the first four trials included two true negative trials and two true positive trials. For the two true positive trials, pulse braking displays were presented that had proven reliably noticeable in previous research described in Section 2.0 of this report. This procedure was an attempt to create the impression that the collision warning system ‘worked’, i.e., warned when the lead vehicle braked. After these first four trials, the order of remaining trials was randomized across the ensemble of test participants with the caveat that the last trial was never a catch trial and catch trials were not run back-to-back. Equipment malfunctions, experimenter error, or inopportune driving conditions on the skid pad occasionally introduced additional unplanned repeated trials.

4.2.4 Independent variables

The two pulse braking display parameters manipulated for this study were jerk rate (J) and duration (D). The nominal levels used are provided in Table 4.1. As can be seen from Figure 4.1 and Table 4.1, three levels each of jerk rate and duration were factorially combined.

Table 4.1 -- Coding Scheme for 2-Factor Pulse Braking Central Composite Design

Treatment	Coded		Uncoded	
Comb.	X1	X2	J (g/s)	D (s)
1	-1	-1	0.08	0.25
2	-1	+1	0.08	1.00
3	+1	-1	0.32	0.25
4	+1	+1	0.32	1.00
5	0	0	0.20	0.65
6	+1	0	0.32	0.65
7	-1	0	0.08	0.65
8	0	+1	0.20	1.00
9	0	-1	0.20	0.25

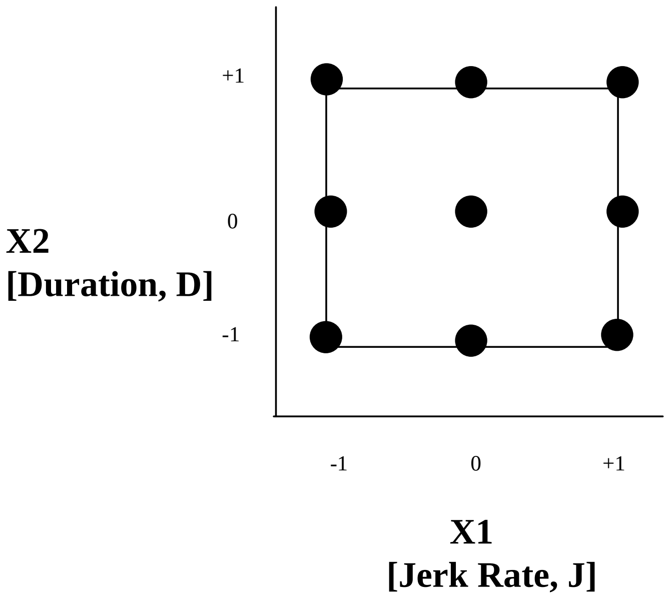


Figure 4.1 -- Pulse Braking Study Central Composite Design, Alpha = 1

4.2.5 Dependent (Response) Variables

The following response variables were used:

- Display Noticed or Not Noticed (count): This was the number of test participants who how reported having noticed the display in a given condition. This measure was intended to provided some indication of how conspicuous a given mono-pulse brake display was in TP and FP trials.
- Brake Reaction Time to the Warning (BRTWARN): This was operationally defined as the time interval between the start of the mono-pulse braking event or warning and the moment when the driver's foot pushed on the brake pedal. Haptic brake display parameters might differentially affect how quickly the driver responded. This response measure was analyzed for both TP and FP trials.
- Maximum Brake Pedal Force (MAXPEDF, ft-lbs): The instantaneous peak force applied by the driver to the brake pedal during a braking maneuver, as measured from load cells attached to the brake treadle. This provides some indication of the effort

exerted by the test participant in braking. This measure was analyzed for both TP and FP trials.

- Minimum Time-To-Contact (TTC_min): This was defined as the minimum value of instantaneous range to the decelerating lead vehicle divided by instantaneous range rate that occurred during the braking maneuver. Thus, this response measure was only analyzed for TP trials. It provides some indication of the greatest magnitude of traffic conflict that arose before being quelled by driver action.
- Speed Difference from Driver-Induced Brake Onset to Release of Brake (SPEEDIFF, kph): This is the difference in host vehicle travel speed achieved during unnecessary braking events in FP trials. It provides some indication of the magnitude of the inappropriate braking event.
- Brake Duration (BRKDUR, sec): The duration of inappropriate braking during false positive FP trials. This measure also provides some indication of the magnitude (in time) of the inappropriate braking event.
- Maximum Deceleration (DECLMAX, g): The peak deceleration applied during a braking maneuver. This measure was analyzed for both TP and FP trials.
- Number of Inappropriate Braking Responses (count): This measure, taken during FP trials, provides some estimate of the propensity of drivers to brake even when the lead vehicle is not braking.
- Acceptability as a Warning Display for Rear-end Collision Avoidance (Ratings): This was taken as a first step toward assessing the acceptability of a pulse braking display for its intended purpose. For TP trials, this assessment was provided after the test participant had brought the subject or host vehicle to a stop. For FP trials, the ride-along experimenter asked toward the end of the straightaway if the test participant had noticed a pulse braking event. Provided the test participant responded affirmatively, the acceptability question was also asked.

4.2.6 Data Analysis Approach

The levels of jerk rate and duration included in the study were established through prior testing described in Section 2.0. The goal was to arrive at jerk rates and durations the combinations of which would span the range of detectability and acceptability. Specifically, pilot testing uncovered a lower value of jerk rate and duration which would sometimes lead to missed detections and acceptability ratings of “much too soft” and upper values of jerk rate and duration that would always lead to detection but would sometimes be judged as “much too strong.” Furthermore, the combinations of jerk rate and duration were selected such that the maximum deceleration achieved by the mono-pulse braking system would be within the range of braking authorities envisioned for adaptive cruise control systems (i.e., approximately 0.3g).

The choice of three levels each of jerk rate and duration was made to allow for up to a quadratic response surface to be fitted to the numeric response variables. The combinations of levels of the two variables represent a face-centered central composite design suitable for fitting up to a quadratic polynomial by means of linear regression techniques and the analysis of variance. Williges (1981) provides more details about the central composite design approach.

The steps in the data analysis were as follows:

- The statistical procedure applied to each of the response measures was an unweighted cell means analysis of variance (ANOVA) (Searle, 1987). Within this framework, an additive repeated-measurements model was assumed for simplicity.
- The analyses were carried out on appropriate data from the true positive (TP) and false positive (FP) trials. Appropriate data were operationally defined as data from TP or FP trials in which the test participant reported noticing the mono-pulse braking event. The analyses were also carried out on TP trials in which the driver braked after the onset of the pulse braking display, regardless of subjective report of noticeability.
- The Statistical Analysis System Version 6.12 (SAS, 1996) PROC GLM procedure was used throughout for the regression and ANOVA modeling. The Type III (simultaneous) Sums of Squares was used for all F-tests as appropriate for the unweighted cell means model applied to unbalanced data (i.e., unequal numbers of observations in each cell of the experimental design matrix).
- All analyses were carried out on coded variables rather than natural variables. This has the advantage of simplifying the models as well as making the magnitudes of the fitted beta-

weights more directly comparable. The linear transformation used for the coded variables was:

$$\text{X[Coded Value]} = \frac{\text{original value} - \left[\dfrac{\text{range minimum + maximum}}{2}\right]}{\{[\text{range maximum - minimum}]\ /2\ \}}$$

- The alpha level of significance was set to $\alpha = 0.10$ for all statistical tests.

4.3 Results of Test Track Evaluation of Rear-End Collision Avoidance System Mono-Pulse Braking Haptic Displays In Car Following

Results are presented here for each of the response measures of interest. After general results on reported detections are presented, the remaining results are presented for True Positive trials and False Positive trials separately.

4.3.1 Noticeability of Mono-pulse Braking Displays

Figure 4.2 presents 3-D bar charts indicating the number of test participants out of seven who reported noticing a specific pulse braking event. Data are presented separately for TP and FP trials. It can be seen that the number of reported detections generally increases with increasing jerk rate and duration. For FP trials, the number of reported detections is 7 of 7 for the four combinations of middle and high jerk rate and the middle and high duration. However, the reported number of detections is never higher than 5 out of 7 for similar display conditions in the TP trials. The reasons for this are unclear. In some cases, the test participant was more sensitive to the lead vehicle braking than the warning onset rule and braked in anticipation of the display onset. The display system was structured to display even if the test participant was already braking at warning onset. Thus, unless the test participant was braking beyond the magnitude programmed for the display, it is possible that he or she might still have noticed the display even though the test participant "anticipated" it somewhat in time. Examination of the number of anticipated braking responses in TP trials unfortunately revealed no systematic relationship between number of detections and number of anticipations.

4.3.2 Results: True Positive Trials

In the case of True Positive (TP) trials, data were analyzed in two different ways. First, all data were analyzed wherein the driver reported noticing the display, whether or not the braking response was in anticipation of the mono-pulse braking display onset. For trials in which the test participant anticipated the pulse braking display, a negative reaction time relative to the pulse braking display onset was used in the analysis. As explained earlier, even if the display was presented after the driver had started to brake, it might nevertheless have had an effect on the driver's behavior. This was the rationale for analyzing this data set. Second, an analysis was carried out only on those data from trials with reaction times sometime after haptic display onset, i.e., where all clearly anticipatory responses were removed. This data set was defined irrespective of whether or not the driver reported noticing the haptic display. Logic behind this analysis was that the driver responded sometime after haptic display onset and may have been affected by it, even if the test participant did not report it. The results of each analysis is described below.

4.3.2.1 Brake Reaction Time to the Warning (BRTWARN, sec)

For the TP trials the ANOVA carried out on trials wherein the test participant reported noticing the display revealed no statistically significant differences in brake reaction time as a function of coded levels of jerk rate, duration, or their interaction. An ANOVA of only trials in which subjects exhibited a braking response after the haptic display was presented also revealed non-significant results.

4.3.2.2 Maximum Brake Pedal Force (MAXPEDF, ft-lbs)

For the TP trials wherein the test participant reported noticing the display, the ANOVA revealed no statistically significant differences in maximum brake pedal force as a function of coded levels of jerk rate, duration, or their interaction. An ANOVA of only trials in which subjects exhibited a braking response after the haptic display was presented also revealed non-significant results for maximum brake pedal force.

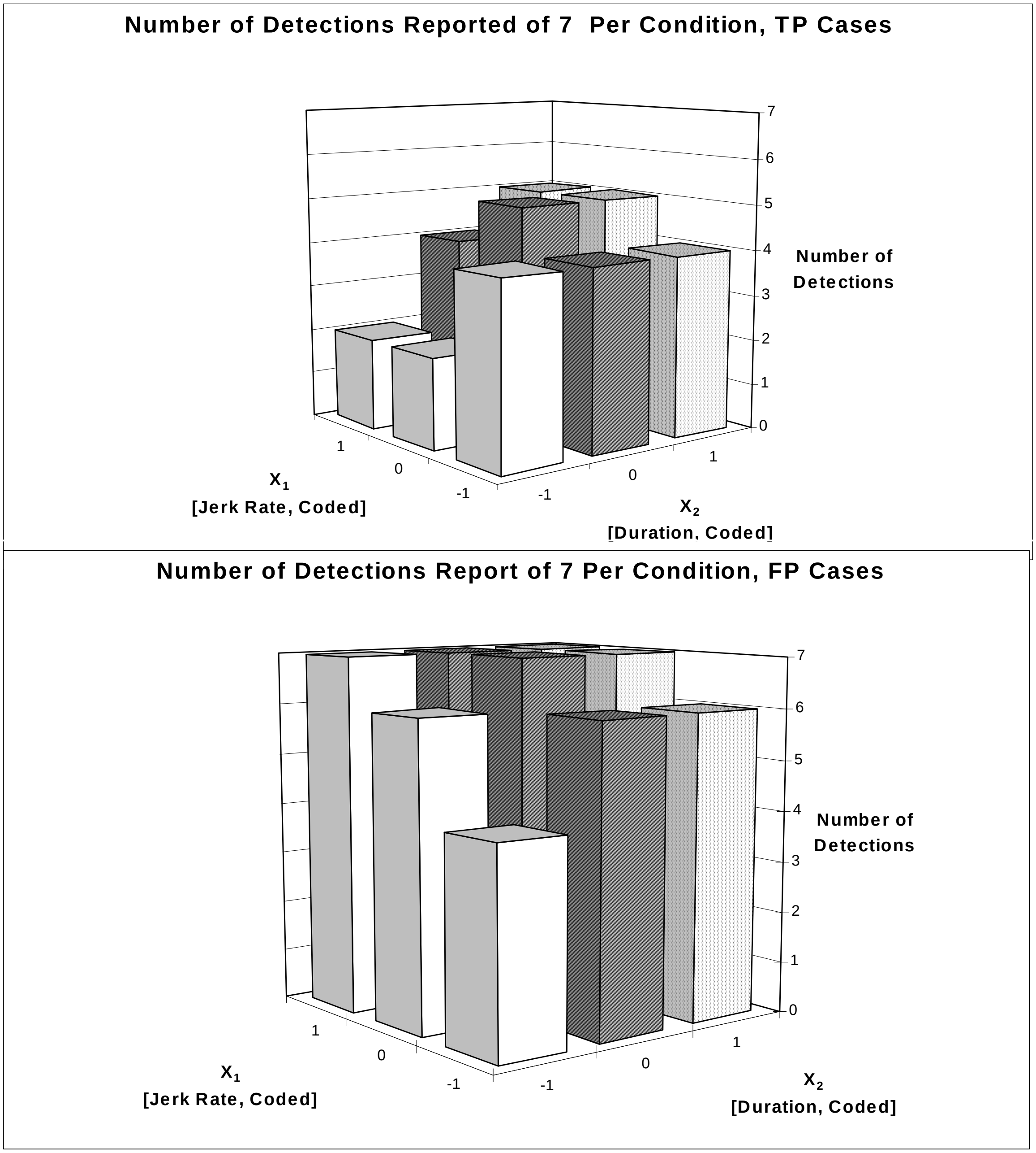


Figure 4.2 -- Number of Reported Detections per mono-pulse braking display condition, True Positive (TP) and False Positive (FP) Cases. Note: Condition (X1, X2) = (-1,+1) and condition (X1, X2) = (+1, -1) represent the number of detections out of six (6) cases. All other conditions represent the number of detections out of seven (7) cases.

4.3.2.3 Minimum Time-To-Contact (TTCMIN)

For the TP trials wherein the test participant reported noticing the display, the ANOVA revealed no statistically significant differences in TTCMIN as a function of coded levels of jerk rate, duration, or their interaction. An ANOVA of only trials in which subjects exhibited a braking response after the haptic display was presented also revealed non-significant results for TTCMIN.

4.3.2.4 Maximum Deceleration (DECLMAX, g;)

For the TP trials wherein the test participant reported noticing the display, the ANOVA revealed no statistically significant differences in peak or maximum deceleration applied as a function of coded levels of jerk rate, duration, or their interaction. An ANOVA of only trials in which subjects exhibited a braking response after the haptic display was presented also revealed non-significant results for maximum deceleration applied.

The summary statistics for each of the response variables analyzed for TP trials are provided in Table 4.2. Only grand means are provided, as is appropriate in the absence of statistically significant effects for the independent variables of jerk rate, duration, or their interaction. Both kinds of data sets analyzed are included in the table. In addition, the table contains one additional measure that was not analyzed. BRTEVENT is the Brake Reaction Time as measured from the onset of lead vehicle braking. The start of lead vehicle braking was determined by a procedure of "verbal telemetry." In this procedure, prior to a TP braking event the driver towing the surrogate lead vehicle counted down "5...4...3...2..1...Brake" and the ride-along experimenter in the subject vehicle, listening over headphones, press an event marker upon hearing the word "...Brake." Thus, BRTEVENT is the elapsed time from when the ride-along experimenter pressed the event marker to when the test participant applied the brake pedal. As can be seen, the average time delay across all test participants and all conditions was approximately 2.0 seconds. If trials with anticipatory braking responses are removed, the mean BRTEVENT time increases slightly to approximately 2.3 seconds.

4.3.3 Results: False Positive Trials

Consider next the results for FP trials. Recall that in a false positive (FP) trial, the pulse brake warning at some point came on even though the surrogate lead vehicle was not slowing down. Despite this, for 7 test participants, each completing one FP trial for each of the 9 mono-pulse braking displays, 20 of the 63 trials involved an unnecessary or inappropriate braking response from the drivers. The inappropriate responses tended to be somewhat idiosyncratic. For example, one of the 7 test participants generated 40 percent of the inappropriate braking responses.

Table 4.3 shows the distribution of these inappropriate braking occurrences as a function of mono-pulse braking display condition. Note that several cells contain only a single observation. Searle (1987) points out that when there is not more than one observation in some cells, a no-interaction cell means model has to be used to allow for useful tests of the main effects. Thus, in this section, only main effects of jerk rate and duration are tested and discussed.

Table 4.2 -- Summary Statistics for True Positive (TP) Trials (see text for explanation)

```
Summary Statistics for TP Trials: Trials Wherein Test Participant Reported
  Noticing Mono-pulse Braking Display, Regardless of Response Onset Time

       Variable   N          Mean       Std Dev       Minimum       Maximum

       -------------------------------------------------------------------
       BRTEVENT  35     1.9922857     0.4682514     1.1200000     3.2600000
       BRTWARN   35     0.0405714     0.4483627    -0.5900000     0.8200000
       MAXPEDF   35   136.4240000    44.0973156    52.9300000   225.2200000
       DECLMAX   35    -0.5694286     0.0980679    -0.7900000    -0.4200000
       TTCMIN    35     0.6191429     0.3199758     0.1100000     1.2400000
```

```
Summary Statistics for TP Trials: Anticipations removed, Regardless of Whether
      or Not Test Participant Reported Noticing Mono-pulse Braking Display

       Variable   N          Mean       Std Dev       Minimum       Maximum
       -------------------------------------------------------------------
       BRTEVENT  29     2.2989655     0.3687173     1.5200000     3.2600000
       BRTWARN   29     0.3603448     0.2462937     0.0400000     0.8200000
       MAXPEDF   29   147.4617241    36.2112228    83.5300000   225.2200000
       DECLMAX   29    -0.6013793     0.0880635    -0.7900000    -0.4700000
       TTCMIN    29     0.7800000     0.3043846     0.2000000     1.4600000
         -------------------------------------------------------------------
```

Table 4.3 -- Number of Inappropriate Braking Responses Out of 7 Per cell to False Positive (FP) Mono-pulse Brake Warnings

	Duration, X2				
Jerk Rate, X1	**Codes**	-1	0	+1	Row ∑
	-1	1	1	2	4
	0	1	3	5	9
	+1	2	2	3	7
	Column ∑	4	6	10	20

4.3.3.1 Brake Reaction Time to the Warning (BRTWARN, sec)

The ANOVA revealed no significant effects of either jerk rate or duration of mono-pulse brake warnings on brake reaction time to that warning.

4.3.3.2 Maximum Brake Pedal Force (MAXPEDF, ft-lbs)

F-tests on this variable revealed no statistically significant effects as a function of either jerk rate or duration of mono-pulse brake warnings.

4.3.3.3 Speed Difference from Driver-Induced Brake Onset to Release of Brake (SPEEDIFF, kph)

Recall that this is the difference in host vehicle travel speed achieved during unnecessary braking events in false positive (FP) trials. ANOVA revealed a statistically significant effect for the main effect of jerk rate ($F(2, 19) = 12.26$, $p < 0.092$, $MS_e = 4.09$). The average magnitude (with standard deviation in parentheses) of slowing was 0.78 kph (sd = 1.04 kph), 0.98 kph (sd = 1.14 kph), and 3.17 kph (sd = 3.94 kph) for the 0.08 g/s, 0.20 g/s, and 0.32 g/s jerk rates, respectively. Note that these speed differences are considered minor given a nominal 45 mph (72 kph) travel speed. The largest average speed difference amounts to only approximately 2 mph of slowing.

Maximum Deceleration Applied (DECLMAX, g): The instantaneous peak deceleration applied varied reliably as a function of mono-pulse brake display jerk rate ($F(2, 19) = 4.03$, $p < 0.049$, MS_e

= 0.008). The average magnitude (with standard deviation in parentheses) of peak deceleration was -0.04 g (sd = 0.008 g), -0.1 g (sd = 0.073g), and -0.19 g (sd = 0.097 g) for the 0.08 g/s, 0.20 g/s, and 0.32 g/s jerk rates, respectively. While these values may be alarming to some, it is important to remember that they represent instantaneous peak decelerations. The speed difference obtained above is perhaps a more appropriate measure on the actual effects of inappropriate braking under the skid pad test conditions.

4.3.3.4 Brake Duration (BRKDUR, sec)

No statistically reliable differences were found in the duration of inappropriate braking as a function of jerk rate or duration of mono-pulse braking display.

Table 4.4 presents the summary statistics for the 20 FP trials in which a test participant exhibited an inappropriate or unnecessary braking response. Only grand means are shown.

Table 4.4 -- Summary Statistics for False Positive (FP) Trials With an Unnecessary Braking Reaction

```
Variable   N          Mean       Std Dev       Minimum       Maximum
--------------------------------------------------------------------
BRTWARN   20     0.8985000     0.2104950     0.5500000     1.2400000
MAXPEDF   20    26.5035000    16.5167734     9.0300000    62.7300000
SPEEDIFF  20     1.7100000     2.6156734    -0.0500000    10.4100000
DECLMAX   20    -0.1185000     0.0937115    -0.3300000    -0.0300000
BRKDUR    20     0.5980000     0.4728369     0.1600000     1.8000000
--------------------------------------------------------------------
```

4.3.4 Subjective Assessments

The last dependent measure to be considered is the rating of each pulse braking event in terms of its perceived suitability as a rear-end collision warning display. When a display was detected, such ratings were provided for both true positive and false positive trials. Table 4.5 provides a listing of each test participant’s rating for each pulse braking display under both conditions.

There were 33 out of 63 cases for pulse braking conditions in which ratings were provided for both TP and FP trials. Of these, a given display was judged “harder” in FP than in TP trials in 21 cases, rated the same in 9 cases, and rated “harder” in TP than in FP trials in 3 cases. This suggests that the same display, when presented at an inappropriate time, will often be perceived as more intrusive than when the display serves as a legitimate warning.

For TP cases, the combination of highest jerk rate and longest duration yielded the greatest number of ratings of 4 (just right) or 5 (slightly hard). This finding is difficult to interpret in light of so many missed detections, many of which are due to braking before the pulse braking display came on. In the earlier parameter setting study, the high jerk rate and intermediate duration received the most favorable ratings. Perhaps the presence of a lead vehicle braking increased either tolerance of or desire for a more noticeable display.

Table 4.5 -- Individual Ratings of Appropriateness of Pulse Braking Display as a Warning Display, True Positive and False Positive Trials

	Duration, X2			
	Codes	-1	0	+1
Jerk Rate, X1	-1	S1[0, 3], S2[0, 0], S3[3, 0], S4[4, 4], S5[2, 3], S6[0, 1], S7[3, 3]	S1[0, 1], S2[0, 0], S3[4, 3], S4[3, 4], S5[2, 4], S6[0, 2], S7[3, 5]	S1[0, 2], S2[0, 0], S3[2, 2], S4[4, 4], S5[0, 4], S6[5, 4], S7[7, 5]
	0	S1[0, 1], S2[0, 0], S3[3, 4], S4[3, 4], S5[0, 3], S6[0, 3], S7[0, 5]	S1[2, 3], S2[6, 0], S3[4, 5], S4[4, 5], S5[0, 4], S6[2, 5], S7[0, 5]	S1[6, 6], S2[5, 5], S3[3, 5], S4[0, 5], S5[0, 5], S6[6, 7], S7[4, 6]
	+1	S1[0, 2], S2[0, 0], S3[4, 4], S4[0, 4], S5[0, 4], S6[2, 4], S7[0, 5]	S1[0, 3], S2[0, 0], S3[2, 6], S4[3, 5], S5[5, 5], S6[3, 5], S7[0, 5]	S1[3, 4], S2[5, 5], S3[4, 5], S4[4, 6], S5[0, 5], S6[0, 5], S7[4, 5]

Notes:

- The S-numbers represent codes for individual test participants
- The first and second numbers within brackets are the appropriateness ratings provided for a given test participant in true positive and false positive trials, respectively.
- The appropriateness question was worded as follows:

“Please judge the appropriateness of the haptic event as a warning display on the following 7-point scale”:

1___ Much too soft
2___ Moderately soft
3___ Slightly soft
4___ Just right
5___ Slightly hard
6___ Moderately hard
7___ Much too hard

- A rating of 0 implies the display was not detected (or the test participant braked early).

5.0 CONCLUSIONS AND RECOMMENDATIONS FOR REAR-END COLLISION AVOIDANCE SYSTEM MONO-PULSE BRAKING HAPTIC DISPLAYS IN CAR FOLLOWING

A theoretical motivation for appropriately chosen haptic displays is that they exhibit high stimulus-response (S-R) compatibility (Wickens, 1992). In the case of a collision avoidance system that warns the driver to brake, a pulse braking display produces a stimulus that matches the sensory feedback produced by the intended response. On the other hand, a vibrating steering wheel motion does not have high S-R compatibility with a braking response. The dimension of S-R compatibility provides a scientific basis to explain the pattern of results obtained for the present study and its two predecessors described in Sections 2.0 and 3.0.

Section 2.0 reported on a mono-pulse braking parameter-setting study on a test track conducted without a lead vehicle present. In that study, test participants were instructed to "... bring the vehicle to a controlled stop..." if a pulse braking event was detected. One unexpected result was that, despite the neutral instruction, drivers braked harder the stronger the pulse braking display.

It is interesting to compare such results with those reported by Section 3.0 in the parameter setting study of active steering displays for rear-end collision avoidance. In that study, the steering wheel was vibrated in a manner that systematically varied frequency, magnitude, and duration of vibration. The instructions and testing procedures were essentially identical to those of the pulse brake parameter setting study. Unlike the pulse brake parameter setting study or the inappropriate braking data from the present study, there was no evidence that test participants braked harder to "stronger" active steering displays. Apparently, this result was due to the lack of S-R compatibility between an active steering display and the braking response. On the other hand, high S-R compatibility would be expected for an application of active steering (e.g., applying a directional torque on the wheel) that involved steering responses. Examples include lane change, road departure, or opposite direction collision avoidance. The study reported on in Section 3.0 concluded their study with a recommendation that active steering displays not be used to prompt a braking response but instead be reserved for future applications in an integrated collision avoidance system that are focused on steering responses.

Both of the preceding studies were carried out in the absence of a lead vehicle. It was thought that the presence of a lead vehicle would eliminate braking behavior modulated by the magnitude of the pulse braking display. In particular, it was believed that the presence of the decelerating lead vehicle would prompt appropriate braking responses unaffected by pulse braking parameters. Such a prediction appears supported by the present study. The pattern of results for true positive (TP) trials revealed no significant differences in braking behavior as a result of pulse braking parameters. What differences in the response variables exist were not systematically related to pulse braking jerk rate, duration, or their interaction. The study results must be interpreted with caution due to the small sample size, unequal number of observations in each cell of the test matrix, and the staged nature of the test track trials. However, the following summary is both plausible and consistent with the data. During true positive trials, it appears that drivers modulated their braking responses based on the constraints imposed by the trajectory of the lead vehicle as it braked to a stop. Drivers did not appear to be systematically modulating their braking maneuver in response to the parameters of the mono-pulse braking display. This is an encouraging result in that it implies that in crash hazard situations, drivers will respond to the situation, not the properties of the mono-pulse braking display.

The data for false positive (FP) trials are not uniformly encouraging. It had been hypothesized that with a lead vehicle present, the absence of deceleration would be directly perceived by drivers during false positive or nuisance warnings. If so, inappropriate braking responses for FP cases would be eliminated as well.

In the present study, a total of 20 out of 63 FP trials resulted in some form of inappropriate or unnecessary braking. Such responses were often idiosyncratic. For example, one test participant was responsible for 40% of these inappropriate braking events. Furthermore, the impact of mono-pulse braking display parameters appears to have been restricted to the jerk rate parameter only. Only jerk rate had a statistically reliable effect on the speed difference that arose between the onset of inappropriate braking and when the driver let up on the brake. Similarly, only jerk rate had a statistically reliable effect on the instantaneous maximum deceleration applied. In both cases, the trend toward “harder” braking in response to a “harder” mono-pulse braking display was obtained. It should be noted, however, that these inappropriate braking events were generally short and mild. It appears reasonable to think that the test participants surmised that the lead vehicle occasionally stopped unexpectedly and without brake lights. The ordering of initial trials were such as to encourage the perception that the pulse brake warning system "worked." The inappropriate braking events might, therefore, be interpreted to represent a cautiousness on the part of some test participants to slow down until they were able to perceptually verify that the lead vehicle was not braking to a stop. For other test participants or other trials, this judgement apparently came more readily or was made without any apparent need to slow down.

The benefits of an appropriately designed haptic display are fast response and response of the intended kind. If the haptic display is incorrectly presented, however, these benefits may become liabilities for some people. The present study provides evidence that FP presentations of mono-pulse braking displays will sometimes prompt braking responses even in the presence of a lead vehicle that is not slowing down. Such inappropriate braking responses were generally both short and mild in the present study, indicating an initial cautiousness tempered by a more or less accurate situational assessment. Whether such results will be obtained for drivers in real-world circumstances that do not provide a context similar to the skid pad trials requires further empirical evaluation. At this point, the results of this small scale study suggest guarded optimism that mono-pulse braking may be useful as a warning for rear-end collision avoidance. Nothing substantive can be said from this study about how false positive mono-pulse braking will affect driver acceptance but it is reasonable to presume that such a nuisance alarm will impact driver acceptance negatively.

These results would appear to apply both to rear-end collision warning systems and to Adaptive Cruise Control (ACC) systems with limited braking authority. In a terminus crash situation, the ACC with braking authority would apply the vehicle's brakes, perhaps with a high jerk rate. This will serve, *de facto,* as a type of pulse brake haptic warning. ACC system design will likely maintain the maximum authorized braking level until some driver action occurs. This in turn will grab the driver's attention and hopefully prompt a braking response that is appropriate and effective in alleviating the crash hazard.

This study also uncovered methodological difficulties associated with testing crash warnings. First, there was a need to provide more or less constant initial time headway conditions for each of the TP and FP trials. Manual driving did not provide this; drivers during pre-pilot testing had great difficulty maintaining a requested headway. This difficulty grew when the driver attempted a distracting task like entering destinations into a route guidance system. In the present study, this methodological problem was addressed by introducing an adaptive cruise control that provided more or less constant initial time headway of 2.0 seconds at approximately 45 mph. The driver's perception of hazard and selection of response is likely to be a function of car following parameters like time headway at the start of an event. Thus, either time headway during trials must be controlled or they should be factored into subsequent statistical analyses.

A second methodological difficulty uncovered in this study concerns the assessment of the effects of last-second imminent crash warnings. In the present study a very early warning onset rule was applied. Specifically, a Time-to-Collision (TTC) threshold of TTC < 25 seconds was used to trigger a mono-pulse brake display during TP conditions. This value was selected in the hope that such an early warning would largely preclude a braking response by the driver in anticipation of the mono-pulse brake warning onset. In this way, inferences about the pulse braking displays could be based on the most logically relevant trials. Despite this early onset warning rule and the distracting destination entry task, 33 out of 63 TP trials involved the driver applying the brakes at some point prior to the mono-pulse brake onset. One can only assume that a late-onset, imminent crash warning would have even more trials where the driver responded before the display was presented. At a minimum these results imply that care must be taken to separate out trials in which the display could not have affected the response. In the present study, TP cases were analyzed in two ways. One included all trials wherein the test participant reported sensing or detecting the display. The other included only trials in which the test participant responded sometime after the onset of the display. In the present study, the results did not change due to removing trials in which subjects exhibited a response prior to presentation of the haptic warning.

The third study described in this report was undertaken to determine how drivers in a car following situation would react to a mono-pulse braking display under two different conditions. In a true positive (TP) condition, a lead vehicle was braking to a stop when the haptic braking display came on. The data indicated that drivers, on average, modulated their braking according to the constraints of the lead vehicle coming to a stop. No consistent evidence was found that drivers modulated their braking according to the jerk rate or duration of the mono-pulse pulse braking display in TP trials.

No strong inferences should be drawn due to the small sample size, the test track conditions, limited exposure and methodological difficulties in providing a haptic warning before drivers responded of their own accord. Nonetheless, the TP trial results are encouraging that in such circumstances, drivers will respond according to the car following situations if a mono-pulse braking display is presented and not to the properties of a mono-pulse brake display itself.

This study also examined how drivers might respond to a mono-pulse braking display in a car following situation for which the lead vehicle is not slowing down. These conditions, termed false positive (FP) conditions here, produced more ambiguous results. In approximately one-third of the FP trials, uncalled-for or inappropriate braking responses were recorded. Both instantaneous maximum deceleration and speed differential reliably varied as a function of haptic braking display jerk rate. On average, higher jerk rates were associated with greater maximum decelerations and greater momentary drops in speed. However, these inappropriate braking responses were generally both mild and of short duration. This suggests guarded optimism that mono-pulse braking displays might be of use in rear-end collision avoidance applications. There is nonetheless a need to conduct further testing to better understand the nature of such driver responses in a real-world setting with prolonged exposure.

At present, it is recommended that haptic braking displays be considered for further application to rear-end collision avoidance and Adaptive Cruise Control (ACC) with braking authority. Useful further studies would examine the effectiveness of haptic, visual, and auditory warnings, both singly and in combination. In addition, a limited field test should be conducted as a preliminary to any broader-scale field operational test. The purpose of such a preliminary field test would be to examine driver response to a haptic (as well as other modalities) display in real-world driving over a more extended period of time (e.g., 1-2 weeks). Such a test would lend substantial insight into any safety problems that might be lurking in wait for a field operational test. It will also provide a more useful venue to address issues associated with driver acceptance.

6.0 References

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APPENDIX A

CENTRAL COMPOSITE DESIGNS: A BRIEF INTRODUCTION

A.1 CENTRAL COMPOSITE DESIGN APPROACHES

The fractional factorial design (along with confounded factorial designs and single-observation factorial designs) supports economical data collection for hypothesis testing, i.e., to test whether a driver-performance measure reliably varies with some factor. It is well suited to the analysis of categorical variables (at two levels, usually, though 3-level and 5-level fractional factorial designs are also possible). In other situations, however, the evaluator may seek to determine a quantitative relationship between driver performance and several quantitative independent factors, e.g., in-cab device parameters. Such a functional relationship is useful in that it allows for comparative predictions of various alternative system configurations, during, say, product development (Williges, 1981). The empirical model form that has been recommended for human factors use is a second-order polynomial, i.e.,

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_1 + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + e$$

where y is a dependent measure (i.e., response variable),
β_i terms are the estimated model coefficients for pure linear effects,
β_{ii} terms are the estimated model coefficients for pure quadratic effects,
β_{ij} terms are the estimated model coefficients for two-factor interactions,
x_i is the main effect of the ith factor,
x_i x_j is the interaction between the ith and jth variables,
x_i^2 is the pure quadratic term for the ith factor, and
e is the error term or difference between actual and estimated response values.

Least squares regression estimates of the beta parameters specified in the second-order polynomial response surface is given by the expression.

$$\hat{\mathbf{B}} = (\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}'\boldsymbol{Y}$$

where	**X**	is an n x p design matrix for a particular fractional factorial design (see Appendix N), augmented so that column 1 is a column of 1s so that the intercept may be estimated;
	X’	is the p x n transpose of the X design matrix (augmented);
	$(X'X)^{-1}$	is the p x p inverse of the sum of squares and cross products matrix; and
	Y	is the n x 1 column vector of responses for each condition run; and
	X’Y	is the p x 1 column vector that is the matrix product of the two matrices involved.

As with the fractional factorial design, the central composite design data is analyzed with regression methods and the ANOVA to assess the statistical significance of each of the terms of the fitted regression equation. The selection of levels of each variable to economically collect data to build the empirical second-order polynomial equation has been discussed by Williges (1980) and Williges and Williges (1992).

In order to build such a model, data are needed to solve the least squares regression equations. Box and Wilson (1951, cited in Williges, 1981) developed an experimental methodology that determines optimal combinations of various quantitative factors to define the response surface. The design approach is to use a composite three separate parts: a) 2^k factorial or 2^{k-1} fractional factorial design portion; b) 2k additional points that outline a star pattern in the factor space; and c) 1 center point from which the entire composite of points radiates. For this reason, this is referred to as a central composite design. Generally, any second order, central composite design can be specified with a total of T points:

$$T = F + 2k + 1$$

where F = 2^k (or 2^{k-p})

k = the number of factors under investigation.

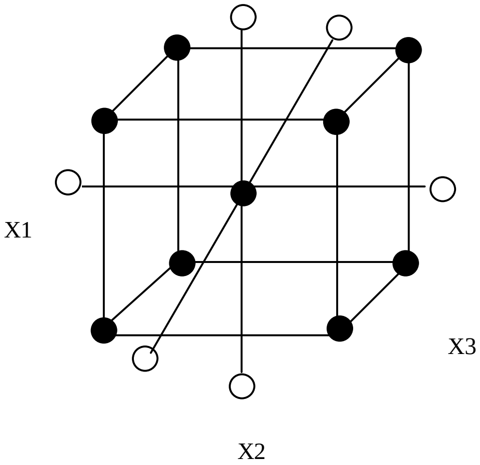
p = a number that represents the degree of fractionation in the fractional factorial design (1 = one-half fraction; 2 = one-fourth fraction; 3 = one-eighth fraction; 4= one-sixteenth fraction)

For example, consider a three-factor evaluation. If one substitutes k = 3 in the equation above, the value of T = 15, i.e., fifteen unique combinations are required to specify the second-order polynomial response surface. If one used a complete factorial experimental design, then with each factor at 5 levels (the number of levels needed to map out a second-order polynomial), there would be 5^3 or 125 combinations. The economy of approach is apparent.

Like the fractional factorial approach, this economy comes at a price. Care must be taken such that the 2^k combinations of factors, if substituted by a fractional factorial design portion due to the large number of factors of interest, be chosen so that all first- and second-order components are present and are not aliases of each other so that a complete second-order response surface can be generated (Williges, 1981). Clearly, all factors must be quantitative, else it makes little sense to discuss linear and quadratic components. While minimally only 3 levels of a factor are needed to outline a curve, 5 levels, appropriately chosen, will provide sufficient detail to develop an entire surface.

Figure A.1 shows an example of a three-factor central composite design to evaluate automobile driving performance (y) as a function of wind gust characteristics (Williges, 1981). Only 15 unique treatment combinations are required, as indicated in the coding scheme at the bottom of the figure. Replication is needed to allow for the analysis of variance mean square error term to be defined. This may involve running two (or more) subjects in each of the treatment conditions or perhaps having a single group of subjects in a repeated measures format drive in all treatment conditions and thus provide replication over the entire design surface. See Williges (1981) for more details about replication decisions.

Second-order, Central Composite Study Design
in 3 Variables, X1, X2, X3



Treatment Comb.	Level Codes X1	X2	X3
1	+1	+1	+1
2	+1	-1	+1
3	+1	+1	-1
4	+1	-1	-1
5	-1	+1	+1
6	-1	-1	+1
7	-1	+1	-1
8	-1	-1	-1
9	+1.9	0	0
10	-1.9	0	0
11	0	+1.9	0
12	0	-1.9	0
13	0	0	+1.9
14	0	0	-1.9
15	0	0	0

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + e$$

Figure A.1 -- Central Composite Design Illustration

The value of α remains to be specified. While there are alternative ways to define the α level (see Williges, 1981), one simple way is such that the first and second-order beta weights are orthogonal (which facilitates least squares regression and analysis of variance:

$$\alpha = \left(\frac{QF}{4}\right)^{1/4}$$

where Q = $[F + 2k + C)^{½} - F^{1/2}]^2$

C = the total number of center points (1 if equal replication is used)

F = 2^k (or 2^{k-p})

k = the number of factors under investigation.

p = a number that represents the degree of fractionation in the fractional factorial design (1 = one-half fraction; 2 = one-fourth fraction; 3 = one-eighth fraction; 4= one-sixteenth fraction)

For the three factor design, $Q = [(8 + 2(3) + 1)^{½} - 8^{1/2}]^2 = 1.092$. This implies that $\alpha = [(1.092)(8)/4]^{1/4} = 1.216$. The application of the coding scheme is then applied by assigning the α codes to the lower and upper limits of the factor range of interest, the code 0 is assigned to the midpoint of the range, and the -1 and +1 codes are assigned to factor values determined through linear interpolation. An example is provided in Table A-1. The design factors of interest are in-cab visual display luminance (x_1) (selectable over a range from 14 cd/m^2 to 140 cd/m^2), visual display contrast ratio (x_2) (selectable over a range from 2:1 to 30:1), and symbol size (x_3) (selectable over a range from 10 to 28 arc-min). The response (y) is driver visual allocation time (number of glances x mean glance duration). The levels of each factor are included in Table A.1.

An alternative criterion for α supports blocking of trials such that blocks are orthogonal to any first-order or second-order effects. This criterion has been used to develop the levels. Under the assumption of equal replication across the entire design, the orthogonal blocking condition can be met by (Williges, 1981):

$$\alpha = [\frac{F(2K+1)}{(2F)}]^{1/2}$$

The central composite design, then, gets its name from the fact that it is a composite of a 2^k (or 2^{k-p}) design, augmented by a star pattern of data collection points that radiate from a center point. the Automated Experimental Design (AED) Assistant software (System Development Corporation, 1986) will also automatically generate central composite designs.

Table A.1 -- Levels of three independent factors in Central Composite Experimental Design. (See text for explanation)

	Central Composite Design Codes and Associated Regressor Variable Values				
Regressor Variable	-α = -1.216	-1	0	+1	α =1.216
x_1: Display Luminance	14 cd/m^2	23 cd/m^2	63 cd/m^2	127 cd/m^2	140 cd/m^2
x_2 : Contrast Ratio	2	4	14	27	30
x_3 : Character Size	10 arc-min	12 arc-min	19 arc-min	26 arc-min	28 arc-min

Notes:

- See previous discussion for derivation of α.
- -α value is set to minimum of factor (regressor) range of interest
- +α value is set to maximum of factor (regressor) range of interest
- 0 value is set to mid-point of range from maximum to minimum of regressor range.
- -1 value is set to 1/1.216 = .822 of the range between 0 and -α below the midpoint value
- +1 value is set to 1/1.216 = .822 of the range between 0 and -α above the midpoint value
- Note that all regressor values have been rounded.

Efficient data collection supports efficient data analysis. For this reason, the data collection strategies presented here are beneficial to driver performance research. It is usually the case that the actual data collection and data capture vary somewhat from what was planned, especially in on-the-road evaluations or studies.

A.2 Central Composite Design References

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APPENDIX B

TEST PARTICIPANT CONSENT FORM

TEST PARTICIPANT CONSENT FORM

Title of Study: **Haptic Display Study No. 1a**

Study Description: Rear-end crashes are among the most common types of crashes. Research is under way into ways to use sensors and computer technology to detect potential crash hazards and warn a driver in time to avoid such hazards. Various auditory displays (tones) and visual displays (lights) have been proposed as rear-end crash warning displays. However, it may also be possible to warn the driver by a display that is felt rather than seen or heard. One type of ‘felt’ display is called a Pulse Braking Display. The brakes are applied for very brief period of time to alert the driver of a possible hazard ahead.

Haptic display systems are those which use tactile means to provide the driver with information. Haptic displays being developed for use in cars and trucks can be used in lieu of auditory or visual displays to call the driver’s attention to urgent information. Such systems allow a driver to receive information without diverting his eyes from the roadway, and use this information to perform the driver’s primary job of safely controlling the vehicle. The National Highway Traffic Safety Administration (NHTSA) is conducting research to measure the effects on driver performance of using such display methods. One area of research is the effect on driver behavior and performance when these displays advise drivers in a car following situation that their time headway to a lead vehicle has fallen below a predetermined limit.

As a participant, you will be shown a haptic display system, and oriented on the actions you are to take when displays occur. The display system in this study, referred to as Pulse Braking, is a proposed method of alerting a driver to an imminent crash with a vehicle or object ahead of them. Pulse Braking provides a brief brake application to achieve a predetermined rate or level of deceleration. In this study, the correct response for this display is to apply the vehicle’s brakes. As soon as you perceive a signal, apply the brakes as quickly as possible. Apply the brakes as if a vehicle ahead of you on the highway had suddenly decelerated. It is not necessary to apply maximum braking or to come to a full stop, but brake hard enough to bring the vehicle to a controlled stop. We will measure the elapsed time from display presentation to brake application.

The purpose of today’s testing is to help determine what might be the most appropriate type of Pulse Braking Display. You will be driving an instrumented vehicle on the TRC Skid pad at a speed of 45 mph. You will be driving under conditions where you are working on a distracting in-vehicle task and under conditions where you are only driving. **From time to time, a pulse braking event will be presented. When this happens, you are to press on the brake pedal as quickly as possible after you notice such a braking event and bring the vehicle to a controlled stop.** You will then be asked to rate the particular level of pulse braking in terms of appropriateness as a warning. The rating scale will be presented to you later in this session. Do you have any questions about the intent of the study and the procedure?

You will also receive training on how to complete destination entry tasks with a commercially available route guidance system. The experimenter will show you a set of “target” destinations that you are to write down on individual 4x6 index cards so that you will be able to use them for destination entry during practice as well as while driving on the TRC skid pad. You will have an opportunity to practice entering destinations with the system in a parked vehicle and ask any questions you wish of the experimenter.

The experimenter will accompany you during all testing. During testing, you will be asked to wear protective headphones to shield you from potentially distracting sounds. These headphones contain speakers through which you will hear modified ocean sounds to mask any remaining unwanted noise. The ride-along experimenter will be responsible for all radio communications with the control tower and other test units. You will be asked to drive a series of laps in an assigned lane on the TRC skid pad. When you are not in a turnaround loop, the ride-along experimenter will ask you to maintain a speed of 45 mph. Periodically, the haptic display system will signal you to apply the vehicle's brakes. This signal can be expected to vary slightly with each occurrence, but will always be characterized by a brief, automatic application and release of the vehicle's brakes. After you have then applied the brakes, the experimenter will ask you a series of questions about the appropriateness and acceptability of the display as a warning. As the headphones may make it difficult to hear the experimenter, he will show you a series of cards containing ratings for each display. Using a scale which the experimenter will present to you, you will be asked to assign a number from 1 through 7 for each display. You will be reminded of this scale at the start of the test session. After the experimenter records your response, you will continue with the next trial and rating. The ride-along experimenter will also periodically hand you a 4x6 index card with a destination written on it, a signal that you are to enter that destination into the route guidance system, WHEN AND IF YOU BELIEVE IT IS SAFE TO DO SO GIVEN THE CURRENT DRIVING CONDITIONS ON THE SKID PAD. The experimenter may sometimes ask you to begin a destination entry task, then subsequently determine that it is not necessary to complete that task. After you have completed a series of laps, you will return to Building 60. The complete series of orientations and trials will take approximately four hours.

You, as the driver of the test vehicle, are responsible for maintaining safety at all times. Do not perform any task which you believe would be unsafe. Remember, you must be the final judge of whether or when to work on a task or make a response. Do you have any questions?"

It is very important to always remember that you, as the driver, are in control of the vehicle and you must be the final judge on when or whether to respond to any request or engage in any task. You should follow a request or prompt or complete a task or maneuver only when, in your judgement, it is safe and convenient to do so. The ride-along experimenter will not be able to insure safety; you as the driver are responsible for that. Remember, safety while driving on the skid pad is your primary responsibility. Complete requests only when and if you believe it is safe to do so.

Risks: While driving for this study, you will be subject to all risks normally associated with driving on the TRC skid pad plus any additional risks associated with completing in-vehicle tasks while driving. There are no known physical or psychological risks associated with participation in this study beyond those indicated.

Be aware that accidents can happen any time when driving. You remain responsible for your driving during this testing. If the ride-along experimenter should make a request, or the display prompt an action, you are not to do it unless you judge it is safe to do so.

Benefits: This testing will provide data on driver behavior, performance judgements, and preferences regarding the haptic display methods presented. This data will provide a scientific basis for guiding recommendations on standards for haptic display systems in the future.

Confidentiality: The data recorded on you will be analyzed along with data gathered from other test participants during this testing. Your name will not be associated with any final report, publication, or other media that might arise from this study. However, your video-recorded likeness (in video or still photo formats created from the video) and engineering data from you specifically may be used for educational and research purposes. A waiver of confidentiality for permission to use the video and engineering data (including data or images derived from these sources) is included for you to sign as part of this form. It is not anticipated that you will be informed of the results of this study.

Informed Consent: By signing below, you agree that participation is voluntary and you understand and accept all terms of this agreement. **You have the option of not performing any requested task at any time during the test without penalty.**

Compensation: Should you agree to participate in this testing, it will be considered part of your normal work day activities. There is no special compensation associated with participation in the test.

Principal Investigator: Contact Dr. Louis Tijerina (TRC) or Dr. Riley Garrott (NHTSA VRTC) if you have questions or comments regarding this study. They may be reached at the address and phone number given below:

Vehicle Research and Test Center
10820 SR 347
East Liberty, OH 43319
Phone: (937) 666-4511

Disposition of Informed Consent: The VRTC will retain a signed copy of this Informed Consent form. A copy of this form will also be provided to you.

INFORMED CONSENT:

I, _________________________, UNDERSTAND THE TERMS OF THIS AGREEMENT AND VOLUNTARILY CONSENT TO PARTICIPATE.

____
Signature/Date

____
Witness/Date

WAIVER OF CONFIDENTIALITY:

I, ________________________, grant permission, in perpetuity, to the National Highway Traffic Safety Administration (NHTSA) to use, publish, or otherwise disseminate the video-tape (including still photo formats derived from the videotape) and engineering data collected about me in this study for educational, outreach, and research purposes. I understand that such use may involve widespread distribution and may involve dissemination of my likeness in videotape or still photo formats, but will not result in release of my name or other identifying personal information.

____
Signature/Date

____
Witness/Date

APPENDIX C

SKID PAD INSTRUCTIONS FOR MONO-PULSE BRAKING STUDY

C.1 HAPTIC DISPLAY STUDY 1A: PULSE BRAKING STUDY

INSTRUCTIONS FOR SKID PAD

(To be read upon arrival at the skid pad).

You will be driving the instrumented vehicle on the TRC Skid pad at a speed of 45 mph except when directed otherwise by the experimenter (me). You will be driving under conditions where you are only driving and sometimes when you are both driving and entering in a destination on the route guidance system in the instrumented vehicle.

From time to time, a pulse braking event will be presented. That is, the brakes will be applied by a computer for a brief period of time. As soon as you perceive a pulse braking event, bring the vehicle to a controlled stop. Afterwards, you will be asked to rate the pulse braking event in terms of its appropriateness as a warning display using a rating scale (Show them the rating scale card).

Do the best you can to complete the destination entry tasks. If a display occurs during a destination entry task, follow the normal procedure and, as soon as you perceive a pulse braking event, bring the vehicle to a controlled stop. You do not need to complete the destination entry task

Remember that you, as the driver of the test vehicle, are responsible for maintaining safety at all times. Do not perform any task which you believe would be unsafe. Remember, you must be the final judge of whether or when to work on a task or make a response. Do you have any questions?”

APPENDIX D

SUBJECTIVE RATING SCALE FOR MONO-PULSE BRAKING APPROPRIATENESS

D.1 SUBJECTIVE RATING SCALE FOR MONO-PULSE BRAKING APPROPRIATENESS

The test participants answered the subjective assessment question below after each detected pulse braking event after having brought the vehicle to a complete stop:

“Please judge the appropriateness of the haptic event as a warning display on the following 7-point scale”:

1___ Much too soft
2___ Moderately soft
3___ Slightly soft
4___ Just right
5___ Slightly hard
6___ Moderately hard
7___ Much too hard

APPENDIX E

”BEST” RESPONSE SURFACE MODELING RESULTS FOR DISTRACTION CONDITION

E.1 "BEST" RESPONSE SURFACE MODELING RESULTS FOR DISTRACTION CONDITION

Note: In all models provided below,

X1 = coded variable for Jerk Rate
-1 signifies 0. 08 g/s
0 signifies 0.20 g/s
+1 signifies 0.32 g/s

X2 = coded variable for Duration
-1 signifies 0.25 seconds
0 signifies 0.65 seconds
+1 signifies 1.0 second

X3 through X7, when used, are binary (0, 1) indicator variables for Subject Effects (i.e., effects attributable to variation among the test participants or subjects).

Dependent Variable: AccelRT. Distraction Condition

No statistically significant models were found as a function of jerk rate or duration. All variation in accelerator release time after pulse brake onset appears attributable to random variation.

```
Dependent Variable: MAXPEDF, Best Model with Test Participant Effects, Distraction Condition

Source                  DF              Type III SS          Mean Square   F Value     Pr > F

X1                       1            4681.19420905        4681.19420905     11.25     0.0017
X2                       1            2555.87893204        2555.87893204      6.14     0.0174
X3                       1            4461.34580000        4461.34580000     10.72     0.0022
X4                       1           17181.63635556       17181.63635556     41.28     0.0001
X5                       1            7622.42045000        7622.42045000     18.31     0.0001
X6                       1           22269.59193545       22269.59193545     53.50     0.0001
X7                       1             296.04368391         296.04368391      0.71     0.4039
Error                   41           17065.44994929         416.23048657

                  R-Square                     C.V.             Root MSE         MAXPEDF Mean

                  0.859657                 14.25191          20.40172754         143.15081633

                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                   155.2711111              22.83          0.0001        6.80057585
X1                           12.3905793               3.35          0.0017        3.69470888
X2                            8.9500679               2.48          0.0174        3.61179536
X3                          -31.4866667              -3.27          0.0022        9.61746659
X4                          -61.7911111              -6.42          0.0001        9.61746659
X5                          -41.1566667              -4.28          0.0001        9.61746659
X6                           79.7470065               7.31          0.0001       10.90247761
X7                            8.7315708               0.84          0.4039       10.35336260
```

```
Dependent Variable: MAXPEDF, Best Model without Participant Effects, Distraction Condition

Source                  DF           Sum of Squares          Mean Square   F Value     Pr > F

Source                  DF              Type III SS          Mean Square   F Value     Pr > F

X1                       1           12854.88887897       12854.88887897      5.81     0.0200
X2                       1            8215.40726087        8215.40726087      3.71     0.0603
Error                   46          101863.57990511        2214.42565011

                  R-Square                     C.V.             Root MSE         MAXPEDF Mean

                  0.162295                 32.87280          47.05768428         143.15081633

                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                   140.5311838              20.73          0.0001        6.77958298
X1                           20.1949017               2.41          0.0200        8.38181619
X2                           15.8607955               1.93          0.0603        8.23457082
```

```
Dependent Variable: TOTSTOP, Best Model with Test Participant Effects, Distraction Condition

Source                  DF              Type III SS            Mean Square   F Value     Pr > F

X1                       1            2984.88737307          2984.88737307     28.52     0.0001
X2                       1            2456.35100323          2456.35100323     23.47     0.0001
X3                       1            1177.25693889          1177.25693889     11.25     0.0017
X4                       1             690.18508889           690.18508889      6.59     0.0140
X5                       1              70.84467222            70.84467222      0.68     0.4154
X6                       1            3161.73567230          3161.73567230     30.21     0.0001
X7                       1               5.22227500             5.22227500      0.05     0.8244
Error                   41            4291.65743535           104.67457159

Corrected Total         48           21037.46611020

                  R-Square                     C.V.                Root MSE         TOTSTOP Mean

                  0.795999                 13.20759             10.23105916          77.46346939

                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                   76.34777778              22.39          0.0001         3.41035305
X1                          -9.89412187              -5.34          0.0001         1.85282276
X2                          -8.77407627              -4.84          0.0001         1.81124328
X3                          16.17444444               3.35          0.0017         4.82296754
X4                          12.38444444               2.57          0.0140         4.82296754
X5                           3.96777778               0.82          0.4154         4.82296754
X6                         -30.04837840              -5.50          0.0001         5.46737492
X7                           1.15969651               0.22          0.8244         5.19200470
```

```
Dependent Variable: TOTSTOP,Best Model without Test Participant Effects, Distraction Condition


Source                  DF              Type III SS            Mean Square   F Value     Pr > F

X1                       1            4678.62800817          4678.62800817     16.56     0.0002
X2                       1            3916.81564649          3916.81564649     13.86     0.0005
Error                   46           12999.20451994           282.59140261

Corrected Total         48           21037.46611020

                  R-Square                     C.V.                Root MSE         TOTSTOP Mean

                  0.382093                 21.70114             16.81045516          77.46346939

                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                   79.12853405              32.67          0.0001         2.42187599
X1                         -12.18335333              -4.07          0.0002         2.99424307
X2                         -10.95158512              -3.72          0.0005         2.94164249
```

```
Dependent Variable: BRKSTOP, ‘Best’ Model with Test Participant Effects, Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1            1156.76089798           1156.76089798     15.44     0.0003
X2                       1             755.24455923            755.24455923     10.08     0.0028
X3                       1             769.75800556            769.75800556     10.28     0.0026
X4                       1             504.34880000            504.34880000      6.73     0.0131
X5                       1              52.94205000             52.94205000      0.71     0.4054
X6                       1            3255.86173151           3255.86173151     43.47     0.0001
X7                       1               0.61906441              0.61906441      0.01     0.9280
Error                   41            3070.92297646             74.90056040

                  R-Square                     C.V.                Root MSE          BRKSTOP Mean

                  0.788667                 13.60969              8.65451099           63.59081633

                                                T for H0:        Pr > |T|       Std Error of
Parameter                             Estimate        Parameter=0                        Estimate

INTERCEPT                          63.20555556              21.91          0.0001         2.88483700
X1                                 -6.15935280              -3.93          0.0003         1.56731328
X2                                 -4.86519212              -3.18          0.0028         1.53214097
X3                                 13.07888889               3.21          0.0026         4.07977560
X4                                 10.58666667               2.59          0.0131         4.07977560
X5                                  3.43000000               0.84          0.4054         4.07977560
X6                                -30.49237391              -6.59          0.0001         4.62488346
X7                                 -0.39928445              -0.09          0.9280         4.39194623
```

```
Dependent Variable: BRKSTOP, ‘Best’ Model without Test Participant Effects, Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1            2229.83746924           2229.83746924      9.37     0.0037
X2                       1            1599.36570250           1599.36570250      6.72     0.0127
Error                   46           10947.62003816            237.99173996

                  R-Square                     C.V.                Root MSE          BRKSTOP Mean

                  0.246613                 24.25976             15.42698091           63.59081633


                                                T for H0:        Pr > |T|       Std Error of
Parameter                             Estimate        Parameter=0                        Estimate

INTERCEPT                          64.70588233              29.11          0.0001         2.22255937
X1                                 -8.41093323              -3.06          0.0037         2.74782154
X2                                 -6.99816707              -2.59          0.0127         2.69954990
```

APPENDIX F

”BEST” RESPONSE SURFACE MODELING RESULTS FOR NO DISTRACTION CONDITION

F.1 “BEST” RESPONSE SURFACE MODELING RESULTS FOR NO DISTRACTION CONDITION

Note: In all models provided below,

X1 = coded variable for Jerk Rate
-1 signifies 0. 08 g/s
0 signifies 0.20 g/s
+1 signifies 0.32 g/s

X2 = coded variable for Duration
-1 signifies 0.25 seconds
0 signifies 0.65 seconds
+1 signifies 1.0 second

X3 through X7, when used, are binary (0, 1) indicator variables for Subject Effects (i.e., effects attributable to variation among the test participants or subjects).

```
Dependent Variable: ACCELRT, ‘Best’ Model with Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1               0.49337194              0.49337194     12.94     0.0009
X3                       1               0.34742290              0.34742290      9.11     0.0045
X4                       1               0.03373378              0.03373378      0.88     0.3528
X5                       1               0.00810000              0.00810000      0.21     0.6475
X6                       1               0.01111441              0.01111441      0.29     0.5924
X7                       1               0.00455625              0.00455625      0.12     0.7315
Error                   38               1.44870878              0.03812392

                 R-Square                    C.V.               Root MSE         ACCELRT Mean

                  0.467934               33.66439              0.19525346           0.58000000

                                                 T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                         Estimate

INTERCEPT                  0.5760273475               8.32          0.0001         0.06919939
X1                         -.1382187803              -3.60          0.0009         0.03842188
X3                         0.3054012239               3.02          0.0045         0.10116733
X4                         -.0893606809              -0.94          0.3528         0.09499761
X5                         -.0450000000              -0.46          0.6475         0.09762673
X6                         0.0609039206               0.54          0.5924         0.11279782
X7                         -.0337500000              -0.35          0.7315         0.09762673
```

```
Dependent Variable: ACCELRT,‘Best’ Model without Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1               0.52809191              0.52809191     10.35     0.0025
Error                   43               2.19470809              0.05103972

                  R-Square                    C.V.               Root MSE         ACCELRT Mean

                  0.193952               38.95168              0.22591973           0.58000000

                                                 T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                         Estimate

INTERCEPT                  0.5985784314              17.52          0.0001         0.03416980
X1                         -.1393382353              -3.22          0.0025         0.04331813
```

```
Dependent Variable: MAXPEDF,‘Best’ Model with Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1            1026.98572238           1026.98572238      2.53     0.1199
X2                       1            3466.03764190           3466.03764190      8.55     0.0059
X3                       1            7805.44199872           7805.44199872     19.27     0.0001
X4                       1           13100.32356406          13100.32356406     32.33     0.0001
X5                       1            3447.15765625           3447.15765625      8.51     0.0060
X6                       1           16097.18438114          16097.18438114     39.73     0.0001
X7                       1            1861.70675625           1861.70675625      4.60     0.0387
Error                   37           14990.71702654            405.15451423

                  R-Square                     C.V.                Root MSE         MAXPEDF Mean

                  0.828694                 15.18662             20.12845037         132.54066667

                                                  T for H0:        Pr > |T|       Std Error of
Parameter                         Estimate        Parameter=0                       Estimate

INTERCEPT                      149.3447672              20.87          0.0001         7.15616270
X1                               6.3792082               1.59          0.1199         4.00677462
X2                              11.4926544               2.92          0.0059         3.92928972
X3                             -45.8412399              -4.39          0.0001        10.44402604
X4                             -55.7803227              -5.69          0.0001         9.80957863
X5                             -29.3562500              -2.92          0.0060        10.06422518
X6                              73.3871770               6.30          0.0001        11.64274978
X7                             -21.5737500              -2.14          0.0387        10.06422518
```

```
Dependent Variable: MAXPEDF,‘Best’ Model without Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1            7965.12461585           7965.12461585      4.43     0.0412
X2                       1            5765.44620115           5765.44620115      3.21     0.0804
Error                   42           75435.81926650           1796.09093492

                  R-Square                     C.V.                Root MSE         MAXPEDF Mean

                  0.137961                 31.97533             42.38031306         132.54066667

                                                  T for H0:        Pr > |T|       Std Error of
Parameter                         Estimate        Parameter=0                       Estimate

INTERCEPT                      128.2759829              19.64          0.0001         6.53010221
X1                              17.2819189               2.11          0.0412         8.20653520
X2                              14.7032093               1.79          0.0804         8.20653520
```

```
Dependent Variable: TOTSTOP, ‘Best’ Model with Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1            3249.33480058           3249.33480058     39.90     0.0001
X2                       1            3018.42336892           3018.42336892     37.06     0.0001
X3                       1            3971.01992975           3971.01992975     48.76     0.0001
X4                       1             255.11310461            255.11310461      3.13     0.0850
X5                       1              71.99522500             71.99522500      0.88     0.3532
X6                       1            2414.16408742           2414.16408742     29.64     0.0001
X7                       1              18.16890625             18.16890625      0.22     0.6395
Error                   37            3013.33987601             81.44161827

                  R-Square                     C.V.                Root MSE         TOTSTOP Mean

                  0.863594                 11.11571              9.02450100          81.18688889

                                                T for H0:        Pr > |T|       Std Error of
Parameter                         Estimate        Parameter=0                         Estimate

INTERCEPT                  79.51149160              24.78          0.0001         3.20843365
X1                        -11.34701956              -6.32          0.0001         1.79641954
X2                        -10.72491326              -6.09          0.0001         1.76167953
X3                         32.69705504               6.98          0.0001         4.68253252
X4                          7.78406395               1.77          0.0850         4.39808085
X5                          4.24250000               0.94          0.3532         4.51225050
X6                        -28.42029721              -5.44          0.0001         5.21997496
X7                          2.13125000               0.47          0.6395         4.51225050
```

```
Dependent Variable: TOTSTOP,‘Best’ Model without Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1            6212.10300766           6212.10300766     18.79     0.0001
X2                       1            3051.61454492           3051.61454492      9.23     0.0041
Error                   42           13883.66523515            330.56345798

                  R-Square                     C.V.                Root MSE         TOTSTOP Mean

                  0.371525                 22.39451             18.18140418          81.18688889


                                                T for H0:        Pr > |T|       Std Error of
Parameter                         Estimate        Parameter=0                         Estimate

INTERCEPT                  84.64810066              30.22          0.0001         2.80145235
X1                        -15.26212480              -4.34          0.0001         3.52065199
X2                        -10.69696351              -3.04          0.0041         3.52065199
```

```
Dependent Variable: BRKSTOP, ‘Best’ Model with Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1             835.36827322            835.36827322     18.81     0.0001
X2                       1            1561.18511770           1561.18511770     35.16     0.0001
X3                       1            1898.27293343           1898.27293343     42.75     0.0001
X4                       1             336.97974860            336.97974860      7.59     0.0091
X5                       1              43.95690000             43.95690000      0.99     0.3262
X6                       1            2454.10071468           2454.10071468     55.27     0.0001
X7                       1              17.32640625             17.32640625      0.39     0.5360
Error                   37            1642.77229219             44.39925114

                  R-Square                     C.V.                Root MSE         BRKSTOP Mean

                  0.873719                 9.827422              6.66327631          67.80288889

                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                   66.51706516              28.08         0.0001         2.36895978
X1                          -5.75338665              -4.34         0.0001         1.32639353
X2                          -7.71313464              -5.93         0.0001         1.30074311
X3                          22.60668759               6.54         0.0001         3.45736656
X4                           8.94626817               2.75         0.0091         3.24734054
X5                           3.31500000               1.00         0.3262         3.33163815
X6                         -28.65440624              -7.43         0.0001         3.85418934
X7                           2.08125000               0.62         0.5360         3.33163815


Dependent Variable: BRKSTOP,‘Best’ Model without Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X1                       1            2381.34187203           2381.34187203     10.67     0.0022
X2                       1            1750.63841884           1750.63841884      7.84     0.0077
Error                   42            9376.44079554            223.24859037

                  R-Square                     C.V.                Root MSE         BRKSTOP Mean

                  0.279224                 22.03668             14.94150563          67.80288889

                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                   70.14308642              30.47         0.0001         2.30223781
X1                          -9.44945042              -3.27         0.0022         2.89327716
X2                          -8.10203106              -2.80         0.0077         2.89327716
```

APPENDIX G

TEST PARTICIPANT CONSENT FORM

G.1 TEST PARTICIPANT CONSENT FORM

Title of Study: **Haptic Display Study No. 1b**

Study Description: Rear-end crashes are among the most common types of crashes. Research is under way into ways to use sensors and computer technology to detect potential crash hazards and warn a driver in time to avoid such hazards. Various auditory displays (tones) and visual displays (lights) have been proposed as rear-end crash warning displays. However, it may also be possible to warn the driver by a display that is felt rather than seen or heard. One type of 'felt' display is called active steering. In this display, a computer vibrates the steering wheel for very brief period of time to alert the driver of a possible hazard ahead. This vibration serves only as an alert; it does not provide steering input to the vehicle or affect its trajectory.

Haptic display systems are those which use tactile means to provide the driver with information. Haptic displays being developed for use in cars and trucks can be used in lieu of auditory or visual displays to call the driver's attention to urgent information. Such systems allow a driver to receive information without diverting his eyes from the roadway, and use this information to perform the driver's primary job of safely controlling the vehicle. The National Highway Traffic Safety Administration (NHTSA) is conducting research to measure the effects on driver performance of using such display methods. One area of research is the effect on driver behavior and performance when these displays advise drivers in a car following situation that their time headway to a lead vehicle has fallen below a predetermined limit.

As a participant, you will be shown a haptic display system, and oriented on the actions you are to take when the display occurs. The display system in this study, referred to as Active Steering, is a proposed method of alerting a driver to an imminent crash with a vehicle or object ahead of them. Active Steering provides a brief steering wheel vibration to alert the driver of a need to brake the vehicle. As soon as you perceive an active steering event, bring the vehicle to a controlled stop. We will measure the elapsed time from display presentation to brake application.

The purpose of today's testing is to help determine what might be the most appropriate type of Active Steering Display. You will be driving an instrumented vehicle on the TRC Skid pad at a speed of 45 mph. You will be driving under conditions where you are working on a distracting in-vehicle task and under conditions where you are only driving. **From time to time, an active steering event will be presented. As soon as you perceive an active steering event, bring the vehicle to a controlled stop.** You will then be asked to rate the particular presentation of active steering in terms of appropriateness as a warning. The rating scales will be presented to you later in this session. Do you have any questions about the intent of the study and the procedure?

You will also receive training on how to complete destination entry tasks with a commercially available route guidance system. The experimenter will show you a set of "target" destinations that you are to write down on individual 4x6 index cards so that you will be able to use them for destination entry during practice as well as while driving on the TRC skid pad. You will have an opportunity to practice entering destinations with the system in a parked vehicle and ask any questions you wish of the experimenter.

The experimenter will accompany you during all testing. During testing, you will be asked to wear protective headphones to shield you from potentially distracting sounds. These headphones contain speakers through which you will hear modified ocean sounds to mask any remaining unwanted noise. The ride-along experimenter will be responsible for all radio communications with the control tower and other test units. You will be asked to drive a series of laps in an assigned lane on the TRC skid pad. When you are not in a turnaround loop, the ride-along experimenter will ask you to maintain a speed of 45 mph. Periodically, the haptic display system will signal you to apply the vehicle's brakes. This signal can be expected to vary slightly with each occurrence, but will always be characterized by a brief, automatic vibration of the vehicle's steering wheel. This vibration will not affect your ability to steer and control the vehicle. After you have then applied the brakes, the experimenter will ask you a series of questions about the appropriateness of the display as a warning. As the headphones may make it difficult to hear the experimenter, he will show you cards containing lists of descriptions of the display's appropriateness, from which you will be asked to choose that which matches your opinion. After the experimenter records your responses, you will continue with the next trial and rating. The ride-along experimenter will also periodically hand you a 4x6 index card with a destination written on it, a signal that you are to enter that destination into the route guidance system, WHEN AND IF YOU BELIEVE IT IS SAFE TO DO SO GIVEN THE CURRENT DRIVING CONDITIONS ON THE SKID PAD. The experimenter may sometimes ask you to begin a destination entry task, then subsequently determine that it is not necessary to complete that task. After you have completed a series of laps, you will return to Building 60. The complete series of orientations and trials will take approximately four hours.

You, as the driver of the test vehicle, are responsible for maintaining safety at all times. Do not perform any task which you believe would be unsafe. Remember, you must be the final judge of whether or when to work on a task or make a response. Do you have any questions?

It is very important to always remember that you, as the driver, are in control of the vehicle and you must be the final judge on when or whether to respond to any request or engage in any task. You should follow a request or prompt or complete a task or maneuver only when, in your judgement, it is safe and convenient to do so. The ride-along experimenter will not be able to insure safety; you as the driver are responsible for that. Remember, safety while driving on the skid pad is your primary responsibility. Complete requests only when and if you believe it is safe to do so.

<u>Risks</u>: While driving for this study, you will be subject to all risks normally associated with driving on the TRC skid pad plus any additional risks associated with completing in-vehicle tasks while driving. There are no known physical or psychological risks associated with participation in this study beyond those indicated.

Be aware that accidents can happen any time when driving. You remain responsible for your driving during this testing. If the ride-along experimenter should make a request, or the display prompt an action, you are not to do it unless you judge it is safe to do so.

<u>Benefits</u>: This testing will provide data on driver behavior, performance judgements, and preferences regarding the haptic display presented. This data will provide a scientific basis for guiding recommendations on standards for haptic display systems in the future.

Confidentiality: The data recorded on you will be analyzed along with data gathered from other test participants during this testing. Your name will not be associated with any final report, publication, or other media that might arise from this study. However, your video-recorded likeness (in video or still photo formats created from the video) and engineering data from you specifically may be used for educational and research purposes. A waiver of confidentiality for permission to use the video and engineering data (including data or images derived from these sources) is included for you to sign as part of this form. It is not anticipated that you will be informed of the results of this study.

Informed Consent: By signing below, you agree that participation is voluntary and you understand and accept all terms of this agreement. **You have the option of not performing any requested task at any time during the test without penalty.**

Compensation: Should you agree to participate in this testing, it will be considered part of your normal work day activities. There is no special compensation associated with participation in the test.

Principal Investigator: Contact Dr. Louis Tijerina (TRC) or Dr. Riley Garrott (NHTSA VRTC) if you have questions or comments regarding this study. They may be reached at the address and phone number given below:

Vehicle Research and Test Center
10820 SR 347
East Liberty, OH 43319
Phone: (937) 666-4511

Disposition of Informed Consent: The VRTC will retain a signed copy of this Informed Consent form. A copy of this form will also be provided to you.

INFORMED CONSENT:

I, ________________________, UNDERSTAND THE TERMS OF THIS AGREEMENT AND VOLUNTARILY CONSENT TO PARTICIPATE.

______________________________ ____________
Signature Date

______________________________ ____________
Witness Date

WAIVER OF CONFIDENTIALITY:

I, ________________________, grant permission, in perpetuity, to the National Highway Traffic Safety Administration (NHTSA) to use, publish, or otherwise disseminate the video (including still photo formats derived from the video) and engineering data collected about me in this study for educational, outreach, and research purposes. I understand that such use may involve widespread distribution and may involve dissemination of my likeness in video or still photo formats, but will not result in release of my name or other identifying personal information.

______________________________ ____________
Signature Date

______________________________ ____________
Witness Date

APPENDIX H

SKID PAD INSTRUCTIONS FOR ACTIVE STEERING STUDY

H.1 HAPTIC DISPLAY STUDY 1B: ACTIVE STEERING STUDY

INSTRUCTIONS FOR SKID PAD

(To be read upon arrival at the skid pad).

You will be driving the instrumented vehicle on the TRC Skid pad at a speed of 45 mph except when directed otherwise by the experimenter (me). You will be driving under conditions where you are only driving and sometimes when you are both driving and entering in a destination on the route guidance system in the instrumented vehicle.

From time to time, an active steering event will be presented. That is, the steering wheel will be vibrated by a computer for a brief period of time. As soon as you perceive an active steering signal, apply the brakes as quickly as possible, bringing the vehicle to a controlled stop. Afterwards, you will be asked to rate the active steering event in terms of its appropriateness as a warning display using a rating scale (Show them the rating scale cards).

Do the best you can to complete the destination entry tasks. If a display occurs during a destination entry task, follow the normal procedure and, as soon as you perceive a pulse braking event, bring the vehicle to a controlled stop. You do not need to complete the destination entry task

Remember that you, as the driver of the test vehicle, are responsible for maintaining safety at all times. Do not perform any task which you believe would be unsafe. Remember, you must be the final judge of whether or when to work on a task or make a response. Do you have any questions?”

APPENDIX I

SUBJECTIVE RATING SCALES FOR ACTIVE STEERING DISPLAYS

I.1 SUBJECTIVE RATING SCALES FOR ACTIVE STEERING DISPLAYS

The test participants answered the subjective assessment question below after each detected active steering display event after having brought the vehicle to a complete stop:

Vibration:

Please judge the vibration of the haptic event as a warning display on the following 3-point scale:

3 ___Too slow
2 ___About right
1 ___Too fast

Strength:

Please judge the strength of the haptic event as a warning display on the following 3-point scale:

3 ___Too weak
2 ___About right
1 ___Too strong

Duration:

Please judge the duration of the haptic event as a warning display on the following 3-point scale:

3 ___Too short
2 ___About right
1 ___Too long

APPENDIX J

”BEST” RESPONSE SURFACE MODELING RESULTS FOR DISTRACTION CONDITION

J.1 “BEST” RESPONSE SURFACE MODELING RESULTS FOR DISTRACTION CONDITION

Note: In all models provided in this Appendix, the following coding scheme is used:

X1 = coded variable for Active Steering Display Frequency
-1.9 signifies 4 Hz
-1 signifies 6 Ha
0 signifies 8 Hz
+1 signifies 10 Ha
+1.9 signifies 12 Hz

X2 = coded variable for Active Steering Display Amplitude
-1.9 signifies 1.0 Nm
-1 signifies 1.2 Nm
0 signifies 1.6 Nm
+1 signifies 1.8 Nm
+1.9 signifies 2.2 Nm

X2 = coded variable for Active Steering Display Duration
-1.9 signifies 0.50 seconds
-1 signifies 0.74 seconds
0 signifies 1.00 seconds
+1 signifies 1.26 seconds
+1.9 signifies 1.50 seconds

X4 through X8, when used, are binary (0, 1) indicator variables for Subject Effects (i.e., effects attributable to variation among the test participants or subjects).

```
Dependent Variable: ACCELRT, Best Model with Test Participant Effects, Distraction Condition


Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X2                       1               0.02668332              0.02668332      6.34     0.0137
X3                       1               0.01595323              0.01595323      3.79     0.0549
X4                       1               0.01875000              0.01875000      4.46     0.0378
X5                       1               0.00768000              0.00768000      1.83     0.1803
X6                       1               0.00065333              0.00065333      0.16     0.6945
X7                       1               0.01633333              0.01633333      3.88     0.0521
X8                       1               0.01633333              0.01633333      3.88     0.0521

                  R-Square                     C.V.                Root MSE         ACCELRT Mean

                  0.290597                 14.60313              0.06485413           0.44411111


                                                T for H0:        Pr > |T|       Std Error of
Parameter                             Estimate        Parameter=0                                Estimate

INTERCEPT                  0.4593333333              27.43         0.0001         0.01674526
X2                         -.0170937363              -2.52         0.0137         0.00678664
X3                         -.0132172580              -1.95         0.0549         0.00678664
X4                         -.0500000000              -2.11         0.0378         0.02368138
X5                         -.0320000000              -1.35         0.1803         0.02368138
X6                         -.0093333333              -0.39         0.6945         0.02368138
X7                         -.0466666667              -1.97         0.0521         0.02368138
X8                         0.0466666667               1.97         0.0521         0.02368138
```

```
Dependent Variable: ACCELRT, Best Model without Test Participant Effects, Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X2                       1               0.02668332              0.02668332      5.23     0.0246
X3                       1               0.01595323              0.01595323      3.13     0.0804

                  R-Square                     C.V.                Root MSE         ACCELRT Mean

                  0.087697                 16.07742              0.07140160           0.44411111


                                                T for H0:        Pr > |T|       Std Error of
Parameter                             Estimate        Parameter=0                                Estimate

INTERCEPT                  0.4441111111              59.01         0.0001         0.00752639
X2                         -.0170937363              -2.29         0.0246         0.00747180
X3                         -.0132172580              -1.77         0.0804         0.00747180
```

Dependent Variable: BRAKERT(Brake Reaction Time), Distraction Condition

No statistically significant models were found as a function of the active steering display variables of Frequency, Amplitude, or Duration. Individual differences among test participants accounted for approximately 49% of the variability in maximum pedal force. The remaining 51% of response variation is due to unknown sources of variability or random variation.

```
Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X4                       1               0.03536333              0.03536333      3.75     0.0561
X5                       1               0.10800000              0.10800000     11.46     0.0011
X6                       1               0.00616333              0.00616333      0.65     0.4210
X7                       1               0.31827000              0.31827000     33.76     0.0001
X8                       1               0.11781333              0.11781333     12.50     0.0007

                  R-Square                     C.V.                Root MSE           BRAKERT Mean

                  0.485834                 12.73996              0.09709266             0.76211111


                                                T for H0:        Pr > |T|       Std Error of
Parameter                     Estimate        Parameter=0                         Estimate

INTERCEPT                  0.8306666667             33.13         0.0001         0.02506922
X4                         0.0686666667              1.94         0.0561         0.03545323
X5                         -.1200000000             -3.38         0.0011         0.03545323
X6                         -.0286666667             -0.81         0.4210         0.03545323
X7                         -.2060000000             -5.81         0.0001         0.03545323
X8                         -.1253333333             -3.54         0.0007         0.03545323
```

Dependent Variable: MAXPEDF (Maximum Pedal Force), Distraction Condition

No statistically significant models were found as a function of the active steering display variables of Frequency, Amplitude, or Duration. Individual differences among test participants accounted for approximately 68% of the variability in maximum pedal force. The remaining 32% of response variation is due to unknown sources of variability or random variation.

```
Dependent Variable: MAXPEDF, Test Participant Effects Only Model, Distraction Condition


Source                  DF          Type III SS          Mean Square   F Value     Pr > F

X4                       1        1970.73075000        1970.73075000      4.57     0.0354
X5                       1       11359.58043000       11359.58043000     26.35     0.0001
X6                       1        2098.19307000        2098.19307000      4.87     0.0301
X7                       1       23104.09505333       23104.09505333     53.59     0.0001
X8                       1        1461.89121333        1461.89121333      3.39     0.0691

                  R-Square                 C.V.             Root MSE         MAXPEDF Mean

                  0.682086             16.59407          20.76269891         125.12122222

                                         T for H0:        Pr > |T|       Std Error of
Parameter                  Estimate     Parameter=0                        Estimate

INTERCEPT               130.1733333           24.28         0.0001         5.36090581
X4                      -16.2100000           -2.14         0.0354         7.58146570
X5                      -38.9180000           -5.13         0.0001         7.58146570
X6                      -16.7260000           -2.21         0.0301         7.58146570
X7                       55.5026667            7.32         0.0001         7.58146570
X8                      -13.9613333           -1.84         0.0691         7.58146570
```

Dependent Variable: TOTSTOP (Total Stopping Distance), Distraction Condition

No statistically significant models were found as a function of the active steering display variables of Frequency, Amplitude, or Duration. Individual differences among test participants accounted for approximately 81% of the variability in total stopping distance. The remaining variation in total stopping distance appears attributable to unknown sources of variability or random variation.

```
Dependent Variable: TOTSTOP, Test Participant Effects Only Model, Distraction Condition


Source                 DF            Type III SS          Mean Square   F Value     Pr > F

X4                      1           425.40736333         425.40736333      6.62     0.0118
X5                      1            10.76403000          10.76403000      0.17     0.6833
X6                      1          3546.66387000        3546.66387000     55.21     0.0001
X7                      1         16056.84675000       16056.84675000    249.95     0.0001
X8                      1           204.88533333         204.88533333      3.19     0.0777

                 R-Square                   C.V.             Root MSE           TOTSTOP Mean

                 0.814483               9.631559           8.01493361            83.21533333

                                             T for H0:        Pr > |T|       Std Error of
Parameter                     Estimate     Parameter=0                           Estimate

INTERCEPT                  96.87733333           46.81          0.0001         2.06944696
X4                         -7.53133333           -2.57          0.0118         2.92663996
X5                         -1.19800000           -0.41          0.6833         2.92663996
X6                        -21.74600000           -7.43          0.0001         2.92663996
X7                        -46.27000000          -15.81          0.0001         2.92663996
X8                         -5.22666667           -1.79          0.0777         2.92663996
```

Dependent Variable: BRKSTOP (Brake Stopping Distance), Distraction Condition

No statistically significant models were found as a function of the active steering display variables of Frequency, Amplitude, or Duration. Individual differences among test participants accounted for approximately 81% of the variability in brake stopping distance. The remaining variation in brake stopping distance appears attributable to unknown sources of variability or random variation.

Dependent Variable: BRKSTOP, Test Participant Effects Only Model, Distraction Condition

```
Source                 DF             Type III SS             Mean Square   F Value     Pr > F

X4                      1            482.08225333            482.08225333      8.59     0.0043
X5                      1             10.52576333             10.52576333      0.19     0.6660
X6                      1           3587.88288000           3587.88288000     63.94     0.0001
X7                      1          11777.83788000          11777.83788000    209.90     0.0001
X8                      1             98.35541333             98.35541333      1.75     0.1891

                 R-Square                    C.V.                Root MSE          BRKSTOP Mean

                 0.800984                10.74008              7.49073882           69.74566667


                                                T for H0:        Pr > |T|       Std Error of
Parameter                     Estimate        Parameter=0                        Estimate

INTERCEPT                  81.73800000              42.26          0.0001         1.93410045
X4                         -8.01733333              -2.93          0.0043         2.73523108
X5                          1.18466667               0.43          0.6660         2.73523108
X6                        -21.87200000              -8.00          0.0001         2.73523108
X7                        -39.62800000             -14.49          0.0001         2.73523108
X8                         -3.62133333              -1.32          0.1891         2.73523108
```

APPENDIX K

”BEST” RESPONSE SURFACE MODELING RESULTS FOR NO DISTRACTION CONDITION

K.1 “BEST” RESPONSE SURFACE MODELING RESULTS FOR NO DISTRACTION CONDITION

Note: In all models provided in this Appendix, the following coding scheme is used:

X1 = coded variable for Active Steering Display Frequency
-1.9 signifies 4 Hz
-1 signifies 6 Ha
0 signifies 8 Hz
+1 signifies 10 Ha
+1.9 signifies 12 Hz

X2 = coded variable for Active Steering Display Amplitude
-1.9 signifies 1.0 Nm
-1 signifies 1.2 Nm
0 signifies 1.6 Nm
+1 signifies 1.8 Nm
+1.9 signifies 2.2 Nm

X2 = coded variable for Active Steering Display Duration
-1.9 signifies 0.50 seconds
-1 signifies 0.74 seconds
0 signifies 1.00 seconds
+1 signifies 1.26 seconds
+1.9 signifies 1.50 seconds

X4 through X8, when used, are binary (0, 1) indicator variables for Subject Effects (i.e., effects attributable to variation among the test participants or subjects).

```
Dependent Variable: ACCELRT, Best Model with Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X2                       1               0.09452304              0.09452304     15.77     0.0002
X4                       1               0.14840333              0.14840333     24.76     0.0001
X5                       1               0.01875000              0.01875000      3.13     0.0806
X6                       1               0.01728000              0.01728000      2.88     0.0933
X7                       1               0.13333333              0.13333333     22.24     0.0001
X8                       1               0.01976333              0.01976333      3.30     0.0730

                  R-Square                     C.V.                Root MSE         ACCELRT Mean

                  0.392572                 19.45874              0.07742417           0.39788889


                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                  0.3273333333             16.37          0.0001         0.01999083
X2                         -.0321725799             -3.97          0.0002         0.00810203
X4                         0.1406666667              4.98          0.0001         0.02827131
X5                         0.0500000000              1.77          0.0806         0.02827131
X6                         0.0480000000              1.70          0.0933         0.02827131
X7                         0.1333333333              4.72          0.0001         0.02827131
X8                         0.0513333333              1.82          0.0730         0.02827131
```

```
Dependent Variable: ACCELRT, Best Model without Test Participant Effects, No Distraction Condition


Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X2                       1               0.09452304              0.09452304     11.48     0.0011

                  R-Square                     C.V.                Root MSE         ACCELRT Mean

                  0.115399                 22.80546              0.09074038           0.39788889

                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                  0.3978888889             41.60          0.0001         0.00956488
X2                         -.0321725799             -3.39          0.0011         0.00949550
```

```
Dependent Variable: BRAKERT, ’Best’ Model with Test Participant Effects, No Distraction Condition

Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X2                       1               0.26035234              0.26035234     18.08     0.0001
X4                       1               0.78732000              0.78732000     54.66     0.0001
X5                       1               0.03400333              0.03400333      2.36     0.1282
X6                       1               0.01408333              0.01408333      0.98     0.3256
X7                       1               0.00341333              0.00341333      0.24     0.6277
X8                       1               0.02640333              0.02640333      1.83     0.1794

                  R-Square                     C.V.                Root MSE         BRAKERT Mean

                  0.610082                 15.90540              0.12001511           0.75455556


                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                  0.7180000000              23.17         0.0001         0.03098777
X2                         -.0533946562              -4.25         0.0001         0.01255894
X4                         0.3240000000               7.39         0.0001         0.04382332
X5                         -.0673333333              -1.54         0.1282         0.04382332
X6                         0.0433333333               0.99         0.3256         0.04382332
X7                         -.0213333333              -0.49         0.6277         0.04382332
X8                         -.0593333333              -1.35         0.1794         0.04382332
```

```
Dependent Variable: BRAKERT,‘Best’ Model without Test Participant Effects, No Distraction Condition


Source                  DF              Type III SS             Mean Square   F Value     Pr > F

X2                       1               0.26035234              0.26035234      8.17     0.0053


                  R-Square                     C.V.                Root MSE         BRAKERT Mean

                  0.084915                 23.66391              0.17855735           0.75455556


                                                T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate        Parameter=0                        Estimate

INTERCEPT                  0.7545555556              40.09         0.0001         0.01882160
X2                         -.0533946562              -2.86         0.0053         0.01868507
```

Dependent Variable: MAXPEDF (Maximum Pedal Force), No Distraction Condition

No statistically significant models were found as a function of the active steering display Frequency, Amplitude, or Duration. All variation in maximum pedal force appears unrelated to the active steering variables at the levels tested in this study. Individual differences among test participants accounted for approximately 81% of the variability in maximum pedal force. The remaining variation in is maximum pedal force is associated with unknown sources of variability or random variation.

```
Dependent Variable: MAXPEDF Test Participant Effects Only Model, No Distraction Condition


Source                 DF           Type III SS           Mean Square   F Value     Pr > F

X4                      1          424.35363000          424.35363000      1.50     0.2242
X5                      1         3061.91621333         3061.91621333     10.82     0.0015
X6                      1         1905.94581333         1905.94581333      6.73     0.0112
X7                      1        50555.53803000        50555.53803000    178.63     0.0001
X8                      1          532.22832000          532.22832000      1.88     0.1739

                 R-Square                  C.V.              Root MSE          MAXPEDF Mean

                 0.813037              13.79903           16.82298614          121.91422222


                                        T for H0:        Pr > |T|       Std Error of
Parameter                  Estimate    Parameter=0                        Estimate

INTERCEPT               111.5973333          25.69         0.0001        4.34367634
X4                        7.5220000           1.22         0.2242        6.14288599
X5                      -20.2053333          -3.29         0.0015        6.14288599
X6                      -15.9413333          -2.60         0.0112        6.14288599
X7                       82.1020000          13.37         0.0001        6.14288599
X8                        8.4240000           1.37         0.1739        6.14288599
```

Dependent Variable: TOTSTOP (Total Stopping Distance), No Distraction Condition

No statistically significant models were found as a function of the active steering display Frequency, Amplitude, or Duration. All variation in total stopping distance appears unrelated to the active steering variables at the levels tested in this study. Individual differences among test participants accounted for approximately 85% of the variability in maximum pedal force. The remaining variation in total stopping distance is associated with unknown sources of variability or random variation.

Dependent Variable: TOTSTOP Test Participant Effects Only Model, No Distraction Condition

```
Source                DF          Type III SS         Mean Square   F Value     Pr > F

X4                     1         416.93952000        416.93952000     10.27     0.0019
X5                     1           3.01467000          3.01467000      0.07     0.7859
X6                     1         558.31788000        558.31788000     13.75     0.0004
X7                     1       10510.15701333      10510.15701333    258.90     0.0001
X8                     1          53.38668000         53.38668000      1.32     0.2547


                R-Square                 C.V.            Root MSE         TOTSTOP Mean

                0.845721             7.816582          6.37144346          81.51188889


                                              T for H0:        Pr > |T|       Std Error of
Parameter                      Estimate      Parameter=0                       Estimate

INTERCEPT                   88.49666667            53.79         0.0001         1.64509963
X4                           7.45600000             3.20         0.0019         2.32652220
X5                          -0.63400000            -0.27         0.7859         2.32652220
X6                          -8.62800000            -3.71         0.0004         2.32652220
X7                         -37.43466667           -16.09         0.0001         2.32652220
X8                          -2.66800000            -1.15         0.2547         2.32652220
```

Dependent Variable: BRKSTOP (Brake Stopping Distance), No Distraction Condition

No statistically significant models were found as a function of the active steering display Frequency, Amplitude, or Duration. All variation in total stopping distance appears unrelated to the active steering variables at the levels tested in this study. Individual differences among test participants accounted for approximately 87% of the variability in maximum pedal force. The remaining variation in is brake stopping distance force is associated with unknown sources of variability or random variation.

```
Source                  DF               Type III SS             Mean Square   F Value     Pr > F

X4                       1               16.81505333             16.81505333      0.60     0.4400
X5                       1                1.16033333              1.16033333      0.04     0.8390
X6                       1              776.63232000            776.63232000     27.80     0.0001
X7                       1             9438.74456333           9438.74456333    337.85     0.0001
X8                       1               57.07681333             57.07681333      2.04     0.1566


                  R-Square                      C.V.                Root MSE         BRKSTOP Mean

                  0.866032                  7.742548              5.28563989          68.26744444


                                                 T for H0:        Pr > |T|       Std Error of
Parameter                       Estimate        Parameter=0                        Estimate

INTERCEPT                    76.02066667              55.70         0.0001         1.36474635
X4                            1.49733333               0.78         0.4400         1.93004280
X5                            0.39333333               0.20         0.8390         1.93004280
X6                          -10.17600000              -5.27         0.0001         1.93004280
X7                          -35.47533333             -18.38         0.0001         1.93004280
X8                           -2.75866667              -1.43         0.1566         1.93004280
```

APPENDIX L

TEST PARTICIPANT CONSENT FORM

L.1 TEST PARTICIPANT CONSENT FORM

Title of Study: **Haptic Display Study No. 2**

Study Description: Rear-end crashes are among the most common types of crashes. Research is under way into ways to use sensors and computer technology to detect potential crash hazards and warn a driver in time to avoid such hazards. Various auditory displays (tones) and visual displays (lights) have been proposed as rear-end crash warning displays. However, it may also be possible to warn the driver by a display that is felt rather than seen or heard. One type of 'felt' display is called a Pulse Braking Display. The brakes are applied for very brief period of time to alert the driver of a possible hazard ahead.

Haptic display systems are those which use tactile means to provide the driver with information. Haptic displays being developed for use in cars and trucks can be used in lieu of auditory or visual displays to call the driver's attention to urgent information. Such systems allow a driver to receive information without diverting his eyes from the roadway, and use this information to perform the driver's primary job of safely controlling the vehicle. The National Highway Traffic Safety Administration (NHTSA) is conducting research to measure the effects on driver performance of using such display methods. One area of research is the effect on driver behavior and performance when these displays advise drivers in a car following situation that their time headway to a lead vehicle has fallen below a predetermined limit; that is, that a collision with the vehicle ahead may be imminent.

As a participant, you will be shown a haptic display system, and oriented on the actions you are to take when displays occur. The display system in this study, referred to as Pulse Braking, is a proposed method of alerting a driver to an imminent crash with a vehicle or object ahead of them. The purpose of the display is to alert the driver that he may need to apply the vehicle's brakes. In order to alert the driver to a need for braking action, Pulse Braking provides a brief brake application to achieve a predetermined rate or level of deceleration. The brakes are then automatically released; subsequent braking action is the responsibility of the vehicle driver. The deceleration effected by the display itself is minimal and insufficient to prevent most impending collisions. To stop the vehicle, the driver must apply the brakes.

The purpose of today's testing is to help determine what might be the most appropriate type of Pulse Braking Display. You will be driving an instrumented vehicle on the TRC Skid pad at a speed of 42 mph. You will be driving under conditions where you are working on a distracting in-vehicle task, the entry of a destination into a route guidance system. During your drive, you will be following another vehicle, known as the lead vehicle, in the same lane at usually the same speed. The lead vehicle is actually an artificial automobile being towed by a real automobile. You will be asked to maintain a constant time headway of two seconds to the artificial automobile ahead. **Your vehicle is equipped with a computer-controlled cruise control system to aid you in maintaining the desired time headway to the moving lead vehicle. You will not normally need to adjust the cruise control or throttle position, unless you feel it necessary in the interest of safety. Braking the vehicle to slow or stop it remains your responsibility. From time to time, this artificial automobile will rapidly decelerate to a stop. Neither the artificial automobile nor the vehicle towing it will have functioning brake lights. Often a pulse braking event will be presented to**

warn you that the artificial automobile is stopping. A pulse braking event may also occur even though the artificial automobile ahead is maintaining a constant speed; in this case it is not necessary for you to stop. <u>As soon</u> as you perceive that the artificial automobile ahead is decelerating to a stop, your job is to avoid a collision by bringing your vehicle to a controlled stop. You will then be asked to rate the particular level of pulse braking event, if applicable, in terms of appropriateness as a warning. The rating scales will be presented to you later in this session. Do you have any questions about the intent of the study and the procedure?

You will also receive training on how to complete destination entry tasks with a commercially available route guidance system. The experimenter will show you a set of "target" destinations that you are to write down on individual 4x6 index cards so that you will be able to use them for destination entry during practice as well as while driving on the TRC skid pad. You will have an opportunity to practice entering destinations with the system in a parked vehicle and ask any questions you wish of the experimenter.

The experimenter will accompany you during all testing. During testing, you will be asked to wear protective headphones to shield you from potentially distracting sounds. These headphones contain speakers through which you will hear modified ocean sounds to mask any remaining unwanted noise. The ride-along experimenter will be responsible for all radio communications with the control tower and other test units. The ride-along experimenter will also periodically hand you a 4x6 index card with a destination written on it, a signal that you are to enter that destination into the route guidance system, **WHEN AND IF YOU BELIEVE IT IS SAFE TO DO SO GIVEN THE CURRENT DRIVING CONDITIONS ON THE SKID PAD.** The experimenter may sometimes ask you to begin a destination entry task, then subsequently determine that it is not necessary to complete that task. You will be asked to drive a series of laps in an assigned lane on the TRC skid pad. On the straight sections of the skid pad, the ride-along experimenter will ask you to maintain a speed of 42 mph. Periodically, the artificial automobile ahead of you will decelerate to a stop. The haptic display system may provide a pulse braking display to warn that the vehicle ahead is stopping. This display will often but not always be associated with the deceleration of the artificial automobile ahead. The haptic display can be expected to vary slightly with each occurrence, but will always be the characterized by a brief, automatic application and release of the vehicle's brakes. The Pulse Braking event will not affect your ability to control your vehicle, and will, in and of itself, have little effect upon your vehicle's speed. After you have applied the brakes and brought the vehicle to a controlled stop, if appropriate, the experimenter will ask you a series of questions about the appropriateness of the display as a warning. As the headphones may make it difficult to hear the experimenter, he will show you cards containing lists of descriptions of the display's appropriateness, from which you will be asked to choose that which matches your opinion. After the experimenter records your response, you will continue with the next trial and rating. After you have completed a series of laps, you will return to Building 60. The complete series of orientations and trials will take approximately four hours.

You, as the driver of the test vehicle, are responsible for maintaining safety at all times. Do not perform any task which you believe would be unsafe. Remember, you must be the final judge of whether or when to work on a task or make a response. The haptic displays serve only as a warning to decelerate or stop -- the vehicle, you must apply the brakes as in any other car. Do you have any questions?"

It is very important to always remember that you, as the driver, are in control of the vehicle and you must be the final judge on when or whether to respond to any request or engage in any task. You should follow a request or prompt or complete a task or maneuver only when, in your judgement, it is safe and convenient to do so. The ride-along experimenter will not be able to insure safety; you as the driver are responsible for that. Remember, safety while driving on the skid pad is your primary responsibility. Complete requests only when and if you believe it is safe to do so.

Risks: While driving for this study, you will be subject to all risks normally associated with driving on the TRC skid pad plus any additional risks associated with completing in-vehicle tasks while driving. There are no known physical or psychological risks associated with participation in this study beyond those indicated.

Be aware that accidents can happen any time when driving. You remain responsible for your driving during this testing. If the ride-along experimenter should make a request, or the display prompt an action, you are not to do it unless you judge it is safe to do so.

Benefits: This testing will provide data on driver behavior, performance judgements, and preferences regarding the haptic display methods presented. This data will provide a scientific basis for guiding recommendations on standards for haptic display systems in the future.

Confidentiality: The data recorded on you will be analyzed along with data gathered from other test participants during this testing. Your name will not be associated with any final report, publication, or other media that might arise from this study. However, your video-recorded likeness (in video or still photo formats created from the video) and engineering data from you specifically may be used for educational and research purposes. A waiver of confidentiality for permission to use the video and engineering data (including data or images derived from these sources) is included for you to sign as part of this form. It is not anticipated that you will be informed of the results of this study.

Informed Consent: By signing below, you agree that participation is voluntary and you understand and accept all terms of this agreement. **You have the option of not performing any requested task at any time during the test without penalty.**

Compensation: Should you agree to participate in this testing, it will be considered part of your normal work day activities. There is no special compensation associated with participation in the test.

Principal Investigator: Contact Dr. Louis Tijerina (TRC) or Dr. Riley Garrott (NHTSA VRTC) if you have questions or comments regarding this study. They may be reached at the following address and phone number:

Vehicle Research and Test Center
10820 SR 347
East Liberty, OH 43319
Phone: (937) 666-4511

Disposition of Informed Consent: The VRTC will retain a signed copy of this Informed Consent form. A copy of this form will also be provided to you.

INFORMED CONSENT:

I, ________________________, UNDERSTAND THE TERMS OF THIS AGREEMENT AND VOLUNTARILY CONSENT TO PARTICIPATE.

______________________________ ____________

Signature Date

______________________________ ____________

Witness Date

WAIVER OF CONFIDENTIALITY:

I, ________________________, grant permission, in perpetuity, to the National Highway Traffic Safety Administration (NHTSA) to use, publish, or otherwise disseminate the video-tape (including still photo formats derived from the videotape) and engineering data collected about me in this study for educational, outreach, and research purposes. I understand that such use may involve widespread distribution and may involve dissemination of my likeness in videotape or still photo formats, but will not result in release of my name or other identifying personal information.

______________________________ ____________

Signature Date

_____________________________ ____________

Witness Date

APPENDIX M

MONO-PULSE BRAKING STUDY 3: SKID PAD INSTRUCTIONS

M.1 MONO-PULSE BRAKING STUDY 3: SKID PAD INSTRUCTIONS

INSTRUCTIONS FOR SKID PAD

The object you will be driving behind is an “artificial” rear-end of a car. This artificial car is not equipped with working brake lights/stop lamps. You will be asked to follow the artificial car at a distance to be indicated by the experimenter (me). You will be instructed to engage the cruise control and a computer will then maintain the following distance and adjust your vehicle speed as necessary. A third car will be following your vehicle.

From time to time, the lead vehicle will brake to a complete stop. A pulse braking event may be presented to warn you that the lead vehicle is coming to a complete stop. That is, your brakes will be applied by a computer for a brief period of time. It is also possible that the pulse braking event may be presented even if the lead vehicle is not braking. As soon as you notice that the lead vehicle is braking to a stop, bring your vehicle to a controlled stop. Failure to bring the vehicle to a controlled stop may result in a collision with the artificial lead vehicle. Afterwards, you will be asked whether or not you noticed a pulse braking event. If so, you may be asked to rate the pulse braking event in terms of its timing and appropriateness as a warning display using a rating scale format. (Show them the rating scale card).